TEMPORAL VARIATION IN SOIL GAS COMPOSITION IN RELATION TO SEISMICITY IN SOUTH-WEST ENGLAND

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As part of a European geochemical seismic zonation project, soil gas measurements have been made in two areas of south-west England for comparison with seismicity data. A fault zone on the south-east side of the Carnmenellis granite in Cornwall was chosen for the historic seismicity and good seismic monitoring network in the area. In Devon the Sticklepath Fault was selected as a large regional structure with low intensity and infrequent seismic activity. The soil gases measured were helium, radon and carbon dioxide. After initial soil gas mapping of each area, a small number of monitoring sites were selected and then sampled every two weeks for over one year. The temporal variations of soil gas concentrations were compared to meteorological factors which could cause them to vary, and also with recorded seismic activity. Anomalously high values of soil gas concentrations could be matched to minor seismic events, both as precursors and following activity.

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INTRODUCTION

A number of authors have recognised changes in radon (Rn) activity in relation to seismic activity. In the Provence area of France, Abbad *et al.* (1995) used continuously logged Rn measurements from detectors buried in specially designed chambers, and considered that variations not attributable to meteorology were seismically related. A Rn peak perhaps double the usual activity would occur one or more days before an earthquake. In Algeria Djeffal *et al.* (1995) found that increased Rn was present just before or after large magnitude earthquakes. The Rn readings were based on monthly track-etch recordings with the detectors placed 0.70 m deep in shallow boreholes.

Great Britain lies within an area of generally low seismicity, however there are faults that are geologically similar to those involved in higher seismic activity in other countries. As part of a European geochemical seismic zonation project it was decided that soil gas analysis gave an opportunity to study Rn changes over time, in relation to faulting, as well as allowing helium (He) and carbon dioxide (CO_2) to be included. This research aimed to collect soil gas geochemical data and to study its variation over time in an area of low seismicity.

Historical seismic activity across Devon and Cornwall is covered by Musson (1989). His report shows eight main groupings of historical earthquakes with the most frequent occurring in the area of the Carnmenellis granite of Cornwall. Other groupings in Cornwall include the areas around Penzance, the Scilly Isles, offshore from Newquay and around Liskeard and Launceston. In Devon there are groupings around the Dartmoor granite and North Devon. Examples of earthquakes include one near Penzance in 1904, with an intensity of 5 on the MSK scale, centred offshore in Mounts Bay, and another at Helston in 1966. The latter is described as the only certain earthquake occurring in Cornwall between 1920 and 1966 and it had a maximum intensity of 6 MSK. The MSK scale, named after its originators in 1964, Medvedev, Sponheuer and Karnik, is based on the intensity of the earthquake as felt by people in the area. Intensity 5 is strong but not damaging to buildings whereas intensity 6 would cause slight damage. In 1992 (Grünthal, 1993) this intensity scale was modified to become the European Macroseismic Scale or EMS. Over Dartmoor seismic activity has been rare, the most significant event being in 1923 at South Brent on the south side of the granite and giving a maximum intensity of 5 MSK. Newspaper and parish records researched by Musson (1989) for the British Geological Survey (BGS) show that there has been some seismicity in the area of the Sticklepath Fault in historical time; an example is the Bovey Tracey earthquake of 5 January 1756.

SAMPLING METHODOLOGY

The methodology has been previously described in Duddridge *et al.* (1991) and Duddridge (1994) and is based on the extraction of gases from 0.5 m depth using soil probes, as gas concentrations within the pores of the unsaturated zone of soils may in part be determined by the bedrock below.

Radon was measured by using Lucas ZnS (Ag) scintillation cells on both an EDA Electronics RD-200 meter and a Pylon AB5 meter. Calibration was based on a standard source of Rn and comparative tests between the two different instruments was also carried out to cover periods of instrument breakdown. A Leybold UL400 mass spectrometer was used to determine ^4He differences (ΔHe) from the atmospheric air value of 5220 ppb (Holland and Emerson, 1987) to an accuracy of ±30 ppb. Carbon dioxide was measured principally by a Geotechnical Instruments Infra-red Gas Analyser, but for some sites gas chromatography was used throughout, as a backup and as a check.

SOIL GAS MAPPING FOR SITE SELECTION

Carnmenellis Area

The Carnmenellis area in Cornwall has had a recent history of low intensity, but frequent seismicity. This fact, together with the siting on this granite of the Hot Dry Rocks geothermal project, has led to a good network of BGS seismic monitoring stations. BGS records (Walker and Browitt, 1995) show that in south-west England the area of the Carnmenellis granite was the most seismically active with magnitudes up to 3 local magnitude (ML) on the Richter Scale (the Richter scale is a measure on a logarithmic scale of the magnitude or amplitude of the earthquake at its focus, and is not directly comparable to the intensity MSK scale). The Carnmenellis granite is one of the granite plutons of the south-west England batholith cutting country rock of Palaeozoic age.

The work by Heath (1982) on the Carnmenellis granite showed Rn

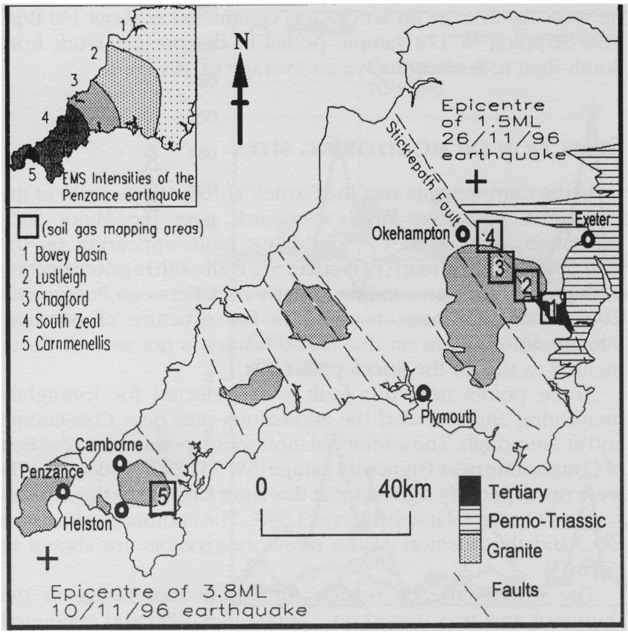

Figure 1. Location map, showing the 1996 Penzance and Okehampton earthquakes, simplified geology from BGS information and the soil gas mapping areas. The inset map shows the EMS intensities of the Penzance earthquake (after Walker, 1997).

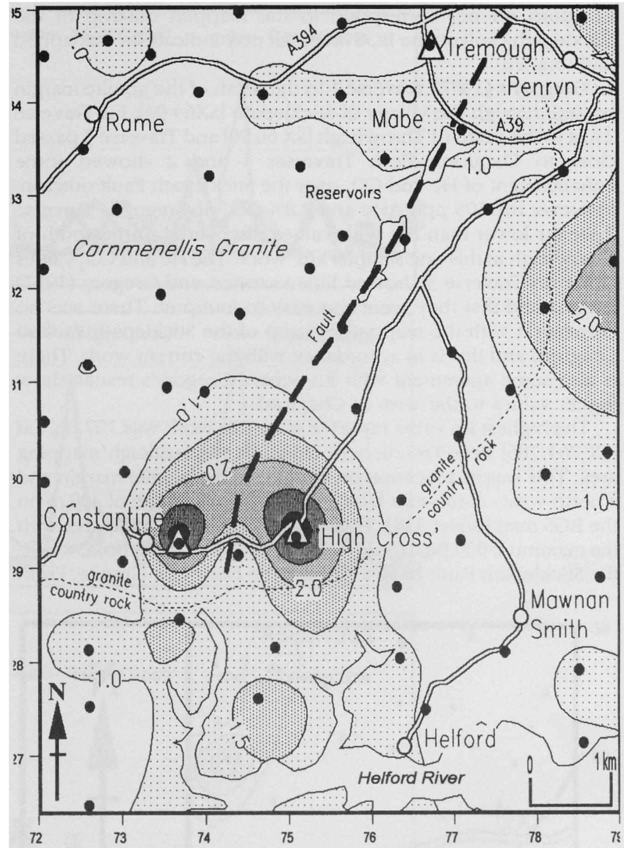

Figure 2. Location map of the Carnmenellis soil gas mapping area, showing contoured CO_2 concentrations and the 3 monitoring points selected for He, Rn and CO_2 monitoring (see Figure 3 for key).

activity in surface water to be highest on a north-west - southeast elongated zone through the western side of the outcrop. No high values or trends in the data were revealed by the stream waters from the south-eastern part of the granite where soil gas measurements are reported in this paper. Gregory (1987) also surveyed the Carnmenellis granite and adjacent areas for He and Rn in surface waters. His sampling density was 0.5 samples/km^2 with 91 samples in total.

In the work reported here in the Carnmenellis area 58 sites were sampled for He, Rn and CO_2 over 58 km^2 of land between Constantine and Penryn and north of the Helford River (Figures 1 and 2). The area mapped covers the south-eastern part of the Carnmenellis granite and the country rock to the south as far as the Helford River. The eastern boundary of the area is marked by the urban areas of Penryn and Falmouth.

The anomalous soil gas values found were relatively low, however, at one point near Constantine [SW 737 293] soil gas was slightly enhanced in ΔHe at 51 ppb, together with above average ^{222}Rn of 77 Bq/l and 3.56% CO_2. The area around Penryn was the most anomalous and a sample site at Tremough [SW 767 346] gave 103 Bq/l of ^{220}Rn against a mean of 14 Bq/l. At this point ^{222}Rn was 59 Bq/l, CO_2 was 0.95% and ΔHe 65 ppb. Away from the Constantine and Penryn areas most ΔHe values were less than 10 ppb or negative.

No correspondence has been noted between Gregory's (1987) survey and the soil gas work reported here, with the exception of a high concentration of Rn in surface water shown by Gregory to the north of Constantine. This is close to, but does not exactly coincide with the soil gas anomaly found on the recent survey closer to the village.

Dartmoor Area

The Sticklepath strike-slip fault system in Devon is an example of one of the more extensive faults in the United Kingdom. It consists of 80 km of en echelon north-west - south-east trending faults across Devon with further extensions offshore. It has a long history of movement, probably initiated within the Variscan orogeny, with up to 10 km of displacement. Carboniferous rocks are seen to overthrust Tertiary clays at the southern margin of the Bovey Basin and are, therefore, further evidence of the activity of this fault. As soil gas mapping had already been done over the Bovey Basin (Duddridge, 1994) it was considered that this large regional structure, with low intensity and infrequent seismicity was a good target for soil gas monitoring work.

Previous soil gas research in the area of Dartmoor transected by the Sticklepath Fault was done by Gregory (1987). This consisted of three traverses crossing the outcrop of the fault, as shown on the BGS map (Sheet 324), in the area between the villages of Sticklepath and Chagford. Further Rn work is reported by Varley (1993).

A 30 km section of the Sticklepath Fault where it cuts through the Dartmoor granite was chosen for soil gas study. The area was divided into 4 mapping sub-zones of approximately 56 km^2 (Figures 1 and 3). The first sub-zone was in the south-east where the Bovey Basin had already been mapped for He, Rn and CO_2 at 2 samples/km^2 (Duddridge, 1994). The more recent work covered the Lustleigh, Chagford and South Zeal sub-zones at 1 sample/km^2. A higher sampling density would have been desirable to resolve better the gas permeable features of the area, however cost and time constraints meant that priority was to be given to selecting suitable monitoring points for temporal studies.

The highest value of ΔHe recorded at the time of the Chagford area mapping was 196 ppb at Aysh [SX 662 898]. Carbon dioxide was 4.88% and ^{222}Rn 282 Bq/l at this position. Other high results were obtained at [SX 665 853]: 172 ppb ΔHe, 2.9% CO_2 and 272 Bq/l of ^{222}Rn; [SX 671 833]: 121 ppb ΔHe, 2.27% CO_2 and 462 Bq/l of ^{222}Rn and [SX 679 849]: 113 ppb ΔHe, 3.07% CO_2 and 514 Bq/l of ^{222}Rn; all these sites are underlain by granite. Previous soil gas surveys have shown that high ΔHe often accompanies high CO_2, values indicating a carrier gas effect, whereas high Rn and high CO_2 are often mutually exclusive at individual sampling points. The patterns of anomalous gas results from Dartmoor were slightly unusual as there was little mutual exclusivity of high Rn and CO_2. The anomalously high soil gas values to the west of Chagford do not correspond to the mapped outcrop of the Sticklepath Fault on the BGS map, but may indicate an unmapped fault branch.

Gregory's (1987) Traverse 1 to the north of the granite margin passed through the village of Sticklepath [SX64 94], his Traverse 2 just to the north of Throwleigh [SX 66 90] and Traverse 3 passed close to Chagford. Both Traverses 1 and 2 showed some enhancement of He and CO_2 over the Sticklepath Fault outcrop. However the 105 ppb ΔHe and 2.8% CO_2 of Gregory's Traverse 2 are far lower than the high values discovered to the south of Throwleigh in this one sample/km^2 work. The He and CO_2 values along his Traverse 3 showed little variation and Gregory (1987) commented that they were less easy to interpret. There was no correlation with the mapped outcrop of the Sticklepath Fault at Chagford and this is in accordance with the current work. There is also some agreement with Rn, where Gregory's results show higher values to the west of Chagford.

The highest Rn value reported from this work was 707 Bq/l at [SX 764 785] near Trendlebere Down in the Lustleigh mapping area. This was at a location on or close to the granite margin and a north-west - south-east fault is mapped for a length of 400 m on the BGS map (Sheet 338). This level of Rn activity compares with the maximum 900 Bq/l found by Varley (1993) from a point where the

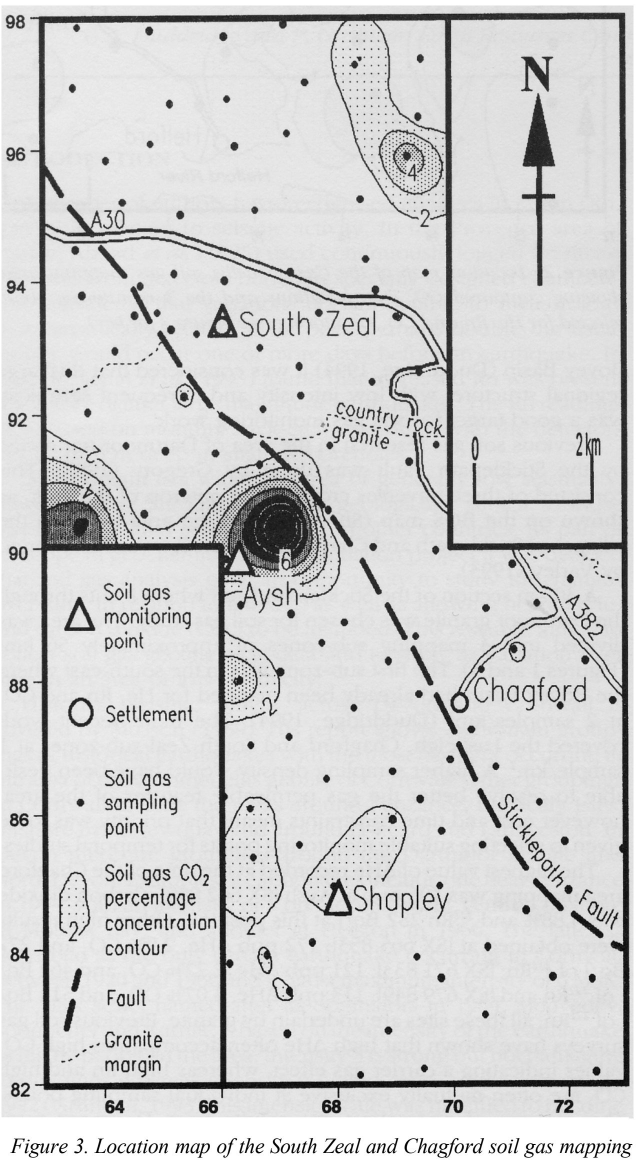

Figure 3. Location map of the South Zeal and Chagford soil gas mapping areas, showing contoured CO_2 concentrations and the 3 monitoring points selected for He, Rn and CO_2 monitoring.

Sticklepath Fault passes through the Dartmoor Granite. From his work the average Rn activity was determined as about 150 Bq/l. The mapping of 178 sample points in the present work from South Zeal to Lustleigh gave an average of 101 Bq/l.

SELECTION OF MONITORING SITES

In the Carnmenellis area the Carrick Thrust carries rocks of the Portscatho Formation north-westwards over the Mylor Slate Formation. A north-east - south-west fault, appearing on the 1:50,000 geological map (BGS sheet 352 Falmouth) and transecting both granite and surrounding country rock between Penryn and Constantine, has been targeted as the structure of potential interest. Information on this fault's history is not as well documented as that of the Sticklepath Fault.

Three points near this fault were selected for fortnightly monitoring and included the anomalous sites near Constantine and at Tremough. The additional monitoring point was to the east of Constantine near Highcross garage [SW 751 294]. Radon and He were not especially significant at this latter site, but in the original survey CO_2 was relatively high at 3.59%. The contoured results for CO_2, and the position of the monitoring points are shown in Figure 2.

The programme of regular fortnightly monitoring in the Dartmoor area was started on 2 September 1996 and continued until 8 December 1997. One of the two main sites was in South Zeal [SX 650 936] and the second at Aysh [SX 661 898] to the south of the village of Throwleigh. The site at South Zeal was selected as a secure point off the granite, but relatively close to the Sticklepath Fault. That at Aysh was chosen as it recorded high soil gas He, CO_2 and Rn during the soil gas mapping. On 17 February 1997 a further 4 monitoring points were established in the Dartmoor area close to the Sticklepath Fault zone and monitored until December 1997.

RESULTS FROM THE CARNMENELLIS AREA

Ten days before the start of soil gas monitoring a magnitude 0.6 ML earthquake had occurred 11/2 km south-west of the Constantine monitoring point, but no residually high soil gas values could be attributed to this event. Just 10 weeks after the start of monitoring, the Penzance earthquake of magnitude 3.8 ML occurred on 10 November 1996 (Figure 1). The monitoring points in the Carnmenellis area were within EMS intensity area 4 of the earthquake and 30 to 35 km from the known epicentre 12 km south of Penzance (Walker, 1997). This period coincided with higher than normal CO, of 5.93% compared to 3.59% in the original survey at the High Cross monitoring point (Figure 4). However, this point at High Cross was chosen for its high CO_2 value, thought possibly to be over a fault. High rainfall may well have trapped CO_2, which would otherwise have dispersed to atmosphere more readily at the time of the first survey in the summer of 1996. A 7.56% CO_2 concentration was recorded on 27 May 1997, but this was closely coincident with periods of rainfall 11 to 8 days previously of 15.7, 9.7 and 12.6 mm. The records show that 46.2 mm of rain fell on 5 June 1997, but the monitoring at High Cross just 4 days later only recorded 1.19% CO_2 and it was also low at the other sampling points. This suggests, as the other peaks perhaps indicate, that CO_2 flux may be intermittent in nature and that soil gas concentrations are dependent not only on rainfall.

The monitoring on 1 September 1997 at Constantine showed the culmination of a rise in CO_2 level to 8.46%. This rise became noticeable on 21 July 1997 when it was 3% and was followed by a 5% value on 18 August 1997, however no sample could be taken on the intermediate date of 4 August due to waterlogging of the ground, a factor which may be significant. In each case the periods of increased CO_2 at both the High Cross and Constantine sites coincided with similar periods of above average ΔHe, although at no time can the observed values be considered to be especially anomalous. There is therefore no evidence that either He or CO_2 values are related to the Penzance seismic event, but it may be of note that one of the periodic

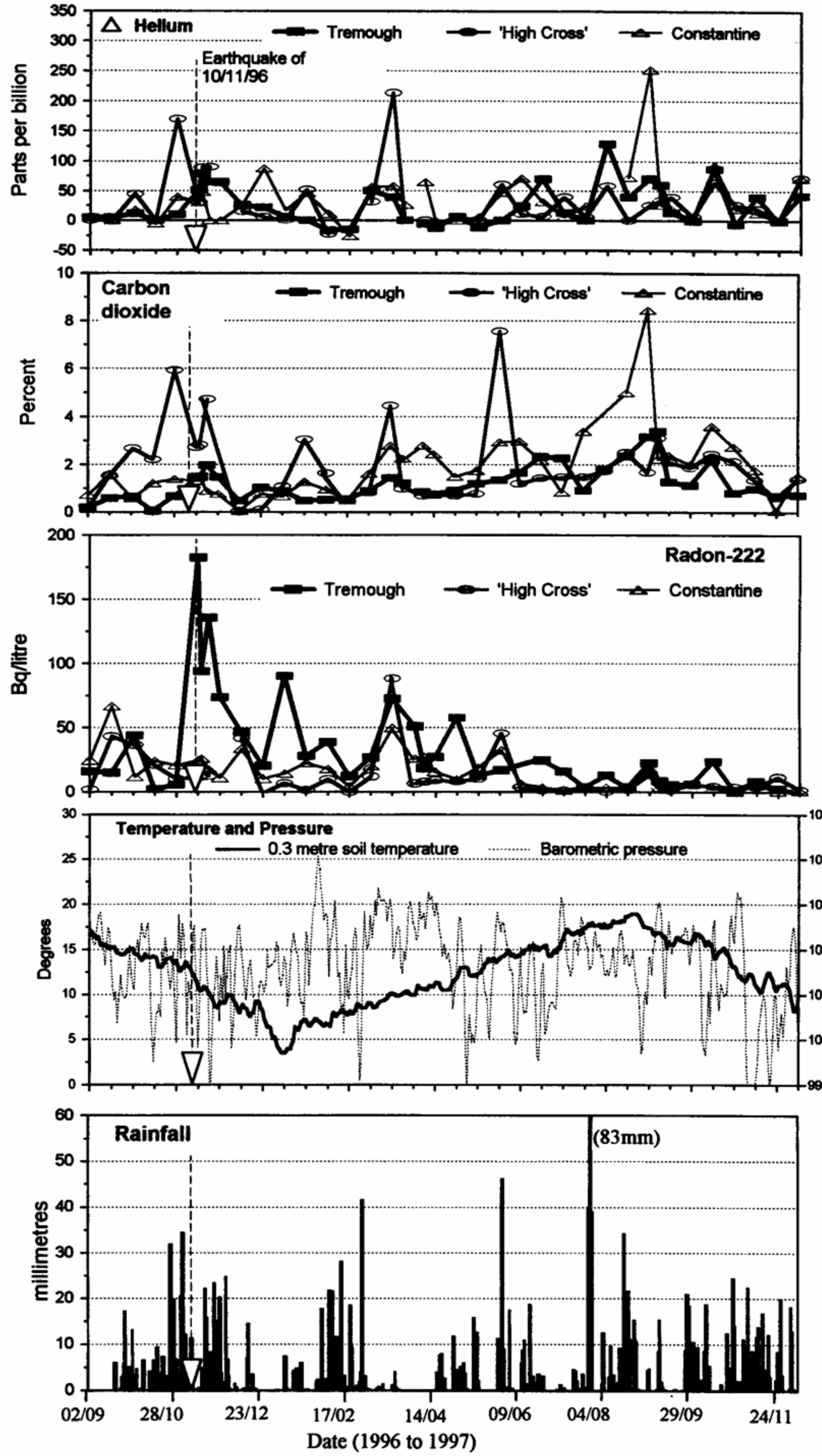

Figure 4. *Soil gas He, Rn and CO_2 monitoring results from the Carnmenellis area, together with soil temperature, barometric pressure and rainfall data.*

increases in the level of the gases was coincident.

The monitoring site at Tremough is of interest in relation to the Penzance earthquake as it recorded a Rn activity of 182 Bq/l the day after, followed by a moderately steady decline. The activity on 11 November 1996 was against an average of 39 Bq/l and a maximum of 46 Bq/l in the preceding weeks. Two days after the earthquake Rn was 94 Bq/l, 136 Bq/l 8 days after and then 74Bq/114 days later on 25 November 1996. The regular fortnightly monitoring then recorded 46, 20, 90 and 28 Bq/l settling into a background level where the variation in the obtained values may be as much dependent on sampling conditions from the soil as true values themselves. The Rn result from Tremough is a strong indicator that the earthquake did give rise to a geochemical anomaly, but it is not known whether the geochemical anomaly arose in the days immediately preceding the earthquake although it is clear that values were normal 13 days previously.

RESULTS FROM THE DARTMOOR AREA

During the course of the monitoring the site at South Zeal remained consistently low in soil gas He and little variation occurred in CO_2 and ^{222}Rn (Figure 5). Peaks of just 51 Bq/l of ^{222}Rn and 1.5% CO_2 were reached on 28 October 1996. In contrast there was much more variation at Aysh. The site at Aysh which had recorded 4.88% CO_2 in the initial soil gas mapping survey remained high for 6 out of 8 subsequent monitoring periods. The highest value of 7.56% CO_2 was recorded on 16 September 1996, whilst the low values (close to atmospheric levels) from the 2 and 30 September are almost certainly due to poor sampling conditions. On the 25 November 1996 CO_2 was still high at 6.27% and on the following day, 20 km to the north, a magnitude 1.5 ML earthquake was recorded near Winkleigh by the BGS. Following the earthquake the CO_2 concentrations dropped remarkably and for the following 3 months remained relatively low. Only in March 1997 did CO_2 start to rise towards a peak of 5.26% on 23 June 1997 and significantly decline through the Autumn of 1997 with no repeat of the Autumn 1996 levels.

This rise and fall of CO_2 throughout the summer period may in part be a response to biogenic processes and the graph of rainfall also indicates that the soil was heavily water laden prior to the earthquake. It is not unusual for wet ground to prevent soil gas from dispersing to the atmosphere and where a gas flux is present, from faults and fractures below, high values can build up. This could be offered as an explanation for the high CO_2 values recorded during November 1996, but the He in the 4 weeks leading to 25 November 1996 showed a steady increase from 145 ppb to 280, 547 and 570 ppb of ΔHe. The steady rise of the main He peak is not so easily explained by ground conditions and is the most distinctive feature of the monitoring records. Its coincidence with high CO_2 up to 6.53% suggests that these figures result from large variations in gas flux through a fault. As the site at Aysh is further west than the mapped Sticklepath Fault outcrop, this may be evidence for another parallel fault or even that the main fault in terms of gas flux is here rather than further to the east.

However, the fact that neither He or CO_2 regained such high values after the earthquake is a strong indicator that the impending earthquake was exerting a control on the release of gases from deep fault structures below, although the rainfall at the time is likely to have enhanced the trapping of these gases in the soil medium so as to give an amplified response. The high 7.56% CO_2 value recorded in mid-September before any significant rainfall and the 10.88% CO_2 found near Throwleigh on the soil gas mapping survey in July 1996, support the contention that the area had become geochemically anomalous. The 10.88% CO_2 value, obtained as the average of two analyses of 10.49 and 11.27% CO_2, was accompanied by 0_2 at 11.01% and N_2 at 77.39%. The concentration of N_2 just below the atmospheric value helps to rule out an oxidation of methane origin for the CO_2, methane itself being absent from the samples. Such high soil gas values have not been recorded since, suggesting that in both Cornwall and Devon seismicity produced a soil gas geochemical response at some locations.

Radon activity also dropped markedly although not immediately after the 25 November 1996 earthquake, but the activity again increased from the Spring to Autumn of 1997 and indeed the highest recorded activity was 162 Bq/l on 17 March 1997 and 179 Bq/l on 29 September 1997. The highest ^{222}Rn activity recorded in the Dartmoor monitoring exercise was 406 Bq/l at Shapley, one of the additional points established in February 1997. Whilst seismicity may have exercised some control on the Rn activity, it is all but masked by other controlling factors. It is probable that rainfall has had a greater influence on trapping Rn and making sampling conditions for analysis more difficult than it was for other gases.

CONCLUSIONS

The high Rn recorded from the Tremough monitoring point near Penryn, Cornwall on the day after the magnitude 3.8 Penzance earthquake in November 1996 is a strong indicator that seismicity gave rise to a gas geochemical anomaly. From this result alone it is not possible to determine whether the anomaly arose before or merely after the event. However, the coincidence of increasing He and anomalous CO_2 values in the north Dartmoor area prior to the magnitude 1.5 Okehampton event are as distinctive in the data set obtained over 15 months monitoring as the Tremough Rn event in Cornwall was.

If the He and CO_2 recorded in the Dartmoor area arose as a result of the impending seismicity then the possibility is that the high CO_2 and He seen at High Cross and Constantine were similarly related. However, the fact that CO_2 and He may vary without any apparent seismic events suggests that their presence may be used as an indicator of possible increased seismic risk rather than an absolute indicator of earthquake activity. To substantiate these results it would be necessary to continue the monitoring work as well as establish similar methods in more seismically active areas of the world. Additionally, the anomalous values must be significantly different from those which may be attributed to biological, pedological and meteorological variations. Above all the results recorded in this paper were only obtained by the fortuitous occurrence of seismic activity in the short period when this work could be funded. It was unfortunate that the work could not be continued as a further event occurred in the Penzance area on 8 February 1998 with an epicentre just 7 km from the November 1996 event.

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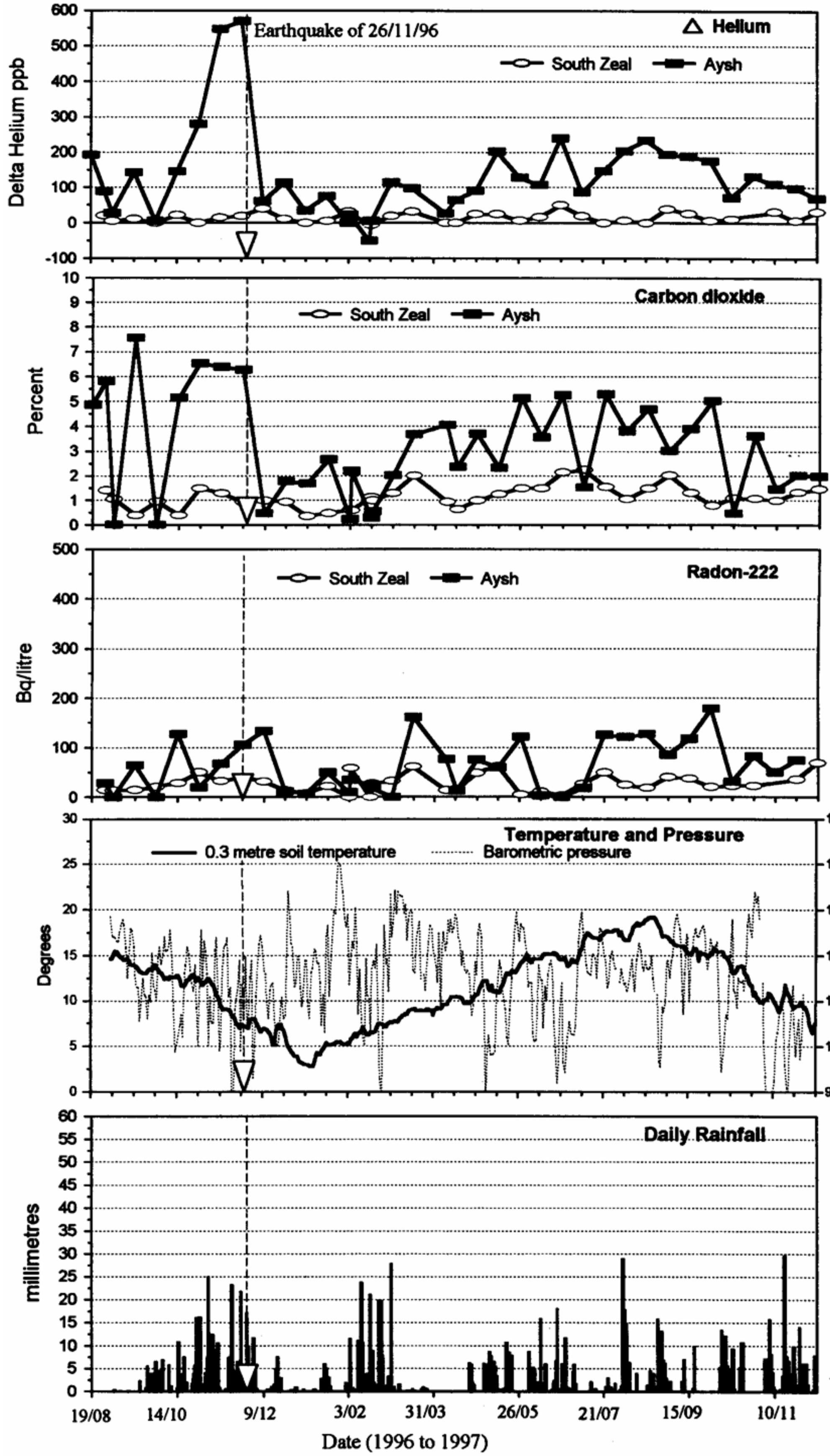

Figure 5. Soil gas He, Rn and CO_2 monitoring results from the north Dartmoor area, together with soil temperature, barometric pressure and rainfall data.

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