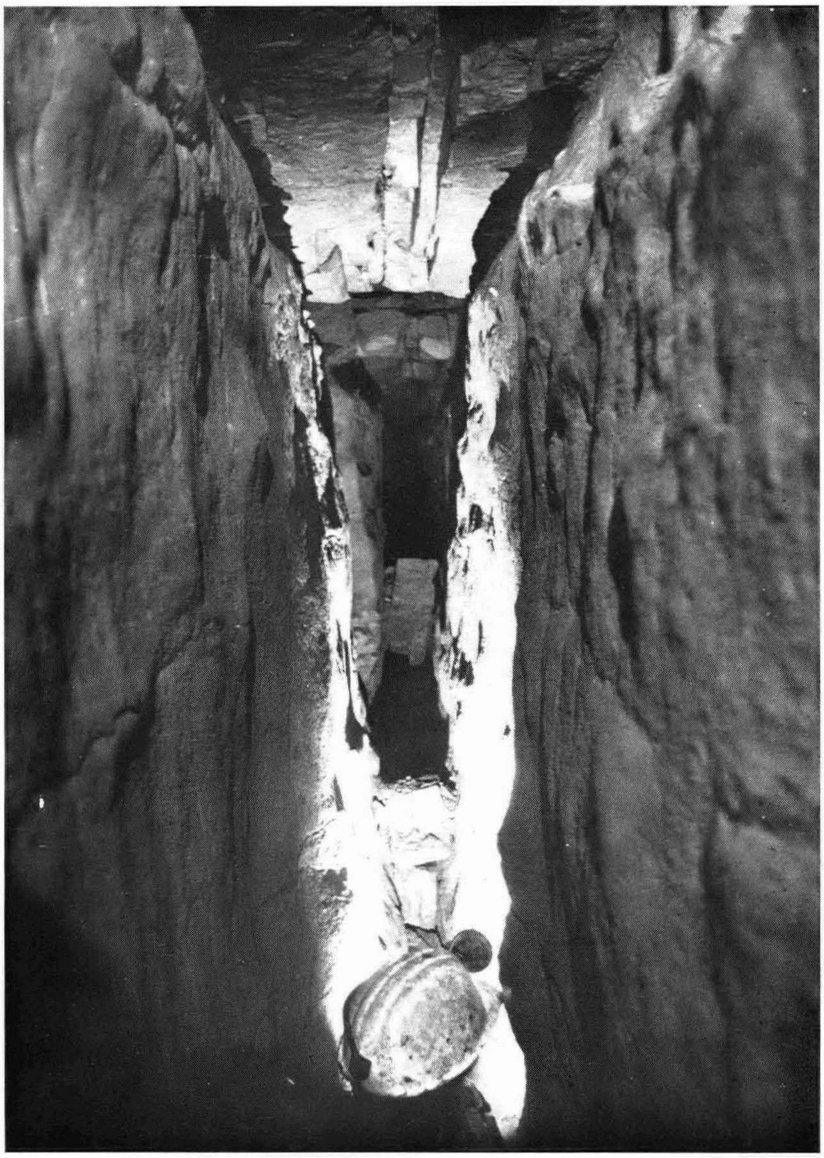
BCRA

TRANSACTIONS

BRITISH CAVE RESEARCH ASSOCIATION

Volume 2 Number 4 December 1975



Rift in the Central Maze of Devis Hole Mine Cave, Swaledale

Survey traverse closure

Cave location by resistivity

Hypothermia detection

Phreatic Network Caves

INSTRUCTIONS TO CONTRIBUTORS

These notes are meant for guidance of contributors in the hope of reducing the amount of labour for both the editor and the contributors! Adherence to the rules is desirable but not absolutely essential.

As far as possible all material submitted for publication in the Transactions should be typed on one side of the paper only with double spacing to allow for editorial corrections where necessary. Paragraph sub-headings should be clearly marked. Metric measurements should be used wherever possible.

A very short summary of the principal conclusions should accompany every contribution.

References to other published work should be cited in the text thus . . . (Bloggs, 1999, p.66) . . . and the full reference with date, publishers, journal, volume number and page numbers, given in alphabetical order of authors at the end, thus . . .
Bloggs, W., 1999. The speleogenesis of Bloggs Hole. Bulletin X Caving Assoc. Vol. 9, pp. 9-99.

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ISSN 0305-859X

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 2 Number 4 December 1975.

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Published by and obtainable from
The British Cave Research Association

Bryan Ellis,
7 School Lane,
Combwich,
Bridgwater,
Somerset. TA5 2QS.

One copy issued free to members
Extra copies to members £1.00
Non-members price £1.50

Trans. British Cave Research Assoc. Vol.2. No.4. pp.151-165. December 1975.

ACCURACY AND CLOSURE OF TRAVERSES IN CAVE SURVEYING

by D.J. Irwin and R.D. Stenner

Summary

Curves showing the theoretical accuracy of "accurate" cave surveys are produced and these are compared with practical results. For various stated reasons it is concluded that all surveys should show an accuracy not worse then three times the standard deviation for the plan, and twice for the elevations. The optimum length of survey leg for different grades of survey is extracted from the curves. The closure of complex traverse networks is discussed and a relatively simple procedure is described that does not require access to a computer. The results obtained on a specimen complex network are compared with those obtained by the least squares method using a large memory computer. Finally the need for the calibration of instruments is discussed.

It is well known that a closed traverse will not close exactly on to its point of commencement but the magnitude of the closing error has never been established according to the grade or technique employed. Vague generalities have been the order of the day; requirements that all closed traverses should close better than 2%, or 1% have recently been claimed by Ellis (1966) and by Crabtree & Hedley (1974). It is the authors' intention to show the magnitude of the misclosure for any traverse length and the upper limit of acceptability for either B.C.R.A. grade 5 or C.R.G. grade 6 surveys. This limit of acceptability has been derived from a comparison between empirical and practical results; certain conclusions have been drawn and recommendations made enabling the surveyor to determine the precision of his work involving the use of both open and closed traverses.

At the present time, the closing of a traverse is often used to determine the accuracy of a cave survey. This is represented by the relationship of the slope misclosure to the total traverse length, or the slope misclosure has been broken down into the horizontal and vertical components and each plane related separately to the total traverse length. The magnitude of misclosure varies with instrument reading tolerances and traverse length. This being the case it is quite impossible to give a rule of thumb expectancy as to what is a good percentage misclosure for a given survey grade. The presence of compensating gross errors may well result with the traverse closure error very near zero, thus the surveyor deludes himself that his survey is better than it really is.

Before discussing the acceptability of a closed traverse it is necessary to outline the reasons for the traverse closure error. The error can be broken down into three constituent groups:—

(a) random error

(b) systematic error, and

(c) gross error.

A discussion on each type of error is necessary, followed by the construction of empirical curves in order to establish the relationship of the practical results to theory, and so to ascertain the limit of acceptability for any traverse for B.C.R.A. grade 5 and C.R.G. grade 6 standards. The solution offered may not suit the purist but even though much has been written on traverse closing, not one author has backed his arguments with practical results, except Warburton (1963) who was limited to a handful of traverse closures. It is largely due to Warburton that the authors have been able to produce the curves presented with this paper and we acknowledge the extensive use of Warburton's unpublished paper of 1967. The practical material used for the comparisons has been taken from the St. Cuthbert's Swallet survey figures. This survey was carried out to C.R.G. grade 6 in imperial units and so the method of constructing the curves illustrated herein are to this standard (Figs. 1-3). Further curves (Figs. 4-8) have been constructed for both C.R.G. grade 6 and B.C.R.A. grade 5 using metric units. For the B.C.R.A. grade 5 standard three sets of curves have been produced to show the effect of improving and worsening the limits of linear measurement and station positional error. These have been labelled: "BCRA grade 5-", BCRA grade 5, and "BCRA grade 5+" and their tolerances are:—

	"BCRA grade 5-"	BCRA grade 5	"BCRA grade 5+"
Compass and clinometer	± 1°	± 1°	± 1°
Tape	± 20 cm	± 10 cm	± 5 cm
Station positional error	± 10 cm	± 10 cm	± 5 cm

It must be remembered that the limits labelled "BCRA grade 5-" do NOT reach the requirements for a B.C.R.A. grade 5 survey. The tolerances for the curves labelled C.R.G. grade 6 are: compass and clinometer ± 0.5°, tape ± 1.5 cm, and stational positional error zero; these tolerances are tighter than the minimum requirements for a B.C.R.A. grade 6 survey which are: compass and clinometer ± 0.5°, tape and station positional error ± 2.5 cm. In the case of the various limits approximating to B.C.R.A. grade 5 the tolerance for the compass and clinometer has been maintained at ± 1° as it is unlikely that readings better than this can be maintained for long periods when the instruments are hand-held.

The current B.C.R.A. grade 5 is a practical set of tolerances that can be easily achieved with hand-held instruments; to reduce these to "BCRA grade 5+" is not practical and extremely difficult to obtain with known equipment. Therefore it is the authors' opinion that B.C.R.A. grade 6 should be stated as a set of tolerances and not merely quoted as, "A magnetic survey that is more accurate than grade 5". Further, we would recommend that B.C.R.A. grade 6 should be amended to the same standard as that required for C.R.G. grade 6. The reason for this is to ensure that the tolerances are consistent with the equipment required for this standard, e.g. a tripod (or similar) does not require a station position tolerance of ± 2.5 cm — it is a fixed item of equipment. The lack of emphasis on the highest possible grade will detract from its importance and

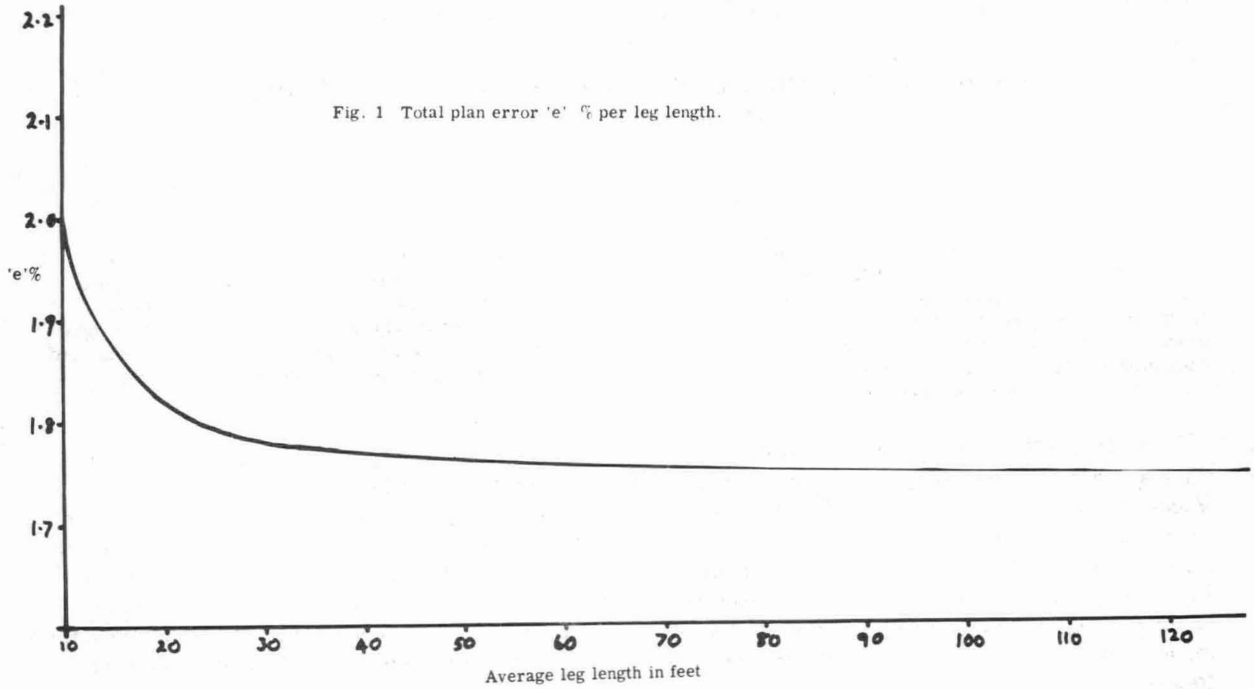


Fig. 1 Total plan error 'e' % per leg length.

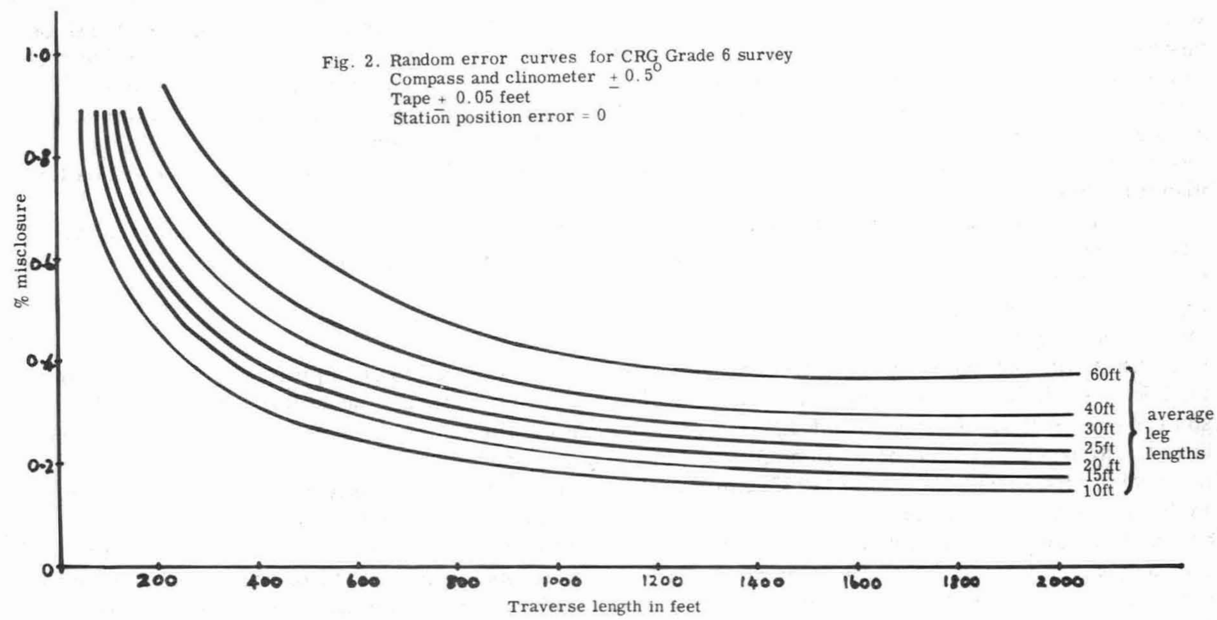


Fig. 2. Random error curves for CRG Grade 6 survey
Compass and clinometer $\pm 0.5^{o}$
Tape $\pm$ 0.05 feet
Station position error = 0

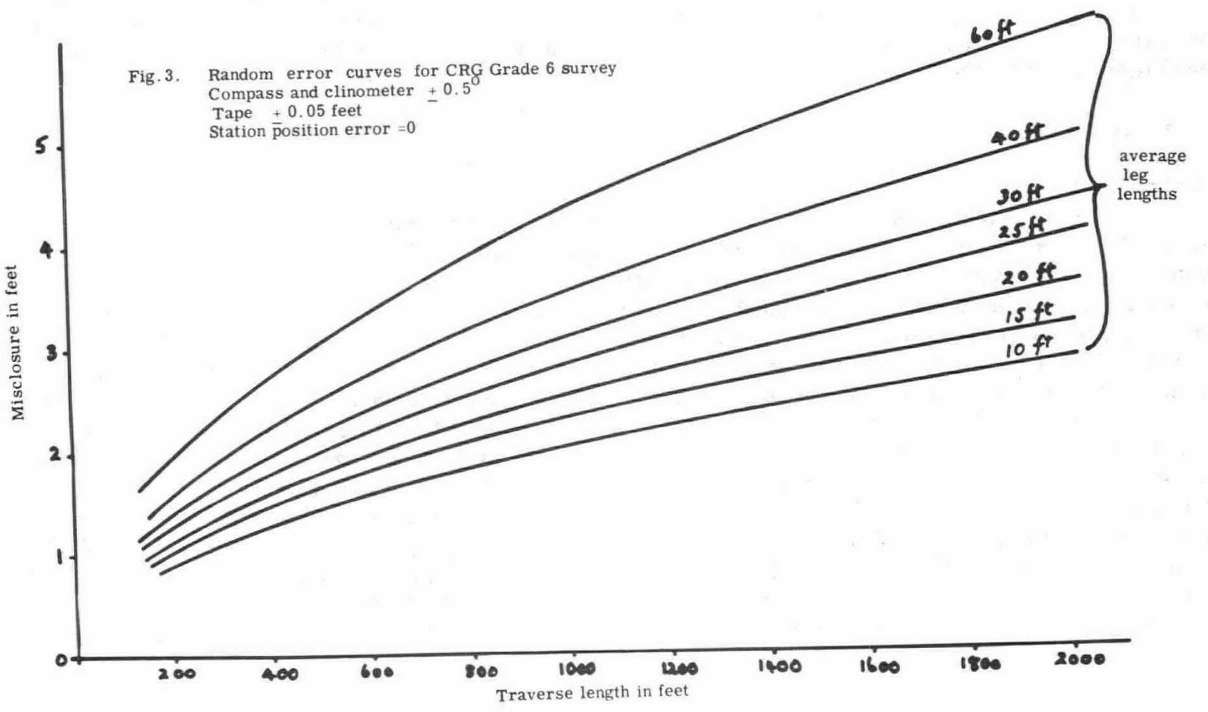


Fig. 3. Random error curves for CRG Grade 6 survey
Compass and clinometer $\pm 0.5^{o}$
Tape $\pm$ 0.05 feet
Station position error =0

is in the authors' opinion serious and a victory for the current group of influential surveyors who are not prepared to accept, nor produce themselves, surveys to the highest possible standards. This may result in a lowering of standards to ensure that the grades now generally accepted, and being worked to, are the maximum standard attained.

BRIEF REVIEW OF ERRORS

Gross Error. A gross error is a mistake – a human error that must be completely eliminated by careful reading of instruments and alert recording by the clerk.

Systematic Error. The systematic error is best defined by a simple example. Suppose a surveyor uses a 100 ft cotton tape that has shrunk by five feet. All of his slope distance measurements made in the cave will be in error of 5%. Though this will not affect the **shape** of the cave it will certainly affect the size. Another type of systematic error that will affect the survey as a whole is the magnetic deviation and associated with this is the effect of the local anomaly which will have a further effect of rotating the whole cave about the general magnetic deviation from grid or true north. A third example is the incorrectly set clinometer – one that has not been zeroed.

There is no way in which systematic errors can be corrected statistically and only careful calibration **before** placing the instruments into service and **during** the making of a survey will enable the surveyor to reduce this error to a minimum. Reference to Warburton (1963, 1967) and to Butcher and Railton (1966) will outline the procedures necessary to achieve minimum systematic error and a further discussion will be found in the Appendix to this paper.

Random Error. All measuring instruments provide readings which are approximations of the true quantity being measured, and cave surveying instruments are not exceptions. For example, the compass card is normally graduated in 1° divisions, and when sighting through the eyepiece it is not possible to obtain a value better than $\pm 0.25^\circ$; even this value is optimistic and will largely depend on the individual compass or operator. Similarly, the clinometer reading will be of the same order of precision and if a good commercial tape is used measurements will be to the nearest ½ inch or 1 cm. Generally the caternary effect may be ignored providing the tape is pulled taut before making the reading.

The random error is due entirely to reading approximations and as the survey progresses in length these errors tend to compensate one another. The random error can be treated statistically.

Effect of the random error

To determine the precision of the work carried out for any grade of survey it is first necessary to establish the expected random errors for each plane of the survey (plan and elevation). With the data obtained for a grade 6 survey the authors were able to compare the practical results with the theoretical curves produced for that standard.

As calibration for the instruments will have reduced the systematic error to a minimum, the calculations below are based solely on the reading tolerance made in the cave itself – the random error.

The standard deviation (s.d.) of a single reading for a C.R.G. grade 6 survey is given as:–

Compass: $\pm 0.5^\circ$ or one degree allowable spread of error.
Clinometer: $\pm 0.5^\circ$ or one degree allowable spread of error.
Tape: ± 0.05 ft, or 0.1 ft allowable spread of error.
Station positional error: 0.00 ft (tripod mounted).

Stating these figures as percentages of the length of leg we have: compass = 1.75%; clinometer = 1.75%; positional error = 0; tape = 1.0% for 10 ft leg, = 0.91% for 11 ft leg, = 0.834% for 12 ft leg, = 0.77% for 13 ft leg, = 0.715% for 14 ft leg, = 0.667% for 15 ft leg, = 0.625% for 16 ft leg, = 0.588 for 17 ft leg, = 0.555% for 18 ft leg, = 0.526% for 19 ft leg, = 0.50% for 20 ft leg, = 0.40% for 25 ft leg, = 0.333% for 30 ft leg, = 0.286% for 35 ft leg, = 0.25% fot 40 ft leg, = 0.167% for 60 ft leg, = 0.125% for 80 ft leg, and =0.10% for a 100 ft leg.

Consider the plan. Only the compass and tape error will basically affect the plan as the influence of the clinometer will normally be very small in the horizontal plane. The whole of the compass error and the horizontal component of the tape error constitutes the effective plan error so, simplifying, the whole of the tape error is considered as the true error will never exceed this value.

Therefore summing the errors vectorially (as they are independent of each other), the total plan error per leg, 'e' = 2.015% for a 10 ft leg length, 1.97% for 11 ft leg, 1.935% for 12 ft leg, 1.91% for 13 ft leg, 1.89% for 14 ft leg, 1.87% for 15 ft leg, 1.857% for 16 ft leg, 1.845% for 17 ft leg, 1.835% for 18 ft leg, 1.825% for 19 ft leg, 1.815% for 20 ft leg, 1.795% for 25 ft leg, 1.78% for 30 ft leg, 1.77% for 35 ft leg, 1.765% for 40 ft leg, 1.758% for 60 ft leg, 1.752% for 80 ft leg, and 1.75% for a 100 ft leg length.

It will be seen that the effect of the maximum tape error is being reduced as the leg length increases, finally to become so small that only the compass has any effect on the accuracy of the survey (Fig. 1). It should be noted that this condition is also true for the elevation as the clinometer is being read to the same limits.

Continuing: since the value of 'e' is based on the random error and thus is compensatory the random error for the whole traverse (E) will be:–

$E = e\sqrt{N}$ (where N = number of legs).

For each length of leg the error for various traverse lengths were calculated and curves produced representing the error in feet, and as a percentage (Figs. 2 and 3). Similar curves for "B.C.R.A. grade 5-", B.C.R.A. grade 5 and for "B.C.R.A. grade 5+" are to be found in Figures 5-7 (in metric units) and Fig. 8 gives the C.R.G. grade 6 curves in metres.

The curves represent 1 s.d. and so if the random error was wholly responsible for the traverse closure error, then 95% of the resulting misclosures, from a practical point of view, would lie within 2 s.d. limits. Unfortunately, this can only rarely be achieved as the systematic and undetected minor gross errors will increase the scatter range. The systematic error must be reduced to a minimum by careful calibration.

Table 1 Comparison of individual traverses with expected misclosure
(For details of the traverses see: Bristol Exploration Club Caving Report No.13, part E.)

Traverse	Numbers of legs	Length (ft)	Average leg length	Misclosure (ft) Horizon	Vertical	1 s.d.	2 s.d.	3 s.d.
1	35	631	18.03	3.14	1.03	1.97	3.96	5.92
2	20	346	17.30	3.41	0.99	1.37	2.74	4.12
3	7	87	12.43	1.71	1.61	0.63	1.26	1.89
4	27	430	15.93	3.46	0.28	1.55	3.10	4.65
5	26	396	15.23	2.83	0.15	1.42	2.84	4.26
6	34	602	17.71	2.10	0.49	1.92	3.84	5.76
7	34	510	15.00	3.85	4.20	1.62	3.24	4.86
8	29	489	16.86	2.83	2.99	1.65	3.30	4.95
9	75	1616	21.55	3.67	0.98	3.22	6.40	9.60
10	92	1388	15.09	3.24	1.02	2.66	5.32	7.97

Table 1 illustrates the results from a group of traverses taken from the survey of the Rabbit Warren complex in St. Cuthbert's Swallet, Mendip. It will be noted that all the values for the horizontal misclosure exceed 1 s.d. as expected but none exceed 3 s.d. The curves from which the comparisons have been based were for instruments affecting the plan. The elevation is also capable of being compared as the angular tolerance for the clinometer is the same as the compass, therefore the curves are equally valid for vertical misclosure. It is interesting to note that the misclosure for the vertical plane tends to be considerably better than for the plan. The surveying technique employed will affect the vertical error quite considerably. The zeroing of the clinometer is of utmost importance and it is in the nearly horizontal passage where poor zeroing will show up badly. If the zero error is 1° in a passage that slopes at 1° for 1,000 ft the true vertical change is 17.5 ft BUT the vertical error can also equal this value; this is assuming that the clinometer is being read in a forward sequence each time, i.e. A to B; B to C; C to D; etc. This will solve the problem for the surveyor who found his stream flowing uphill!

However, the data used in Table 1 was obtained by using the leap-frog technique, i.e. B to A; B to C; D to C; D to E; etc, and if the total length in the forward direction roughly equals the total length in the backsight direction the error is greatly reduced. The forward and backsight technique is by far the best method to use, providing that time and patience is available, as this has the advantage of zeroing the clinometer at each station, as well as checking the compass reading and tape measurements, and so reducing the chances of gross errors occurring.

From Table 1 it appears that the clinometer error should lie within the 2 s.d. limit. A wider investigation has shown that this appears to be true. This better tolerance is because the clinometer is not affected by external influences such as magnetic objects, nor has it a built in error caused by magnetic deviation; put another way, the effect of the systematic error has an additional effect upon the readings obtained from the compass as these cannot be completely eliminated.

The acid test of the relationship between the expected misclosures and the practically achieved misclosure is in the network system. If one selects any two survey points in a complex and compares the co-ordinate change between them by a number of routes within the network, they should theoretically be the same. Because of various influences this cannot be, unless of course the surveyor has been the victim of good luck and compensating errors! The end point of the survey lines will produce a series of points scattered around a mean. By determining the distance from the mean point of the traverse and point they can be individually compared with the expected misclosure from the relative curve. This allows the surveyor to determine lines that are reliable and unlikely to include any major gorss error.

The network system has the advantage that the calibration and gross errors will be detected quickly, enabling the surveyor to eliminate suspect lines from the basic framework. Once the basic framework has been established then the offending lines may be closed into the framework.

The traverses in Table 1 are individual traverses but in Table 2 these have been treated in network form and each may be identified from the schematic diagram in Fig. 10.

Table 2. (For details of traverses see Fig. 10.)

Trav- erse	Length (ft)	Av. leg length	Co-ordinate change			Difference from mean			Misclosure		1 s.d.	2 s.d.	3 s.d.
			N.	E.	Ht.	N.	E.	Ht.	Plan	Vert.			
1	958.63	13.60	422.83	263.05	150.28	4.80	2.84	3.05	5.59	3.05	2.20	4.40	6.60
2	691.40	20.00	424.53	266.08	149.04	3.10	0.19	1.81	3.10	1.81	2.12	4.24	6.36
3	835.86	20.10	427.10	264.98	148.61	0.53	0.91	1.38	1.06	1.38	2.32	4.64	6.96
4	1031.71	20.07	430.88	264.83	146.88	3.25	1.06	0.35	1.08	0.35	2.54	5.08	7.62
5	934.82	17.30	429.80	265.16	145.16	2.17	0.73	2.07	2.29	2.07	2.30	4.60	6.90
6	910.02	15.95	431.10	268.01	143.74	3.47	2.12	3.49	4.06	3.49	2.25	4.50	6.75
7	1103.49	18.40	428.10	265.68	143.78	0.47	0.19	3.45	0.50	3.45	2.58	5.16	7.74
8	1161.20	17.60	425.32	265.76	145.86	2.31	0.13	1.37	2.31	1.37	2.66	5.32	7.97
9	1087.69	18.70	427.43	266.70	146.21	0.20	0.81	1.01	0.84	1.01	2.65	5.31	7.95
10	991.48	19.40	429.40	268.65	142.75	1.53	2.76	4.48	3.16	4.48	2.52	5.04	7.56
Mean position:			427.63	265.89	147.23								

Using both the example above and the network traverses example used later in the text, the authors came to the conclusion that the maximum limit of acceptability should be 3 s.d. for the plan and 2 s.d. for the elevation. From these and other examples the authors found that values over the stated limits were, in very nearly every case, found to contain a major gross error. A fuller discussion of this will be found later.

Notes on Figs. 4-9 inclusive

The curves shown in Fig. 4 represent the value of the total plan error per leg, 'e', for the various sets of tolerances under discussion. It is obvious from inspection that the effect of the tape and station positional tolerance is reduced with increased leg length. This is because the tape and station positional tolerance is constant irrespective of leg length. When reading off the tape, for example, the value read off is to the nearest few inches or centimetres irrespective of the length of leg. The effects of both these influences per leg thus decreases as the leg length increases leaving, eventually, the effect of the compass error alone, which of course remains constant whatever the length of survey leg.

In the caseof C.R.G. grade 6 the percentage of tape error (station positional tolerance = 0) becomes very small at a leg length of 30m. Above 30m the error per leg is affected only by the limitations of the compass at 1.75%. This is the limiting error for any C.R.G. grade 6 survey, or whenever the compass reading limits are set at $\pm 0.5^\circ$.

In the case of B.C.R.A. grade 5 where the compass limits are $\pm 1^\circ$, the percentage error per leg length cannot be reduced below 3.49%. Thus, summing up, the limiting factor in any survey is the reading limits of the compass.

Figures 5-7 display the random error curves for the three sets of tolerances around B.C.R.A. grade 5 outlined earlier in the text and also in Fig. 8 where the random error curves for C.R.G. grade 6 are shown all in metres.

A maxim generally accepted by surveyors is that "the shorter the leg length, the better the overall survey". This is shown to be true only when the tape and position tolerances are small. Figs. 7 and 8 illustrate this point clearly. In the case of B.C.R.A. grade 5, and also with "BCRA grade 5-", it will be seen that the best obtainable results are with average leg lengths of six and fifteen metres respectively. In fact Fig. 5 shows clearly that the tolerances for "BCRA grade 5-" are such that the shorter leg lengths produce less precise surveys.

An example of the use of the curves is to determine the maximum acceptable misclosures for a survey produced to C.R.G. grade 6 that has a total traverse length of 400m and an average leg length of 4m. Using the curve labelled '4m' in Fig. 8 we find that the theoretical misclosure on a 400m traverse is 0.75m. Therefore the maximum acceptable misclosure for the plan is:

$$3 \times 0.75 = 2.25\text{m},$$

or

$$\frac{2.25 \times 100}{400} = 0.56\%$$

For the elevation it is:

$$2 \times 0.75 = 1.50\text{m},$$

or

$$\frac{1.50 \times 100}{400} = 0.38\%$$

It should be remembered that the maximum values quoted above, or indeed for any set of conditions, will only be exceeded if bad gross errors are present. Failure to carry out the correct calibration procedures will also bring about spurious results that will not align themselves with the values obtained from the curves. In many cases one would expect to find the percentage misclosure to be much better than 3 s.d. for the plan, but those appearing to be very good, i.e. better than 1 s.d., are probably due to compensating errors. However,

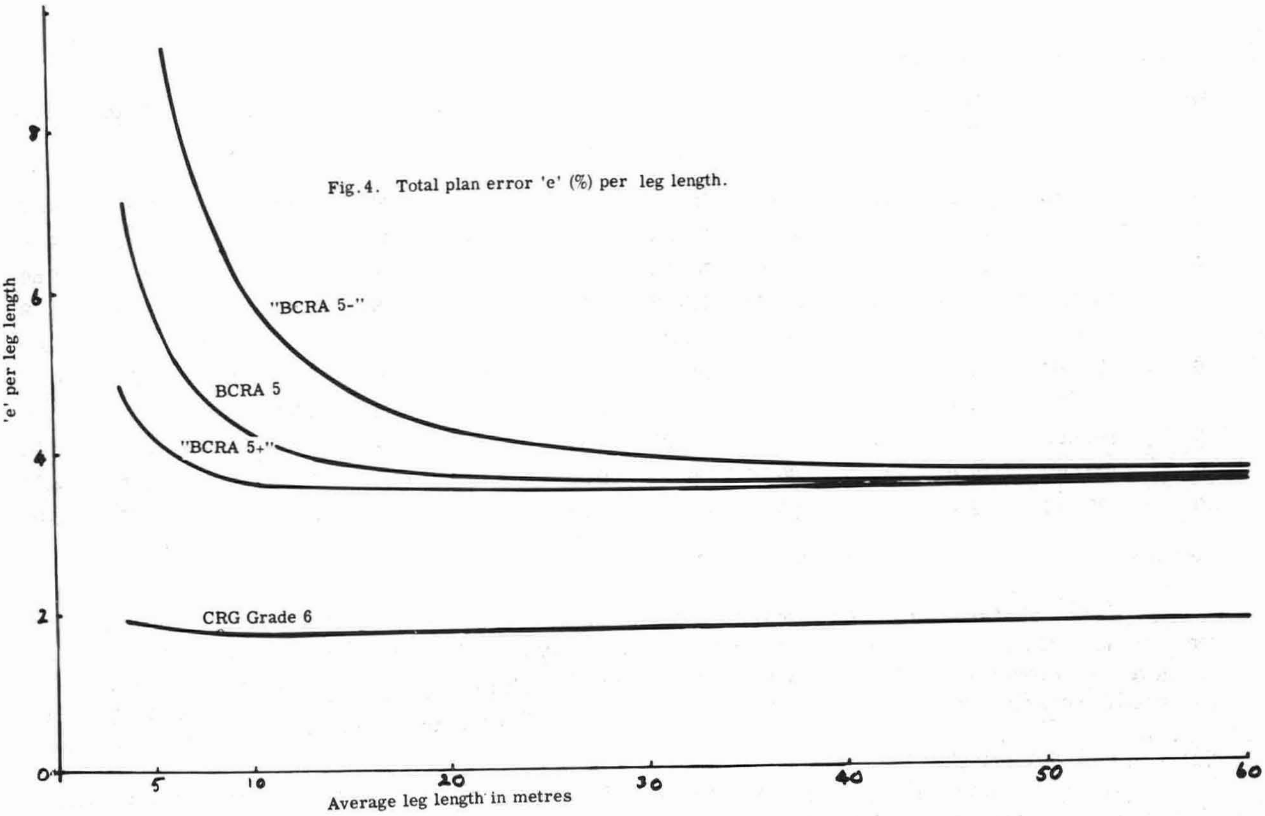


Fig. 4. Total plan error 'e' (%) per leg length.

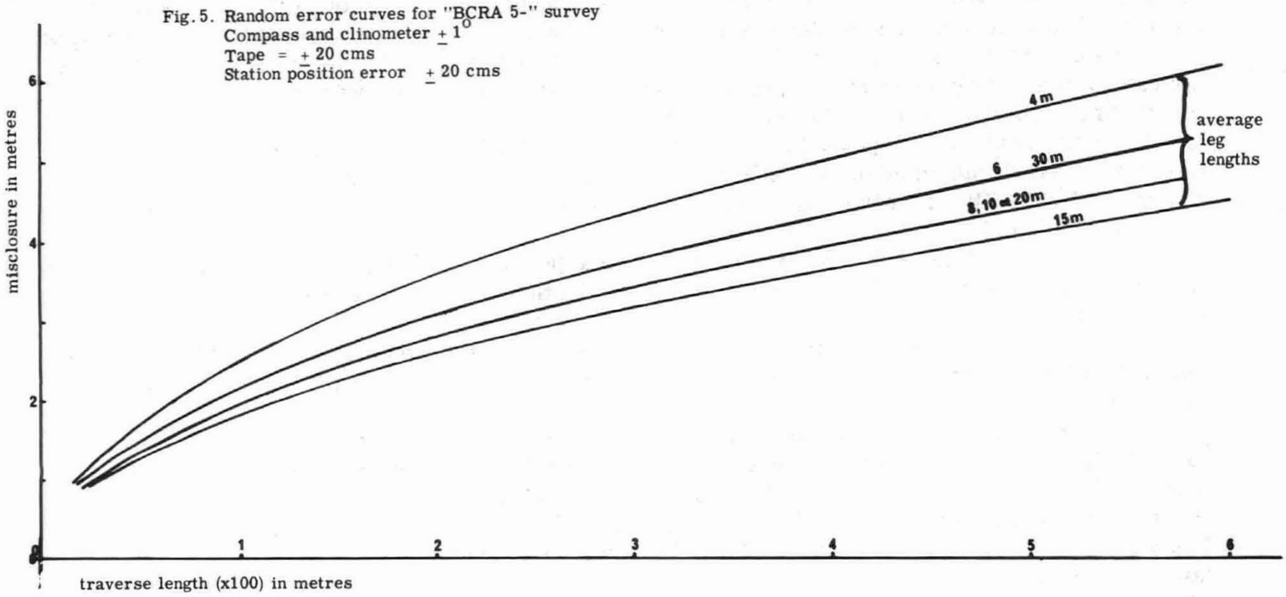


Fig. 5. Random error curves for "BCRA 5-" survey
Compass and clinometer ± 1°
Tape = ± 20 cms
Station position error ± 20 cms

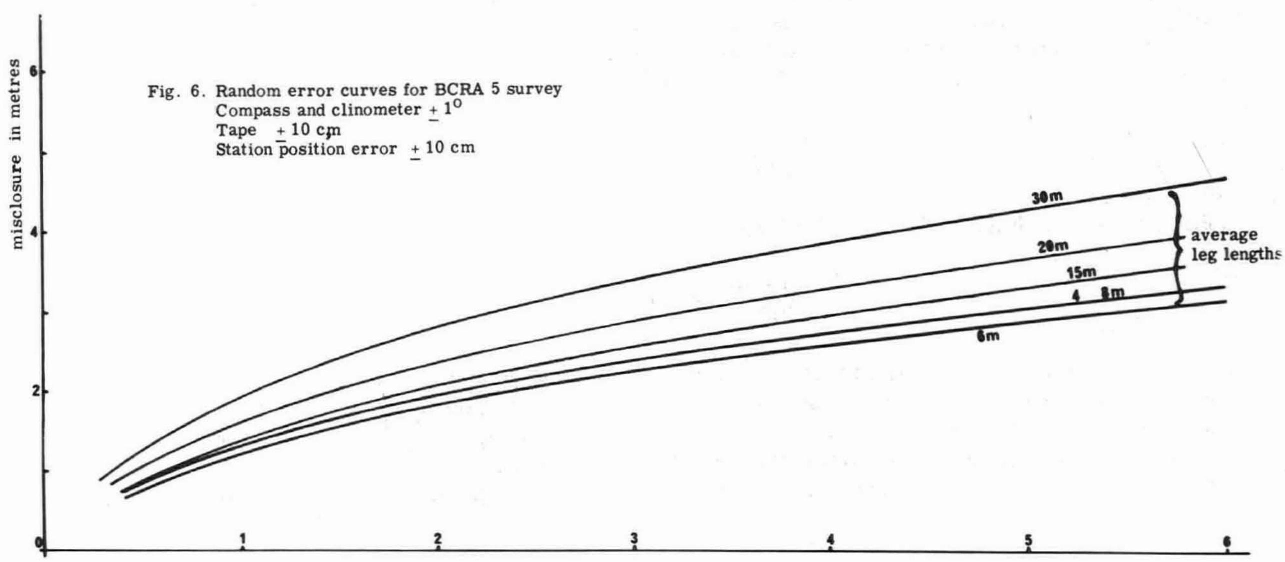


Fig. 6. Random error curves for BCRA 5 survey
Compass and clinometer ± 1°
Tape ± 10 cm
Station position error ± 10 cm

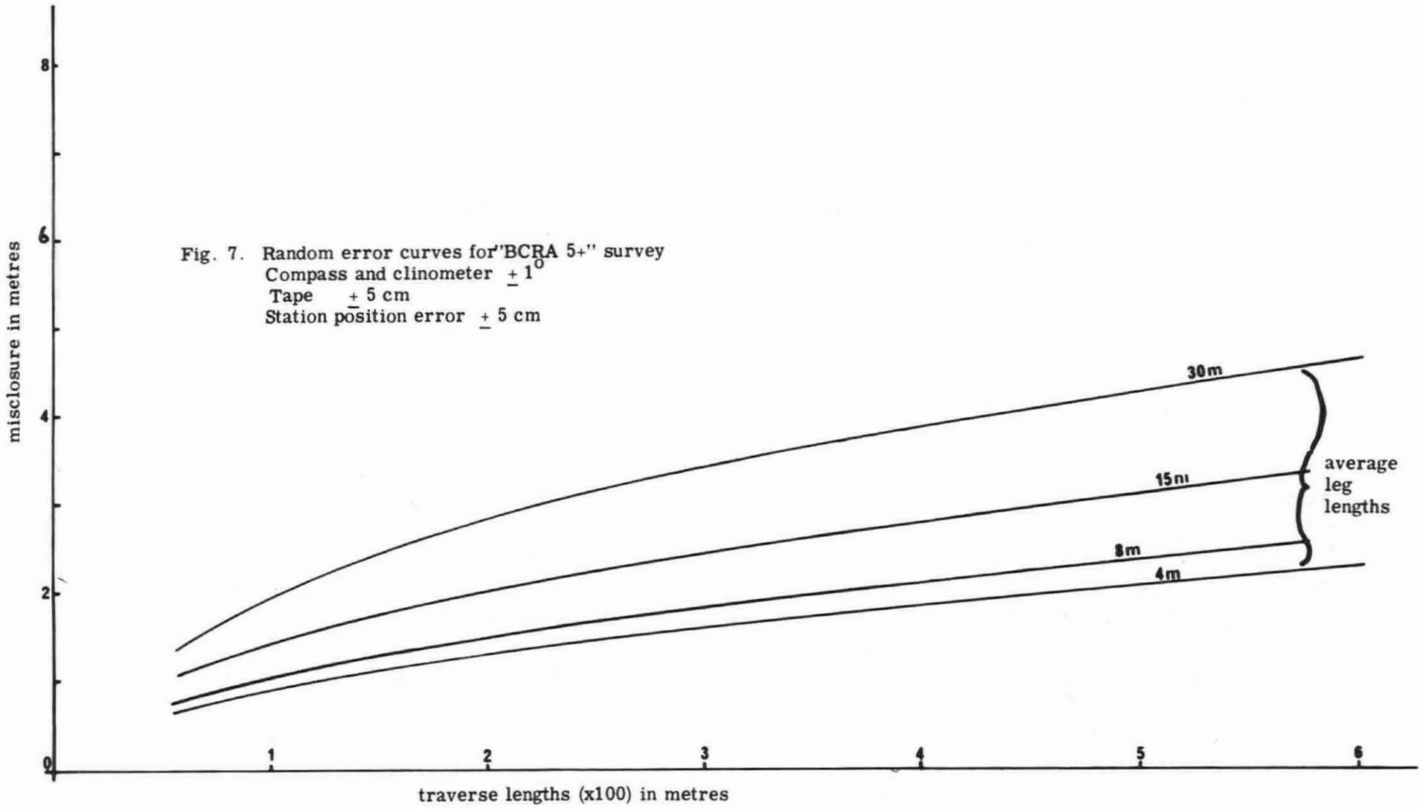


Fig. 7. Random error curves for "BCRA 5+" survey
Compass and clinometer ± 1°
Tape ± 5 cm
Station position error ± 5 cm

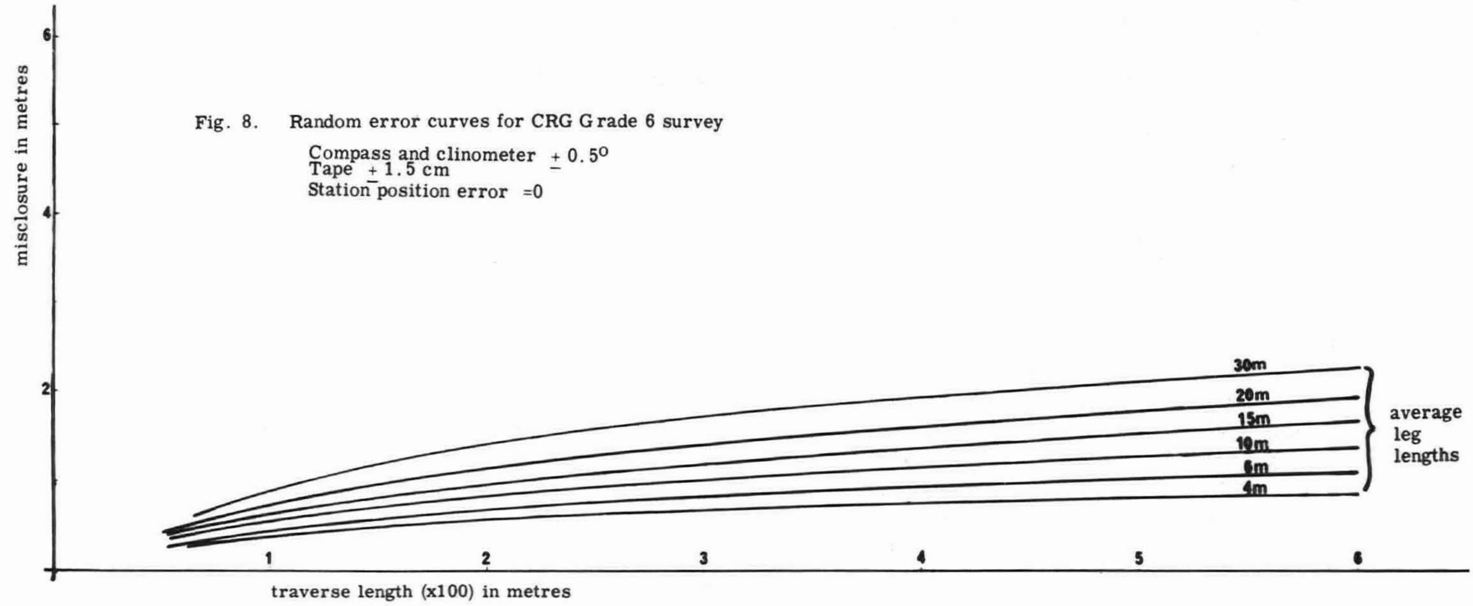


Fig. 8. Random error curves for CRG Grade 6 survey
Compass and clinometer ± 0.5°
Tape ± 1.5 cm
Station position error =0

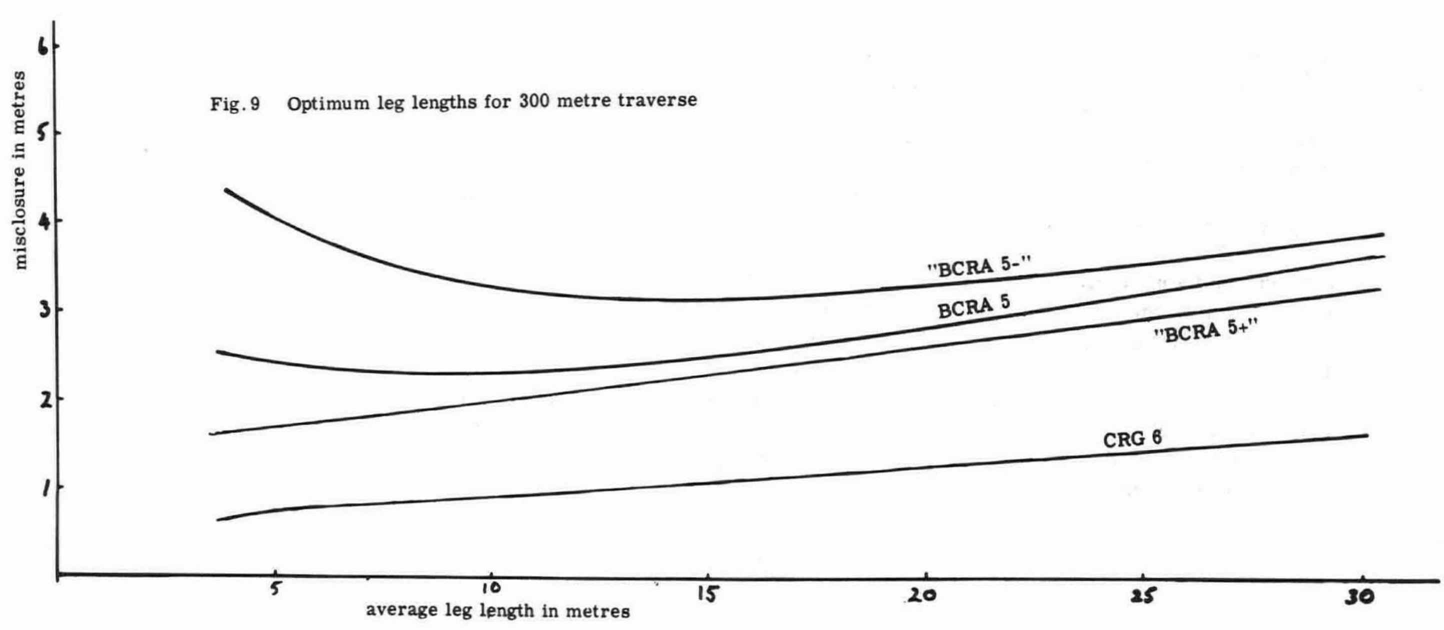


Fig. 9 Optimum leg lengths for 300 metre traverse

should the traverse be part of a network then the chances of determining the good traverses from the suspects is extremely good as the sequence of closing a network will show.

By further examining the curves it will be seen that the optimum leg lengths may be obtained for any traverse length. Fig. 9 illustrates this point clearly. However, if we examine the three sets of tolerances around B.C.R.A. grade 5 it will be noticed that by reducing the reading tolerances for the tape and station positional error the accuracy of the survey is gradually increased. Though the "BCRA grade 5+" offers the best results these are not easily obtained with hand-held pieces of equipment. From Fig. 9, the surveyor carrying out a surveying project to "BCRA grade 5-" would need to be surveying a fairly straight cave to enable him to achieve optimum results as leg lengths of about 12-13m would be required. If he chose to survey to the tolerances of B.C.R.A. grade 5 he is on a much more practical basis as the average leg length for optimum results is about 7m.

Use of the curves

If these curves are found to be acceptable then they can obviously be put to good use in the field of cave surveying. From the previous paragraphs it was pointed out that the limits of 3 s.d. and 2 s.d. seem reasonable for the plan and elevation respectively. It must be pointed out, however, that casual use of the curves will not help the surveyor who ignores the basic rules of calibration and reading tolerances, particularly if he embarks on a network system that requires a considerable amount of time to produce. The minor variations in magnetic deviation will produce quite sizeable misclosure when one attempts to fit the traverse lines together and this will 'unhorse' the surveyor completely – it is a fact of life that no-one dare ignore.

The vast majority of caves are open traverses – that is, their end points do not reconnect with the surface enabling the entrances to be surveyed to a closure and so the only method available at the moment to check this is by radio location. However, providing all the checks and the instrumental readings have been carefully carried out the end point of any cave relative to the surface should be easily established. Should the calibration have been ignored then the cave to surface relationship is impossible to achieve.

Having satisfied oneself that the calibration is acceptable then limits can be placed on the location of the cave and point. Taking a cave 600m long, with an average leg length of 10m and surveyed to B.C.R.A. grade 5, then from Fig. 6 the value for this grade at 1 s.d. is 3.5m. Therefore the cave and point error should not exceed 3 x 3.5m on plan, and 2 x 3.5m on elevation. The details can be written, on the survey or in the survey notes, as: End point location in straight line distance = X metres ± 5.75m, depth = Y metres ± 3.5m.

NETWORK TRAVERSES

Whereas the problem of closing a single traverse has been adequately discussed elsewhere (Ellis, 1966), this is not true in the case of an interlinked network of traverses. The published literature is not much help, for, recently, Wilcock (1971) stated "... the core of the problem lies in discovering all the possible closed traverses for a network ...". In the case of St. Cuthbert's Swallet, this numbers 1.5×10^{13} traverses and for Ogof Ffynnon Ddu the number is considerably greater.

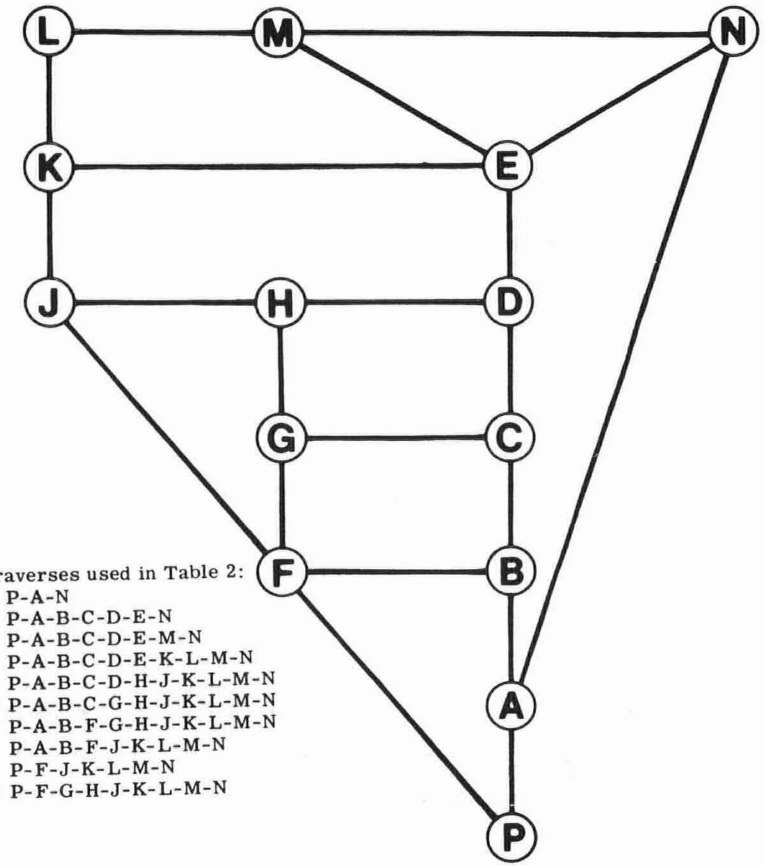
Luckwill closed some of the traverses in the St. Cuthbert's survey, purely as a check exercise, using the least squares method (Luckwill 1968). Recently, Wilkins (1975) has tested a computer programme which will close a multiple traverse by the least squares method. To use this method, access to a computer with a very large memory bank is needed, and this places the method completely beyond the reach of ordinary cave surveyors, now and within the foreseeable future. A method is required which anyone can use, equipped with a slide rule and a desk calculator.

Ellis (1966) attempted to show how the network traverses could be closed and stated "... the first thing is to make a subjective assessment, and if any of the traverses are thought to be more accurate than others, then they can be closed first and the others closed on to them. If all the traverses are of the same expected accuracy, the method favoured by the author is to close the outer traverse and then the inner traverses successively."

As the survey unit is now in general use on Mendip and elsewhere there is little need to lower the survey grading below the requirements of C.R.G. grade 6 and so one will have to think of all the traverses as being of the same expected accuracy; at least for reasons of instrumentation. As to the likely accuracy of traverses, the St. Cuthbert's survey has shown that errors may be found in the most unlikely places. One might be led to think that the difficult passages to both cave and survey through would display some lowering of standards for that part of the survey, but it was found this was not so. Most of the errors that were located were found to occur in parts of the cave where surveying was easy. As a result, it is not possible to assess the accuracy of any section of the survey line simply by relating it to a particular type of cave passage.

Closing a Network Traverse

Before the errors in a multi-traverse network can be thus distributed, it is necessary to determine whether any part of the network contains an error which is larger than the expected positional error. This may be done by examining the co-ordinate changes from one point in the network to another point, taking a variety of routes chosen so as to reveal any bad routes. By a process of elimination between these bad routes, the actual section which is causing the error may be isolated. To make the procedure clearer, consider the following example, a part of the St. Cuthbert's survey; Fig. 11 is a block diagram representing the network of passages.



Traverses used in Table 2:
1 P-A-N
2 P-A-B-C-D-E-N
3 P-A-B-C-D-E-M-N
4 P-A-B-C-D-E-K-L-M-N
5 P-A-B-C-D-H-J-K-L-M-N
6 P-A-B-C-G-H-J-K-L-M-N
7 P-A-B-F-G-H-J-K-L-M-N
8 P-A-B-F-J-K-L-M-N
9 P-F-J-K-L-M-N
10 P-F-G-H-J-K-L-M-N

Fig. 10. A network taken from the Rabbit Warren Series of St. Cuthberts Swallet. Obviously there are many more than ten traverse included in this network but those listed in Table 2 are representative for the purposes herein.

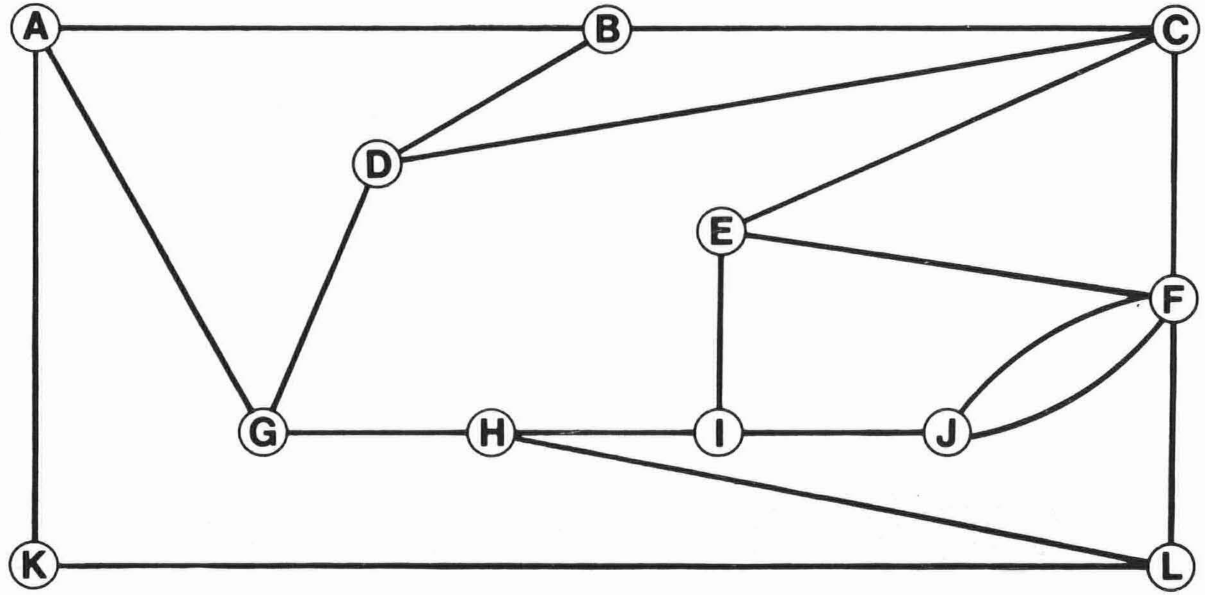


Fig. 11. Diagram of traverses representing a network in St. Cuthberts Swallet as used in Table 3.

Table 3. Details of survey traverses.

Traverse	Length in feet	Legs	Co-ordinate changes North	East	Height
C - E	30	3	+10.81	+15.81	−16.90
C − B	60	4	−37.62	−22.14	+37.19
B − A	510	36	−59.40	+102.69	−108.78
B − D	242	13	− 7.04	+22.80	−79.95
D − G	107	8	− 8.62	+68.54	−18.11
C − D	106	8	−44.33	+ 1.30	−41.26
G − A	58	3	−45.50	+ 9.43	−12.76
G − H	30	1	+28.83	+ 4.57	− 8.37
A − K	69	4	+17.05	+46.92	−35.44
H − L	55	8	− 7.80	+15.00	−33.40
L − K	108	6	−46.45	+36.58	− 3.65
E − F	179	12	+ 0.37	+64.39	−59.00
F − L	66	4	−43.85	+ 6.28	−27.75
H − I	15	1	+11.81	− 8.73	− 0.77
I − J	8	2	+ 5.06	+ 5.06	− 2.08
J − F	35	4	+20.89	+11.88	− 3.34
J − F*	37	22	+22.02	+13.28	− 2.78
C − F**	707	38	+11.64	+83.83	−80.92
E − I	86	5	−22.11	+51.45	−46.24

* Alternative route
** With resurveyed section

In this network, station K appears only as an intermediate point on the A to L traverse. However, in the whole survey it is an important junction, being connected to surveys of two other series in the cave. Because of this reason, and also the position of the station relative to station C, it was decided to establish first of all the co-ordinate changes from C to K by a number of routes. The total number is fifty, and to compute the co-ordinate changes by all of them is cumbersome and unnecessary. The method was to select the smallest number of routes which would test each of the legs of the complex, with the least repetition of any sections of the network. The results are shown in Table 4.

Table 4. Co-ordinate changes by various traverses. (All distances are in feet)

Traverse	Co-ordinate changes North	East	Height	Slope Dist.	Legs	Av. leg Length
1. C-F-L-K	−73.62	+131.47	−114.26	846	48	17.6
2. C-E-F-L-K	−79.12	+123.06	−107.30	347	25	13.9
3. C-D-G-A-K	−81.40	+126.19	−107.57	340	23	14.8
4. C-B-A-K	−79.97	+127.47	−107.03	565	33	17.1
5. C-B-D-G-A-K	−81.73	+125.55	−109.07	536	32	16.8
6. C-E-I-H-G-A-K	−80.37	+127.87	−102.20	288	17	16.9
7. C-D-G-I-J-F(route 1)-L-K	−75.60	+125.09	−108.02	440	34	12.9
8. C-D-G-I-J-F(route 2)-L-K	−74.47	+126.49	−107.44	436	32	13.6
9. C-D-G-H-L-K	−78.60	+125.81	−104.63	405	31	13.1
10. C-F(resurveyed)-L-K	−78.66	+126.69	−112.32	846	48	17.6

Routes 1, 2 and 3 were considered first. Route 1 shows a difference from the other two, and a calculation shows this difference to be greater than can be expected from positional errors. Route 1 therefore contained a mistake. The probable site of the mistake was found, and after resurveying only two legs, the figures for route 10 were obtained, with much better agreement with routes 2 and 3. Routes 4 to 9 of Table 4 were then chosen so as to test each of the other sections of the network. The mean co-ordinate changes, by all the traverses, from station C to station K, approximated to 0.1 feet are: north, −80.0; east, +126.0; and vertical, −107.5 feet. It must be remembered that these are not final co-ordinates, their purpose as yet being merely diagnostic.

For each of the ten traverses, the difference berween the mean co-ordinates and the calculated co-ordinates were found and tabulated, together with the expected positional errors calculated from using the slope length of the traverse. The results are shown in Table 5.

Table 5. Differences from mean in co-ordinate change.

Traverse	Differences from mean (feet) N.	E.	Vertical	Plan	Expected position error 1 s.d.	2 s.d.	3 s.d.
1	−6.4	−5.5	+6.8	8.44	2.25	4.50	6.75
2	−0.9	−2.9	−0.2	3.04	1.33	2.66	4.00
3	+1.4	−0.2	+0.1	1.41	1.35	2.70	4.05
4	0.0	−1.5	−0.5	1.50	1.85	3.70	5.55
5	+1.7	+0.5	+1.6	1.77	1.78	3.56	5.34
6	+0.4	−1.9	−5.3	1.94	1.28	2.56	3.84
7	−4.4	+0.9	+0.5	4.49	1.50	3.00	4.50
8	−5.5	−0.5	−0.1	5.52	1.50	3.00	4.50
9	−1.4	+0.2	−2.9	1.41	1.40	2.80	4.20
10	−1.3	−0.7	+4.8	1.48	2.26	4.52	6.78

The plan differences between the two stations is 149 feet. Thus a 1° compass calibration error would give a plan error of 2.6 feet, and an error of 0.25° gives a plan error of 0.7 feet.

A comparison of the figures for traverses 1 and 10 shows the improvement in the plan as a result of the partial re-survey in the C to F section. However, the vertical error is bigger than the permissible tolerance. This suggests that there is an error in a vertical section of the survey, probably at Pulpit Pitch as a result of a recording mistake. This section of the network was then removed from further consideration in the context of this particular problem, the closure of the network. It will be seen that traverse 6 contains an error greater than the expected error, indicating that there is a mistake in the E to I traverse. Traverses 7 and 8 differ from traverse 9 by a relatively short passage length, and therefore a large change in co-ordinates is not to be expected, but this is not the case in fact. Examination of the co-ordinate changes reveals that there is probably an error common to traverses 7 and 8 and this must be in the very short section from I to J. The remaining routes are within the precision limits of the survey.

The work so far has shown that the sections C to F, E to I, and I to J contain mistakes and must be left out. Most of the network remains, and needs to be closed before drawing can begin. One method would be to establish the most probable co-ordinates of station K relative to C, and to close the other routes on to this station, and in this relatively simple network this procedure would be easy to apply. However, a method is needed which can be applied to networks which are bigger and more complex. In theory the closure can be done by the least squares method, but an alternative method which does not need a computer can be used. Briefly the method is to calculate the mean co-ordinate change of one section relative to the origin, and then progressively calculate the mean co-ordinates of the remaining traverse junctions. This will be explained more clearly by continuing with the example from the St. Cuthbert's survey.

1. Station K

Traverses 2, 3, 4, 5 and 9 were used to compute the plan co-ordinates. The mean position is: northing, –80.1; easting, +125.6; height, –107.1. Comparison with the diagnostic estimate of the co-ordinates of this station, given earlier, shows the effect of the omission of routes 6, 7, 8 and 10, which contained mistakes. The effect is surprisingly small.

2. Station G.

Traverse	Northing	Easting	Height	Slope Distance	Legs
C-D-G	–52.95	+69.84	–59.37	213	16
C-B-A-G	–51.52	+71.12	–58.83	628	43
K-A-G	–51.65	+69.25	–59.20	127	7
K-L-H-G	–54.68	+69.45	–61.98	193	15

The mean position is: northing, –52.7; easting, +69.9; height, –59.8.

3. Station A

Traverse	Northing	Easting	Height	Slope Distance	Legs
G-A	–98.00	+79.33	–72.53	58	3
K-A	–97.15	+78.68	–71.63	69	4
G-D-B-A	–96.24	+81.25	–70.52	859	57
C-B-A	–97.02	+80.55	–71.59	510	36

The mean position is: northing, –97.1; easting, +80.0; height, –71.6.

4. Station B

Traverse	Northing	Easting	Height	Slope Distance	Legs
A-B	–38.70	–22.49	+37.18	66	4
G-D-B	–37.04	–20.84	+38.26	349	21
C-D-B	–37.29	–21.50	+38.69	378	23
C-B	–37.62	–22.14	+37.19	60	4

The mean position is: northing, –37.7; easting, –21.7; height, +37.8.

5. Station F

Traverse	Northing	Easting	Height	Slope Distance	Legs
C-E-F	+11.18	+80.20	–75.90	179	12
G-H-L-F	+12.38	+83.18	–73.82	151	13
K-L-F	+10.20	+81.84	–76.10	174	10

The mean position is: northing, +11.5; easting, +81.7; height, –75.3.

6. Station L

Traverse	Northing	Easting	Height	Slope Distance	Legs
F-L	–32.55	+87.98	–103.05	66	4
K-L	–33.65	+89.02	–103.45	108	6
G-H-L	–31.67	+89.87	–101.57	85	9

The mean position is: northing, –32.6; easting, +89.0; height, –102.7.

7. Station D

Traverse	Northing	Easting	Height	Slope Distance	Legs
B-D	–44.74	+1.10	–42.15	242	13
C-D	–44.30	+1.30	–41.26	106	8
G-D	–44.08	+1.36	–41.69	107	8

The mean position is: northing, –44.4; easting, +1.3; height, –41.7.

The co-ordinates of E may be calculated by the same method which is used for distributing errors along a simple closed traverse. Station E was considered as the third station along a fifteen station line from C to F, both of whose co-ordinates are now fixed, so one fifth of the closure error for this traverse was applied to each of the co-ordinates of the C to E line, giving the co-ordinates of E. The same method was used to establish the co-ordinates of station J.

Having established the co-ordinates of all the junctions, it is a matter of straightforward arithmetic to correct the co-ordinates of all intermediate stations, access to a desk calculator being very much appreciated in this tedious task. There remains the problem of using the discarded sections to complete the survey skeleton. In this case, comparison of traverses 6 and 7 in Table 5 suggests that the H to I survey is free from a mistake, so I can be assigned co-ordinates. If re-surveying is not possible, the error may be distributed evenly throughout a poor section, or it may be justifiable to apply the misclosure correction to a single leg of the survey. The survey notes published with the survey should, of course, be sufficiently detailed to make it clear how sections of poor quality were used in the finished survey.

It has been shown how a multiple traverse may be closed without recourse to a computer. The results will now be compared with other methods, Table 6. The first set of co-ordinates were of most interest to the authors personally, i.e. the co-ordinates used to draw the survey of St. Cuthbert's Swallet, obtained by the old and unwieldy method. A second set of figures was obtained with the help of Adrian Wilkins of the University of Bristol. The program used by Wilkins diagnosed the sections which were low in accuracy, and the network was closed after rejecting these sections. The sections of the survey rejected in the procedure detailed in this paper were also shown by him to be poor in accuracy, and rejected before closing the network. The changes in the junction co-ordinates caused by rejecting the bad sections were small, as found in this paper, but the statistical precision of the junction co-ordinates improved.

Table 6. Comparison of results for the area under consideration by three independent methods

Station	Northings			Eastings			Height		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E	+10.8	+10.6	+ 9.3	+16.1	+15.8	+16.7	–16.8	–16.9	–17.9
A	–97.1	–96.1	–98.2	+80.0	+77.9	+79.5	–71.6	–73.7	–72.1
G	–52.7	–53.1	–52.6	+69.9	+70.1	+69.6	–59.8	–60.1	–59.3
H	–24.3	–24.5	–22.4	+74.4	+74.1	+73.8	–68.8	–68.4	–68.0
L	–32.6	–31.4	–29.8	+89.0	+87.3	+88.5	–102.7	–100.9	–101.7
F	+11.3	+12.8	+13.9	+81.7	+81.0	+81.9	–75.3	–73.1	–73.6
K	–80.1	–78.3	–74.6	+125.6	+123.8	+124.6	–107.1	–104.5	–106.6
B	–37.7	–37.4	–37.7	–21.7	–22.1	–22.2	+37.8	+37.2	+37.4

(1) Mean method – as described in this paper
(2) "Conventional" method – (Ellis, 1966)
(3) Least squares method – (Wilkins, 1975)

Finally, another independent check has been carried out on a computer by Mike Cowlishaw which agrees closely with the results tabulated in Table 6, (Cowlishaw, 1976).

COMPASS CALIBRATION

Why calibrate a compass?

In spite of recommendations published for their use (Warburton, 1963; Butcher & Railton, 1966; Wilcock, 1970), some cave surveyors do not calibrate their compasses, and some have poured scorn on suggestions that there is a need to do so, e.g. Acland & Wilcock (1969); Wilcock et al (1969). Three examples will illustrate the consequence of failing to do this correctly. First, a batch of liquid-filled ex-W.D. prismatic compasses were found to have a spread of 10° in their readings when sighted along the same bearing. The precision of the north arrow on surveys produced by these compasses without calibration would therefore also have had a spread of 10°. Second, the Lamb Leer Cavern survey published by the Mendip Nature Research Committee (1966) depicts a road which is 17° out. An O.S. map shows the magnetic declination in the area to have been 8½° at the time. The surveyor *added* 8½° to his readings instead of subtracting it. Third, the authors were unable to use existing surveys of parts of St. Cuthbert's Swallet in their survey because the previous surveyors had either not calibrated their compasses, or had calibrated them incorrectly. The various north and magnetic north references were not consistent with one another, and the various surveys neither fitted together with each other, nor with the new surveys. A cave survey must be accurately aligned with O.S. maps of a scale at least six inches to a mile to allow prospecting

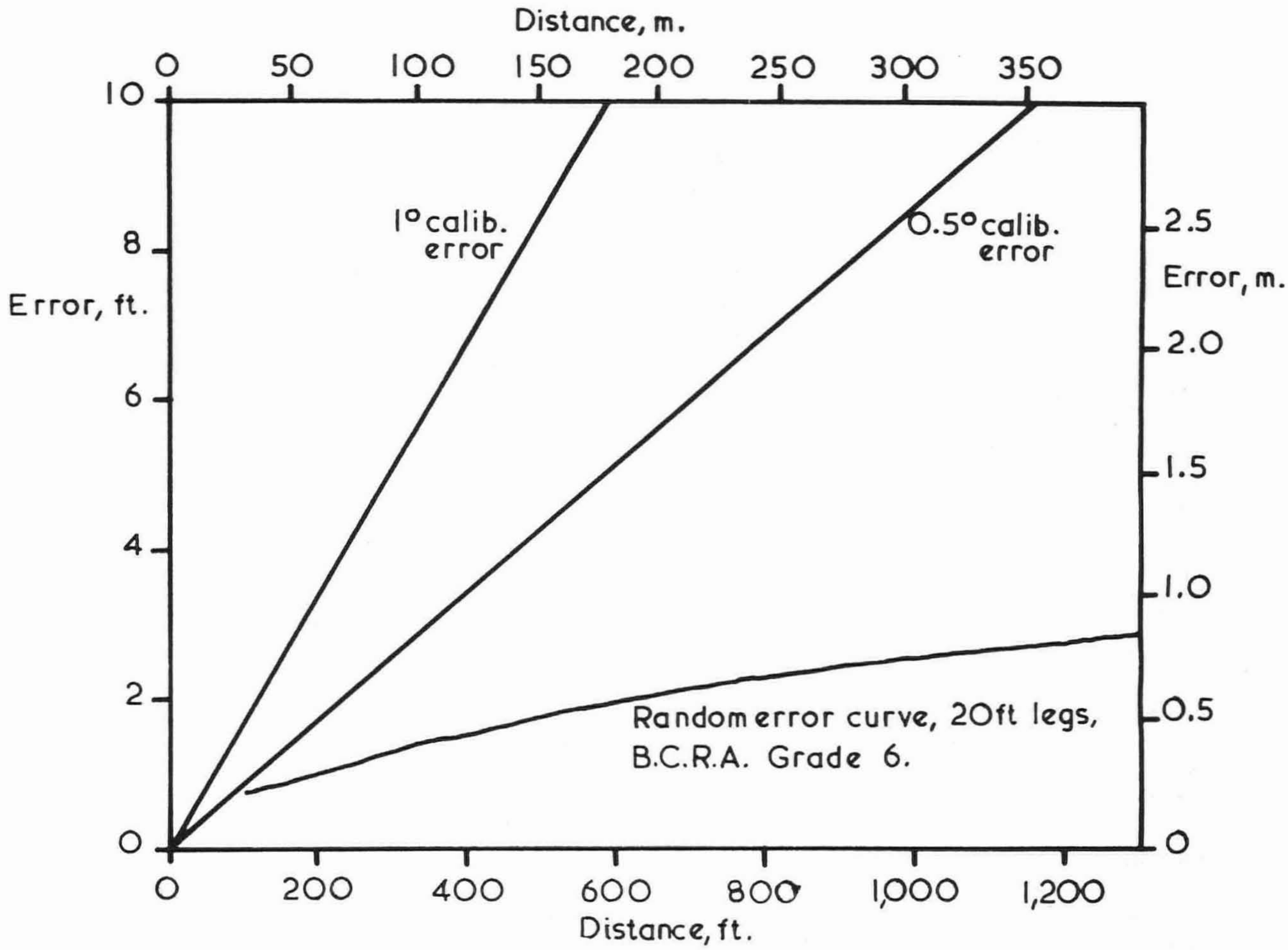


Fig. 12. The random error curve for a CRG Grade 6 survey for an averag leg length of 20 feet (6m) compared with the error caused by miscalibration errors of 0.5^{O} and 1^{O}.

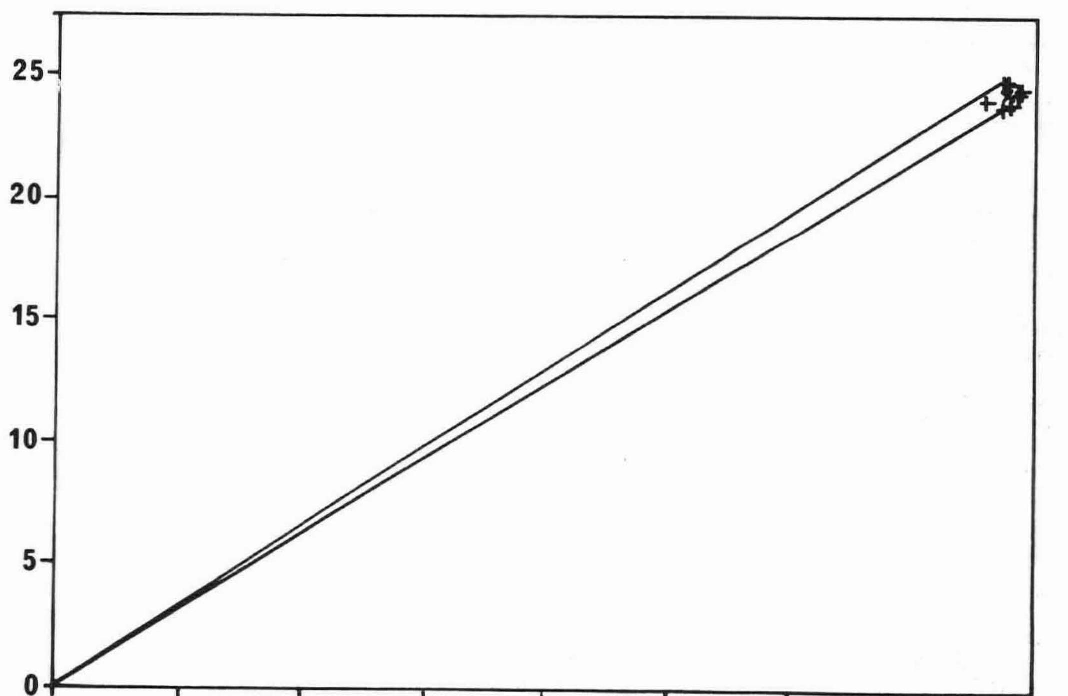


Fig. 13. The plan co-ordinates of one station with respect to a second by seven surveyed routes (+) compared with the mean plan co-ordinate (x) with a spread of 1^{O}.

for alternative entrances, radio location, etc, and for this purpose careful attention to compass calibration is essential.

A theoretical examination of errors caused by inaccurate calibration

Having demonstrated the need to calibrate compasses, the next step is to put an exact figure on errors caused by poor calibration. Figure 12 shows the error caused by calibration errors of 0.5° and 1°. The errors are compared with the random error to be expected from a C.R.G. grade 6 survey with an average leg length of 20 feet (station position error zero, tape ± 0.1 feet, compass and clinometer readings ± 0.5°.

It must be borne in mind that whereas the distance axis for the random error represents the slope distance of the survey, that for the calibration error shows the straight line plan distance of a point from the origin of the survey. Whereas random errors are largely self-compensating, the error due to poor calibration is fixed, and is equivalent to a shift in the north arrow.

Consider two surveys made with different compasses, which both start from the same station and "close" at a second point with a plan distance of 200m from the origin. If each survey line contains 400m of survey line, then Figure 8 shows the systematic error to be 1.60 x 3m, or 4.8m. The error caused by 1° difference in calibration will be 3.35m. Since it has been shown that compasses can differ by 10°, the potential magnitude of calibration errors becomes clear.

Three surveys exist of the Rabbit Warren Extension in St. Cuthbert's Swallet. Each end of the series is marked by stations the positions of which are substantially correct. The earliest survey, 'A', shows a pronounced difference, 6.7m, from the second, 'B', survey, and from the rest of the cave. This difference is, in fact, due to a calibration difference of a little over 3° between the compasses used. It has since been shown that the site used by the surveyor 'A' to calibrate his compass is affected by a local magnetic anomaly caused by buried steelwork. The middle survey, also by surveyor 'A', has a similar, but smaller, discrepancy with both the 'B' survey and the rest of the cave. When the two 'A' surveys are corrected for differences in calibration, the three surveys are very nearly coincident.

Figure 13 shows results which are only possible if care is taken to calibrate compasses accurately. Seven different routes were surveyed from one station in St. Cuthbert's Swallet to a second station. Four different compasses were used, and two different calibration bearings were established and used at different stages of the surveying. All seven points are inside a 1° arc from the origin, in spite of the scattering due to systematic errors.

There will be circumstances when it is impossible to calibrate a compass. What may NOT be done on these occasions is to assume that a compass gives correct magnetic north readings, apply a correction read from a map, and then publish a survey showing "True" (or "Grid") north; this is quite indefensible. It implies that the surveyor has done what he has not. The surveyor should publish precise details of what he has done with respect to calibration. In other words, if he has attempted to calibrate his compass by means of a single surface bearing he should publish sufficient detail to permit later workers to reproduce this bearing precisely. This calibration will be unreliable since the surveyor will not have proved the absence of a magnetic disturbance.

Compass calibration errors cannot be avoided entirely. The procedures described elsewhere will correct bearings to grid north with a precision of ± 0.25°. The procedure should be adopted at each cave, as it will only be valid for the precise area where it was established and will not necessarily be valid over another cave only a few miles away. The compass should be freshly calibrated at an established bearing immediately before or after each surveying trip.

If a surveyor completes a survey quickly using a single compass, errors caused by faulty calibration will not appear, and traverse closure statistics may be most impressive. Nevertheless, the north arrow and hence alignment of the entire survey will be uncertain. The surveyor may be blissfully unaware of the problem; but anyone who has to survey an extension at some later date will certainly find more than his fair share of problems.

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38 Paultow Road,
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CAVE LOCATION BY ELECTRICAL RESISTIVITY MEASUREMENTS, SOME MISCONCEPTIONS AND THE PRACTICAL LIMITS OF DETECTION.

by J.O. Myers

Summary

The importance of the reciprocal relation in four-electrode resistivity measurements is emphasised. Three old misconceptions which have led to fallacious interpretation systems are discussed and resistivity model experiments are used to confirm the practical limits of the method for locating concealed air-filled cavities.

Introduction

Any attempt to write a short paper on the location of caves by the electrical resistivity method, quoting practical examples from the literature, meets with the difficulty that most of the available material is not in English and needs translation. Also it is unfortunately true that a high proportion of the papers published in English on attempts to locate caves by this method either record failure or contain errors of theory or interpretation.

In this discussion it is hoped to pinpoint the probable source of at least some of the errors which appear in previous English publications. In general terms the electrical resistivity method is one in which there is relative ease in obtaining suitable equipment and making field measurements, together with relative difficulty in making a sound interpretation of the data collected. This of course can be a fatal combination. However, the mere fact that precise interpretations are often not possible should not preclude making sensible deductions from field observations.

Where apparent resistivity variations cannot be pre-calculated theoretically, model experiments are a proven substitute. It is suggested that some mistakes that appear in published papers would not have been made if the field work had been preceded by an adequate series of resistivity tank analogue measurements.

The Four Electrode Method

For any array of four electrodes on the earth's surface as in Fig. 1 the apparent resistivity is given by:—

$$\rho a = 2\pi R \left[\frac{1}{a} + \frac{1}{d} - \frac{1}{b} - \frac{1}{c} \right]^{-1}$$

where R is equal to the potential difference between P_1 and P_2 divided by the current flowing in the circuit between C_1 and C_2. If R is in ohms, a, b, c and d in metres, then ρa will be in ohm metres.

For a homogeneous medium the value measured would be the true resistivity, but in the general field case this is never possible and we remind ourselves of this by referring to ρa as the apparent resistivity.

In practice the general array is usually simplified to a linear or square form for speed or working. The arrangement can still be very variable and examples of different linear arrays may be found in any of the introductory textbooks on the subject. Any array may be used in either of two ways.

An area may be traversed by an array used with a fixed spacing between the electrodes in order to pick up the effects of lateral changes in rock resistivity. The extent to which lateral changes can be detected will be affected by the vertical variations in resistivity. For example, if the lateral changes lie beneath layers of very low or very high resistivity, they may be difficult to detect from the surface. If the ground is covered in sufficient detail then an apparent resistivity contour may may be drawn, which is the soundest way of using traversing.

The alternative system of depth probing by keeping an array centred at one point and repeatedly increasing the electrode spacings is appropriate for a layered geological situation with a minimum of lateral changes. It is assumed that as the area covered by the electrode array is increased so the apparent resistivity measured will be progressively more influenced by the resistivities of deeper rock layers. Interpretation in terms of depth and resistivities of layers can be made in simple cases by comparison of field profiles with a series of standard theoretical profiles.

Because the spacing is increased for each successive reading the electrodes are individually being moved across the selected site even though the array is centred about the same point. Hence any lateral changes crossed by individual electrodes will also be picked up and will be combined into the depth probe curves. These effects will vary in sharpness depending on depth below the surface, but if we have been successful in selecting a site free of lateral geological changes, then the lateral effects will be from the surface soil and subsoil. They will appear as sharp deviations in the otherwise smooth depth probe profiles. The sharper the effect the nearer the ground surface is its cause. Recognition of these effects is vital and a simple procedure to aid in their identification is available (Carpenter and Habberjam 1956).

The Reciprocal Relation

About the middle of last century Helmholtz showed that for a homogeneous isotropic medium and a system of two current and two potential terminals the current and potential connections are interchangeable without affecting the measurement. Later, Searle (1910) published the proof of a generalised form of this showing that the reciprocal relation also applies to a non-isotropic non-homogeneous medium. Hence any electrode arrangement such as CPPC may be replaced by PCCP without in any way altering the value of the measurement made. Although Searle was considering this from the point of view of assemblages of resistances in electrical engineering his general case covers any arrangement of four electrodes no matter how asymmetric, in any field geological situation no matter how complex. It is easy to verify this reciprocity in the field and it is quite immaterial whether one uses an array or its reciprocal except for tactical reasons. There are a number of these reasons, an obvious example with large spacing linear arrays being that if we have the current electrodes as the inner pair it is easier to supervise the safe operation of D.C. measurements.

The reciprocal relation is important not merely as a convenience which may come in useful on occasion. Recognising its validity is fundamental to a proper understanding of the way in which the electrical resistivity methods work and the idea of reciprocity needs to be kept in mind at all times when using methods. If this had been done by all workers with the method it is likely that most of the errors and false interpretation methods proposed from time to time would simply not have arisen.

Three old misconceptions

The most common misconception which continues to appear in the literature consists of an assertion that the value of apparent resistivity measured depends mainly on the resistivity of the ground below the potential electrodes. Since in non-homogeneous ground this apparent resistivity does not change if we switch over and use the other pair of electrodes for the potential measurements then the statement is simply not true. It would be more correct to say that the apparent resistivity measured relates to the ground in the region of all four electrodes. The error seems to date back to Wenner's original paper (Wenner 1915, p.475). That is still persists with undiminished vigour may be seen by turning to the revised 2nd edition of "Physics in Archaeology" (Aitken 1974) where it appears on pages 270, 271 and 281, notwithstanding the fact that the last of these comments is immediately followed on the same page by reference to the reciprocal relation and Searle's paper.

The second misconception concerns the attempt to define, however loosely, the volume of ground involved in a single measurement with a given electrode array. It is natural to wish to have some feel for the way in which measurement is sampling the different resistivities in the ground. However, although for simple cases, especially layered systems, we can calculate the apparent resistivity for a given array for any assumed actual rock resistivities, the reverse procedure is not possible. Even in the calculated cases the volume of ground involved cannot be precisely defined. That it is an altogether meaingless idea is best illustrated by the fact that under some conditions it is possible to record negative apparent resistivities (Carpenter, 1955 p.394, Carpenter and Habberjam, 1956 p.459 et seq.).

Although this second misconception is well known as such it still crops up in the literature. It seems to originate from Wenner where a version of it appears together with the first misconception referred to above. The idea was used in various forms during the 1920s and 1930s as the basis of empirical interpretation systems which had to be abandoned as they were found to be fallacious.

A third misconception concerns the idea that it might be possible to measure sharp changes of apparent resistivity at the ground surface from geological features at depth. This relates to depth probing methods where a sharp effect would be defined as one involving not more than two or three adjacent readings at not widely different electrode separations. The accumulated evidence of thousands of calculations for layered cases shows that even for very sharp changes of resistivity at depth the changes observed at the surface appear as a gradual change of apparent resistivity over the readings for a series of different electrode spacings (see Mooney and Wetzel, 1956 and others). Sharp changes of apparent resistivity between adjacent readings for different electrode separations are invariably produced by local lateral changes in the surface material encountered by the electrodes. This applies not only to the regular arrays for which the theoretical profiles have been calculated, but for any arrangement of four electrodes on the ground surface provided that the same arrangement is used throughout the set of measurements. Recognition of lateral effects is assisted by making full use of the electrode array at each measurement as originally suggested by Carpenter and Habberjam (1956) in their tripotential system.

A Fallacious Interpretation System

One recently much quoted (though not by professional geophysicists) paper by Bristow (1966) is an example of how all three of the misconceptions referred to above may appear together in a completely fallacious interpretation system. Without quoting all the detail, which may be readily obtained from the paper, it is seen that Bristow ignores the reciprocal relation, wrongly allots a specific volume to the ground whose resistivity is supposed to be measured and uses an electrode array in such a way as to record a large number of local surface resistivity variations. Selected pairs of the high anomalous values are then combined by a simple geometric construction to give completely fictitious underground locations which are assumed to be cavities.

Using the so-called single electrode probe or asymmetric probe system, as does Bristow, with one fixed electrode, one mobile pair at fixed spacing and with the fourth electrode effectively at infinity two effects are observed. As the mobile pair increases in distance from the base electrode the effect of deeper layers is increasingly reflected in the apparent resistivities measured, this being a slow gradual change. In addition sharp positive and negative variations from the smooth curve are shown which relate to the locations of the moving electrodes. The closer the mobile pair of electrodes are placed together the sharper these variations become, which is a clear indication of their surface origin. This is well shown in a diagram of Carpenter's recently published by Creedy (1975), and further discussion of this problem is given in a paper by Habberjam and Carpenter (1955).

In a typical situation of limestone beneath thin soil cover in which most of Bristow's measurements were made one would expect high local values of apparent resistivity where the limestone is very near the surface and local low values where there are fissures or hollows in the limestone filled with relatively conducting clay or subsoil. In following Bristow's fallacies Bates (1973) recognised that the local low values probably indicated concealed fissures or grikes, but failed to take the next logical step and realise that the highs were probably caused by the more prominent of the ridges of limestone between the grikes.

If this simple proposition is correct then it follows that for either Bristow or Bates an afternoon's work with a soil auger should have shown the correlation between the ups and downs of the concealed limestone surface and the highs and lows of the resistivity profiles. In either case this could presumably have saved two seasons of misdirected field work.

Location of caves, limits on resolution

Since an air-filled cavity represents an effective insulator situated in a conducting medium, the conditions for location by the electrical resistivity method might be thought to be ideal. However, all but the very largest of caves at shallow depth represent a very small volume beneath an electrode spread relative to a continuous layer of rock of the same thickness as the cave diameter. Thus, except where the cave is very near the surface, its presence will scarcely affect the pattern of current flow in the ground from a four electrode array.

An attempt to deal with the simplest case, that of a buried insulating sphere, was made by Palmer (1954) to give a means of plotting a theoretical depth probe curve. Unfortunately this was illustrated by a completely unrealistic diagram (Palmer, 1954, Fig. 3), an accurate plot from Palmer's formula being given by Tagg (1964, Fig. 3.19).

Where a precise theoretical solution is not available the approach of tank analogue modelling may be a practical alternative. Habberjam (1969) has used this to look at the insulating sphere problem in more detail and shows that the limit of detectability is being reached for a depth to top equal to the radius of the sphere. Even this has to assume a low level of background noise from unwanted effects, which, however, are rarely absent from the field case.

A closer approximation to the typical cavern is given by the horizontal cylinder. Although this model must have been examined many times before there do not at present appear to be any published results in the English literature. Fig. 2 shows the profiles from a series of traverses across a perspex tube immersed in a brine tank with a Wenner array moved across laterally. This form of traversing with the electrodes parallel to the strike of the target feature gives the simplest apparent resistivity profiles, avoiding the sharp changes produced when four electrodes are taken across a feature successively in the more normal longitudinal method of traversing. The profiles show clearly that detectability should be possible down to a depth to top equal to the diameter, provided of course that the background noise levels are low enough. Although there is still a measurable anomaly at a depth to top of one and a half times the diameter it is more than likely in a field case that this would be lost in among the sharper background effects due to variable depth of conducting soil cover over the limestone.

There is substantial scope for further work on models of caves including the introduction of near surface variations above the main model to simulate typical background effects. This might be done by using cut-outs of wire gauze or plastic mesh. In any problem of this kind, field work should always be preceded by model work so that the effects of any innovations of either technique or interpretation may be checked.

Suggested field procedure

Although the method of depth probing has been developed for the estimation of depths to horizontal layers in very simple stratigraphic conditions, Palmer (1954) attempted to use it for the determination of the depth of a hidden cavity. This can no doubt be done in some simple cases although the method would need further development. To carry out such a test sensibly it is first necessary to locate the hidden cavity and this can be best done by traversing. Furthermore Habberjam (1969) has shown that both depth and diameter in the case of the buried sphere can also be determined from traverse data.

Since there are so many factors that can affect the measured apparent resistivities on a single traverse line it is better to cover the search area by a series of closely spaced traverses in order to construct a reliable resistivity contour map. Information on these methods is widely available in geophysical literature so that only the question of choice of electrode spacing will be briefly dealt with here.

Fig. 3a illustrates an apparent resistivity space diagram for the case of the horizontal insulating cylinder at a depth to top equal to half the diameter. This is plotted from a number of traverses using the Wenner array on the tank model as for Fig. 2, but with a range of six different electrode separations. The contour pattern suggests that the most effective spacing between electrodes is in the range of two to three and a half times the depth to the top of the cylinder. Fig. 3b shows the less striking contour pattern for a repeat of the experiment with depth to top equal to the diameter.

Conclusions

Tank analogue experiments confirm the generally accepted view that detection of horizontal caves by the resistivity method is unlikely much beyond a depth to top equal to the diameter i.e. a six feet diameter cave at six feet depth to its roof. Claims for the asymmetric probe method which would seem to indicate a marked improvement on this have been shown to be completely fallacious.

It is clear that under ideal field conditions there will be the possibility of locating horizontal passages where relatively large caves lie very close to the present ground surface. Sites of this kind are not

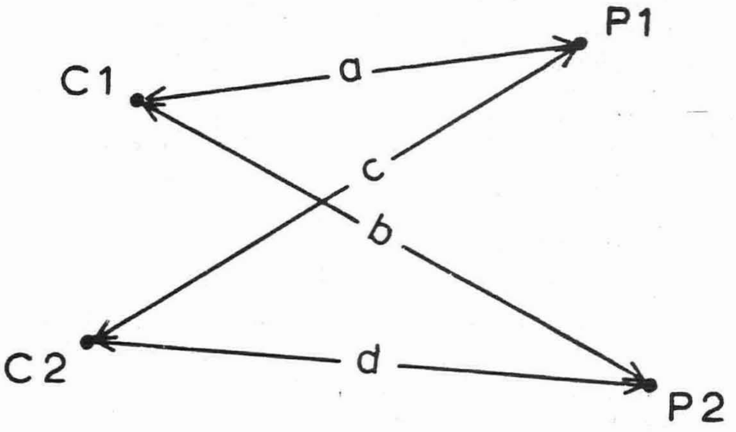


Fig. 1. Four electrodes, plan view of general case.

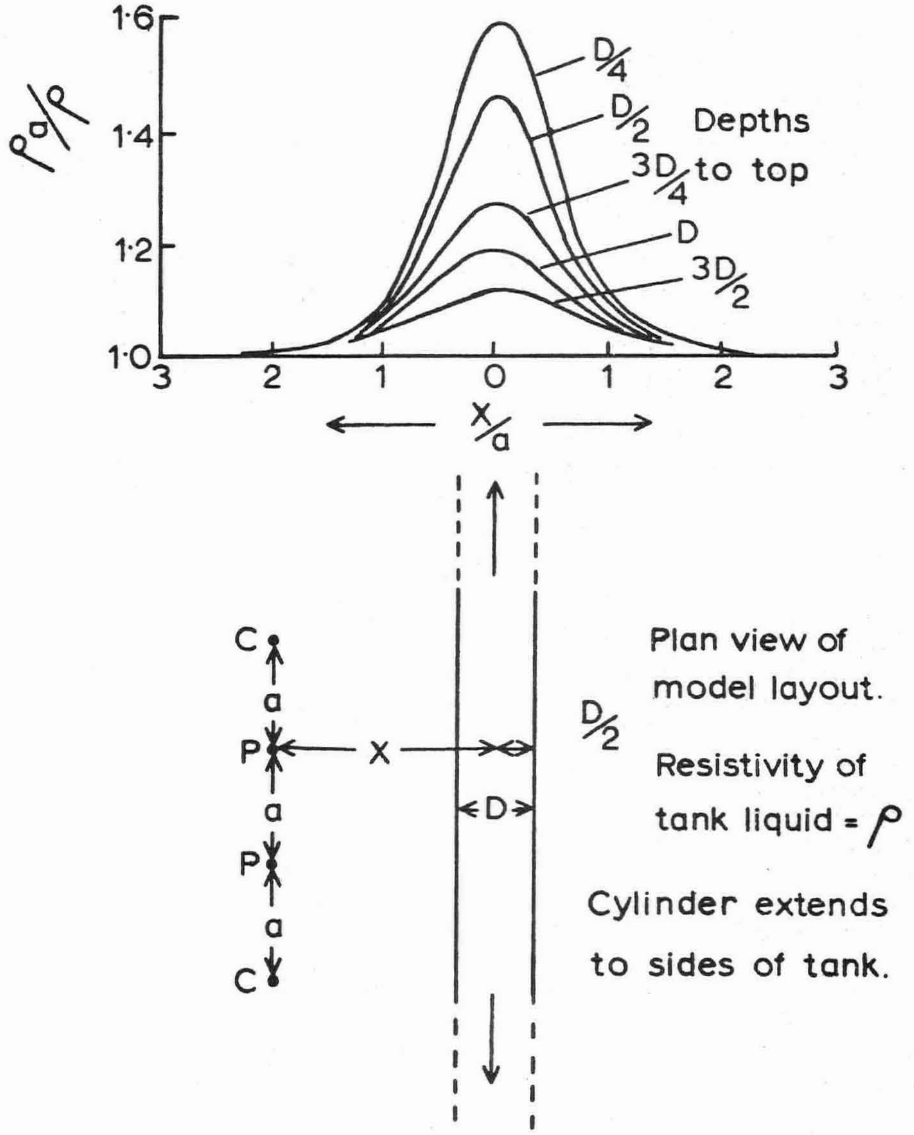
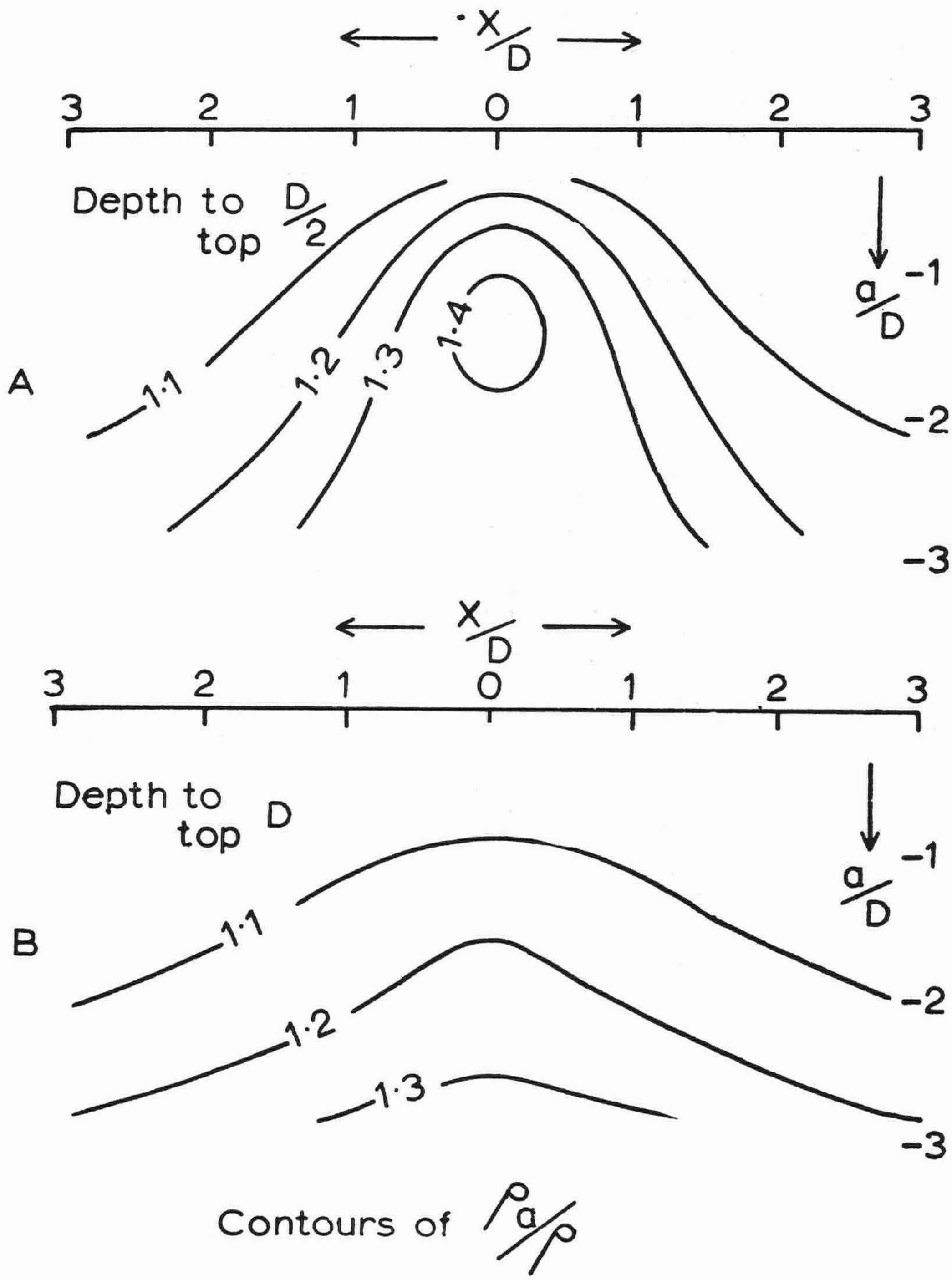


Fig. 2. The horizontal insulating cylinder. Tank analogue resistivity profiles for a fixed electrode spacing with varying depth of cover.



<u>Fig. 3.</u> The horizontal insulating cylinder. Tank analogue resistivity space diagrams for two cases:-

A. Depth to top equal to the radius

B. Depth to top equal to the diameter

common and it is in fact difficult in this country to find sites where the method can be unequivocally demonstrated. Furthermore any cave system at a sufficiently shallow depth usually includes points of collapse where entry may be gained and the use of geophysics is not necessary.

Since from the practical caver's point of view the desired target is usually a small choked opening in the surface which has to be cleared of obstruction before the caverns below can be entered the resistivity method is only likely to be of fringe interest. Examination of published surveys will show that where the excavated parts of new caves reach open horizontal passages, these are already well below the levels of detectability bearing in mind their limited cross sections.

The intriguing possibility remains of the occasional finding of a very large cavern at shallow depth with no obvious way in. This would be of interest to any party who were equipped to drill a proving borehole and then excavate an artificial shaft down to the cavern. There is also the more likely possibility of proving the extension of a known large cavern at shallow depth beyond an underground obstruction.

Acknowledgements

The author wishes to thank Mr. H.A. Baker for setting up and measuring the resistivity model experiments on which Figs. 2 and 3 of this paper are based.

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J.O. Myers,
Dept. of Mining & Mineral Sciences,
University of Leeds.

Trans. British Cave Research Assoc. Vol.2. No.4. pp.173-176. December 1975.

DETECTION OF HYPOTHERMIC STATES BY A SIMPLE ELECTRONIC TEMPERATURE INDICATOR

by I.G. Rogers & P.K. Webb

Summary

In order to assist with the diagnosis of hypothermic states, and particularly to enable cavers with limited medical knowledge to pinpoint the time when it does more harm than good to continue moving a hypothermic caver towards the surface, two electronic temperature sensors were built. The first prototype simply indicates when a patient's mouth temperature drops below 35°C by a red light. The second model has three coloured lights which indicate five temperature states; the colours change at four temperature points. The details of the electronic design and the medical applications of the instruments are described.

Introduction

A cave rescue doctor recently drew attention to some problems of diagnosis and treatment posed by a victim of hypothermia underground (Frankland, 1973).

The problem with a hypothermic patient is decided at what point exertion producing muscular heat ceases to have a beneficial effect. Present medical opinion is that, unless the patient is already exhausted, it is safe for him to move if his core temperature is above 34-35°C. In a recent paper (Harper, 1975) this was described as the 'switch-off' temperature, at which muscle function is so greatly impaired that the heat loss from exertion is greater than the heat production. Further exertion when core temperature has dropped below this 'switch-off' temperature causes rapid deterioration in a patient's condition and may lead to death.

Cavers have taken a particular interest in diagnosing the 'switch-off' point, as the problems of cave rescue necessitate taking all practical self-help action to reach the surface. A doctor has suggested that the level of consciousness and responsiveness is a good guide to whether it is safe to encourage a patient to move or not (Frankland, 1973).

In order to assist with the diagnosis of hypothermic states, and particularly to enable cavers with limited medical knowledge to pinpoint the time when it does more harm than good to continue moving a hypothermic caver towards the surface, the authors tried to produce an efficient hypothermia indicator the size of a matchbox and costing less than £1, that any caver or club could carry in their emergency spares box. Two electronic temperature sensors were built, and some details of their electronic design and medical applications are described below.

An Electronic Indicator of Core Temperature

A thermistor (temperature-dependant resistor) is used as a temperature sensor. It is placed in a network of resistors (see Fig. 1) so that the voltages at points A and B are equal at 35°C. A highly sensitive voltage comparator is used to determine whether the measured temperature is above or below 35°C; if it is below, the comparator operates a small warning lamp.

In addition to the basic design, extra features were incorporated for safety and reliability. The warning lamp used was a red light-emitting diode because of its small size, low pwer requirement, robustness and reliability. A zener diode is incorporated in the circuit so that if the battery voltage falls below that required for accurate operation, the lamp will not illuminate when the unit is first switched on. The design of a simple waterproof switch was given much thought; ultimately a reed relay was used. This consists of an evacuated glass capsule containing gold-plated contacts which make contact when in a magnetic field. The relay was placed mid-way between two ceramic magnets whose fields cancel out in the vicinity of the relay. In the zero net magnetic field the contacts are open. One magnet and the relay were mounted inside the case at a suitable spacing whilst the other magnet was held in a spring clip to the outside of the case (Fig. 2). The unit is switched on by simply removing the exterior magnet. The magnet may be discarded, as they are very cheap, or retained. The prototype has a magnet with a central hole suitable for a retaining cord. The spring clip is useful for attaching the unit to the patient's clothing.

Before placing the thermistor in the patient's mouth, the unit is switched on to check that the lamp illuminates. If the lamp glows dimly, the unit may be used, but the battery will not last much longer. This check may be carried out before an expedition. When the thermistor is placed in the patient's mouth, the lamp should extinguish after a short time. indicating that it is probably safe to move the patient towards the surface. If the thermistor probe is left in the patient's mouth, the lamp will relight if the patient's condition worsens and the mouth temperature falls to 35°C. At this point he should be stopped and all measures taken to preserve his body heat and raise his core temperature. It is advisable when continually monitoring a patient in this way occasionally to withdraw the thermistor in order to check the battery.

It was the aim of the authors to produce an efficient hypothermia indicator in the size of a matchbox and costing less than £1. It was hoped that any caver or club would be able to carry one in their emergency spares box. The unit described cost approximately £1.50 (retail component cost) and measures 41mm by 38mm by 20mm excluding the spring clip (Fig. 3).

A Unit to Indicate Five Ranges of Core Temperature

Following medical advice that it is more desirable to know the rate of fall of mouth temperature than to know when mouth temperature reaches the 'switch-off' point, a second unit was constructed. The mouth temperature gives the most convenient guide to core temperature although it is not identical.

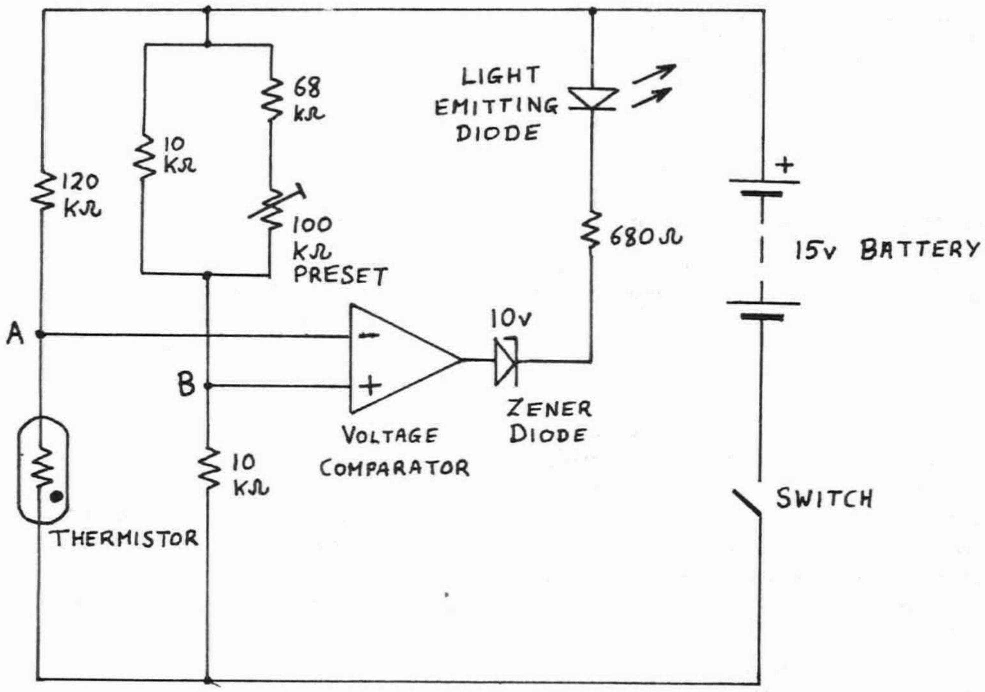

Figure 1: Circuit Diagram of First Design

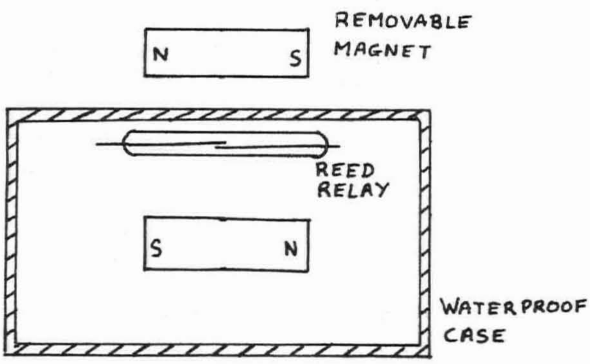

Figure 2: Locations of Reed Relay and Magnets

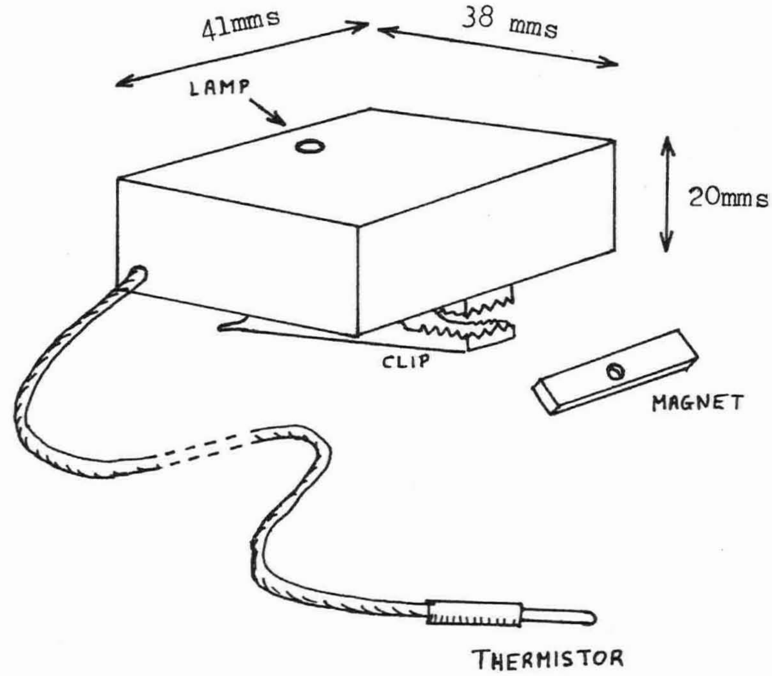

Figure 3: Sketch of Instrument

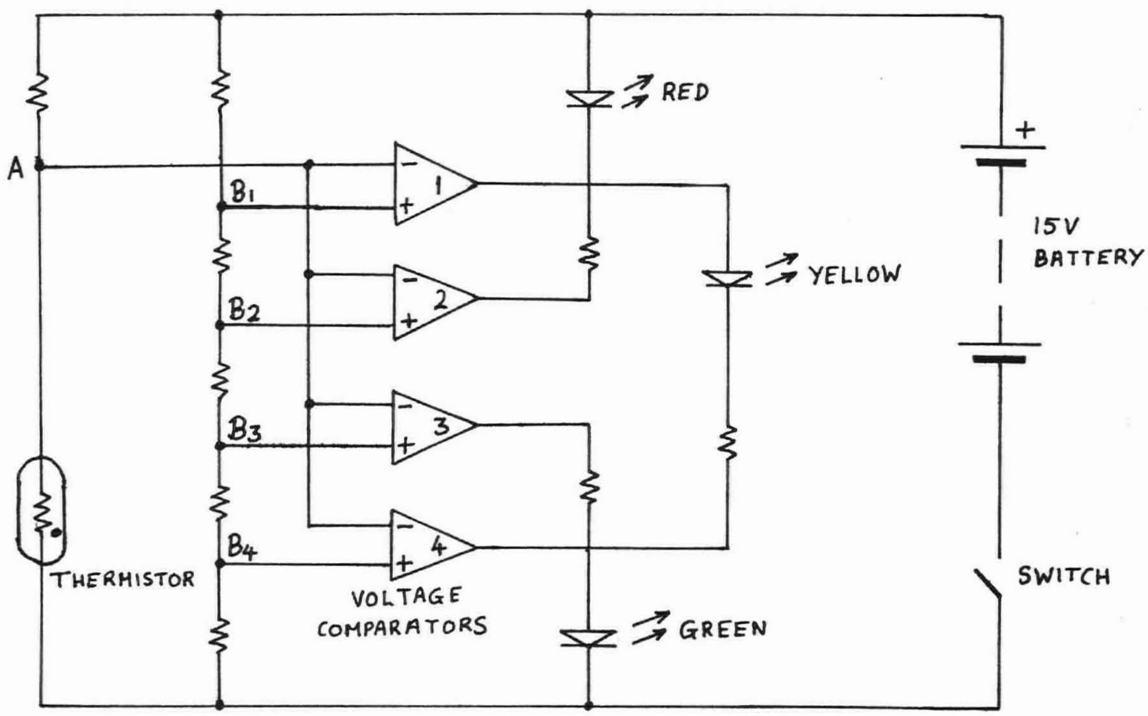

Figure 4: Circuit Diagram of Second Design

The circuit of the second unit was designed with the same principles as that of the first unit. Four voltage comparators are used to determine whether themeasured temperature is above or below four transitional temperatures (Fig. 4). At low temperature the red lamp is illuminated, but when the temperature rises to a preset value T_1, the voltage at points A and B_1 become equal and the first comparator brings the yellow lamp on. Similarly, when the temperature rises to another preset value T_2, the voltages at points A and B_2 become equal and the second comparator switches off the red lamp. At the third temperature T_3, the third comparator brings the green lamp on, and at the fourth preset temperature T_4', the fourth comparator switches the yellow lamp off.

A suggested calibration is:—

Temperature Range	Colour Code
Below 34.5°C	RED
34.5°C to 35.0°C	RED + YELLOW
35.0°C to 35.5°C	YELLOW
35.5°C to 36.0°C	YELLOW + GREEN
Above 36.0°C	GREEN

The second circuit has been fitted into the same size box as the first unit (including battery) and the component cost was about £3.50. The prototype unit does not have a safeguard against operation with inadequate battery voltage; a zener diode may however be included with the red lamp as on the first unit, or with all three lamps.

Possible Further Developments

The thermistor probe on both units was designed to monitor mouth temperature as this appeared to be the most convenient place to position a probe. A cave rescue doctor related that having carried an anal low-reading thermometer he did not find it convenient to use it instead of an oral thermometer (Frankland, 1973), although rectal temperature is thought to be the most accurate parameter of core temperature (Frankland, 1973, personal communication). It should be possible to use a bead-type thermistor which could be pushed through the material of a wetsuit and into a patient's (or possibly victim's?) rectum, leaving the probe in position with the minimum of discomfort.

Conclusions

Although the two versions of core temperature indicator have not been produced in marketable form, they show that it is possible to produce instruments that are suitable for all caving teams to take on every expedition. While they do not give as much information as a calibrated meter, they are cheap, small, almost unbreakable and very easy to use.

Acknowledgement

Whilst accepting full responsibility for the views expressed in this paper, the authors would like to thank Dr. J.C. Frankland for his helpful advice in response to our queries on medical matters.

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M.S. Received September, 1975

I.G. Rogers, B.A.,
Crowden Outdoor Centre,
Hadfield,
Hyde,
Cheshire, SK14 7HZ.

P.K. Webb, B.Sc.,
Suffolk.

Trans. British Cave Research Assoc. Vol.2. No.4. pp.177-192. December 1975.

PHREATIC NETWORK CAVES IN THE SWALEDALE AREA, YORKSHIRE

by P.F. Ryder

Summary

Several phreatic network cave systems, a number of them broken into by 18th and 19th century lead mine workings, are known in the Northern Pennine Dales. Two such systems in Swaledale, Windegg Mine Caverns and Devis Hole Mine Cave, have recently been examined and surveyed. Their morphology and development are discussed. The relationship between the phreatic network caves and the long distance hydrological systems in the Main Limestone of the Swaledale area is examined, and it is suggested that the presence of pre-existing phreatic cavities may be an important factor in the initiation and development of long distance subterranean hydrological systems.

Perhaps a dozen so-called "mine caves" or "mine caverns" have been recorded in the Northern Dales. Several of these systems are simply sections of active stream caves which happen to have been intercepted by old mine workings (e.g. Ayleburn Mine Cave, Hope Level Four Fathom Mine Cave), but others are more interesting in that they demonstrate a type of cave system not known in caves with "natural" entrances in the area, i.e. the extensive phreatic network. Unlike many of the natural cavities in other limestone areas such as Derbyshire termed "mine caves", these complex solutional systems are not necessarily associated with areas of mineralization or mineral veins.

The first of the North Yorkshire Dales phreatic network systems to be described in recent years, Silverband Mine Caverns in Cumbria (Myers, 1967, p.34 et seq), is now inaccessible due to a collapse of the old mine workings through which access was gained. However, two more network caves, Windegg Mine Caverns and Devis Hole Mine Cave, situated within a few miles of each other in Arkengarthdale and Swaledale respectively, have now been studied and surveyed. A description of each follows, proceeded by a brief introduction to the geology and topography of the area, and followed by a comparison of the two systems and suggestions as to their mode of development.

The Swaledale/Arkengarthdale area

Both Swaledale and its tributary Arkengarthdale (Fig. 1) are typical, geologically and topographically, of much of the North of England Dales area, that is, the northern half of the Askrigg Block, and the Alston Block, forming the upland region from Wensleydale north to the Tyne Gap.

The valleys are incised in an extensive area of moorlands and rolling hills, falling in altitude from over 2000 ft. above sea level along the western edge of the two blocks to around 1000 ft. in the east. The geology throughout is of Lower Carboniferous strata locally termed the Yoredale Series, an alternating sequence of limestones, sandstones and shales, passing upwards into the Millstone Grit with appreciably less limestone. The boundary between the Viséan and the Namurian stages of the Carboniferous falls somewhere near the base of the Main Limestone, the thickest, and most significant speleologically, of the Yoredale limestones of the area.

The Main Limestone outcrop is obvious in both Swaledale and Arkengarthdale from the long lines of cliffs and scars, which often form the crest of the steep valley sides. Fremington Edge, running for several miles along the east side of Arkengarthdale and turning east into the main valley of Swaledale where the two valleys join, is a fine example of such a feature. This limestone is generally about 60 feet thick, passing upwards into cherts and mudstones, and, in some areas (e.g. around Windegg Mine Caverns) into more massive sandstones. The natural cave systems in both Windegg and Devis Hole mines are situated in the Main Limestone.

WINDEGG MINE CAVERNS

Entered via Windegg Old Level, a lead mine driven in the mid 19th century, and worked until c.1890, the entrance is above extensive spoil heaps at NZ 012052, at an altitude of approximately 1500 ft. O.D., and is reached by walking up a gully from the Reeth to Barnard Castle road, on the east side of the road about 1¼ miles north of Eskeleth bridge. The Main Limestone, in which the caverns are situated, forms prominent scars (Little Windegg and Windegg Scars) to the south of the mine entrance, but is not apparent to the north, being downfaulted to lower levels.

History of Exploration

The mine level, which had been blocked, perhaps early this century, by a collapse a few feet from the entrance, was re-entered in the early 1960s by the Earby Mine Research Group, who dug out and timbered a 6 ft shaft dropping into the level beyond the blockage (Fig. 2). Their main concern was with the old mine workings, and it was not until 1970, following a visit by D. Carlisle of EMRG and members of Moldywarps Speleological Group that serious attention was paid to the extensive series of natural caverns reached by climbing up through old mine workings above the level.

MSG members surveyed both the cave system and the mine workings, in the course of more than a dozen visits (Stevens, 1972, pp.11-13). Clog prints in the clay of the passage floors indicated that the miners had exploredmuch of the system, although some sections of passages did not appear to have been previously entered.

A recent visit (September 1975) to the mine entrance revealed that the timbered entry shaft was blocked by a collapse, the scale of which is uncertain.

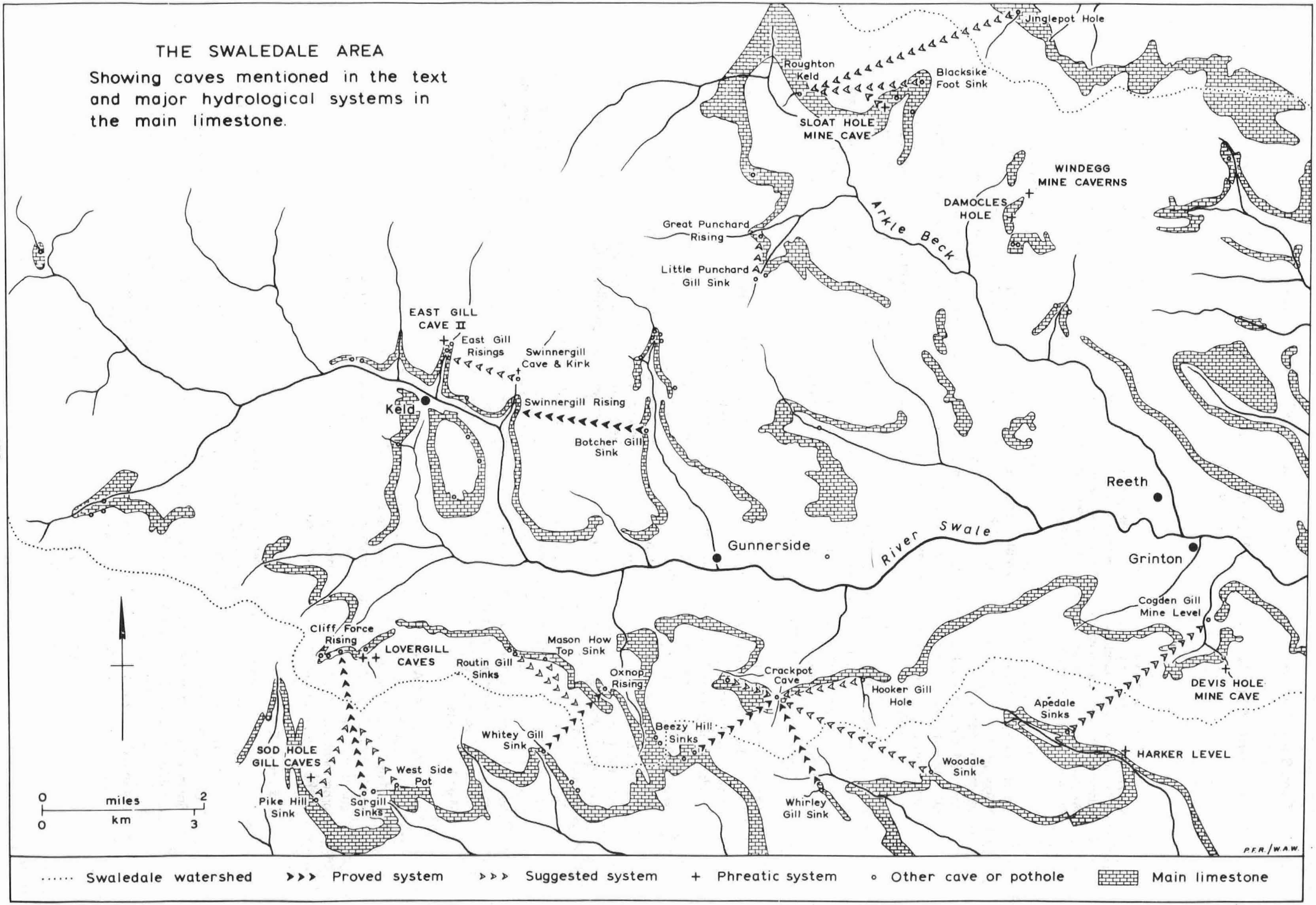

THE SWALEDALE AREA
Showing caves mentioned in the text and major hydrological systems in the main limestone.
Jinglepot Hole
Roughton Keld
Blacksike Foot Sink
SLOAT HOLE MINE CAVE
WINDEGG MINE CAVERNS
DAMOCLES HOLE
Arkle Beck
Great Punchard Rising
Little Punchard Gill Sink
EAST GILL CAVE II
East Gill Risings
Swinnergill Cave & Kirk
Swinnergill Rising
Keld
Botcher Gill Sink
Reeth
River Swale
Gunnerside
Grinton
Cogden Gill Mine Level
Cliff Force Rising
LOVERGILL CAVES
Mason How Top Sink
Routin Gill Sinks
Oxnop Rising
Crackpot Cave
Hooker Gill Hole
DEVIS HOLE MINE CAVE
Apedale Sinks
Whitey Gill Sink
Beezy Hill Sinks
HARKER LEVEL
SOD HOLE GILL CAVES
West Side Pot
Woodale Sink
Pike Hill Sink
Sargill Sinks
Whirley Gill Sink
0 miles 2
0 km 3
P.F.R./W.A.W.
Swaledale watershed
Proved system
Suggested system
Phreatic system
Other cave or pothole
Main limestone

Fig. 1

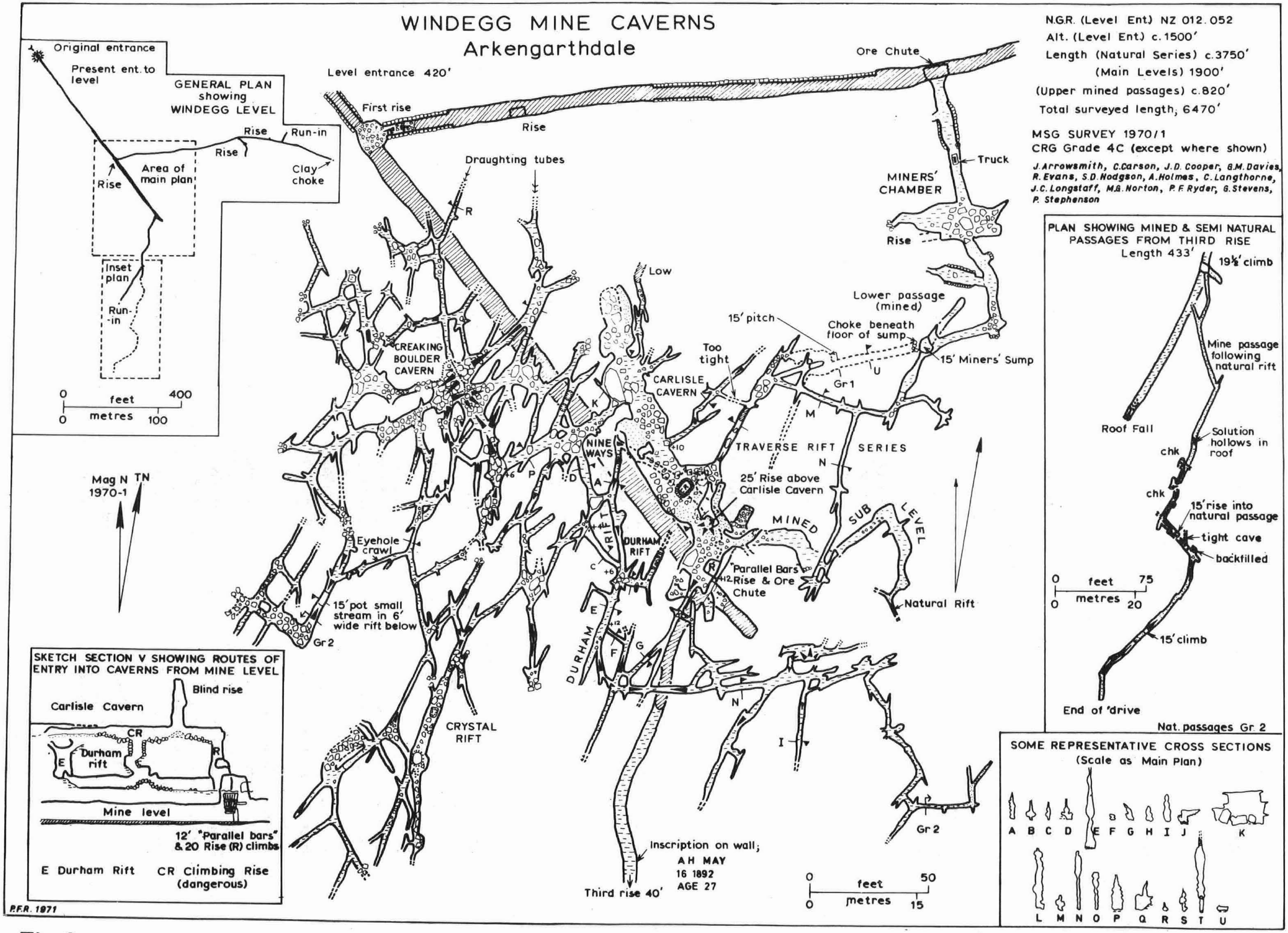

WINDEGG MINE CAVERNS
Arkengarthdale
N.G.R. (Level Ent) NZ 012.052
Alt. (Level Ent) c.1500'
Length (Natural Series) c.3750'
(Main Levels) 1900'
(Upper mined passages) c.820'
Total surveyed length, 6470'
MSG SURVEY 1970/1
CRG Grade 4C (except where shown)
J.Arrowsmith, C.Carson, J.D. Cooper, G.M. Davies, R. Evans, S.D. Hodgson, A.Holmes, C. Langthorne, J.C. Longstaff, M.G. Norton, P.F. Ryder, G. Stevens, P. Stephenson
Original entrance
Present ent. to level
GENERAL PLAN showing WINDEGG LEVEL
Rise
Run-in
Rise
Clay choke
Area of main plan
Rise
Inset plan
Run-in
0 feet 400
0 metres 100
Level entrance 420'
First rise
Rise
Ore Chute
Truck
MINERS' CHAMBER
Rise
Draughting tubes
R
Low
Lower passage (mined)
15' pitch
Choke beneath floor of sump
15' Miners' Sump
Too tight
CREAKING BOULDER CAVERN
CARLISLE CAVERN
Gr 1
U
K
M
NINE WAYS
TRAVERSE RIFT SERIES
N
P
D
A
25' Rise above Carlisle Cavern
Mag N TN 1970-1
RIFT
DURHAM RIFT
MINED SUB LEVEL
Eyehole crawl
C
'Parallel Bars' Rise & Ore Chute
Natural Rift
15' pot small stream in 6' wide rift below
E
DURHAM
F
G
Gr 2
N
CRYSTAL RIFT
I
Inscription on wall; A H MAY 16 1892 AGE 27
Third rise 40'
Gr 2
0 feet 50
0 metres 15
SKETCH SECTION V SHOWING ROUTES OF ENTRY INTO CAVERNS FROM MINE LEVEL
Blind rise
Carlisle Cavern
CR
Durham rift
E
R
Mine level
12' "Parallel bars" & 20 Rise (R) climbs
E Durham Rift
CR Climbing Rise (dangerous)
PLAN SHOWING MINED & SEMI NATURAL PASSAGES FROM THIRD RISE
Length 433'
19½' climb
Mine passage following natural rift
Roof Fall
Solution hollows in roof
chk
chk
15' rise into natural passage
tight cave
backfilled
0 feet 75
0 metres 20
15' climb
End of 'drive
Nat. passages Gr 2
SOME REPRESENTATIVE CROSS SECTIONS
(Scale as Main Plan)
A B C D E F G H I J K
L M N O P Q R S T U
P.F.R. 1971

Fig. 9

Description of the Cave System

The cave system consists of about 3750 feet of passage, crammed into an area little more than 300 ft. square. There are two predominant joint directions along which the passages have developed, roughly on 015° and 170°, Many cf the passage intersections have been enlarged by collapse, which in places has produced quite sizeable chambers.

The caverns are reached, from the level entrance, by following 440 ft. of stone arched level to the First Rise (a branch on the left here, Clay Vein Passage, ends after 770 ft. in a clay blockage with bad air). Straight ahead, another 240 ft. of wading through knee deep water leads to the Second Rise, above a right hand bend in the level. A climb of 15 feet on old timbers, alongside an old ore chute, leads up to a sub-level, and a few feet along this is a 20 ft. rise, climbable with care, leading up into Carlisle Cavern, the largest chamber in the system. Continuing along the sub-level, and turning left at a 'T'-junction, another rise, an easier climb, but very loose, also leads up into Carlisle Cavern. This branch of the sub-level ends in an easy climb up into Durham Rift, part of the network of passages west of Carlisle Cavern, and this is the easiest and safest way into the cave system.

Carlisle Cavern is 150 ft. in length and up to 30 ft. wide, and predominantly low and boulder strewn, although in places it attains a heigh of 15 ft. The mode of formation of this chamber is interesting — there appears to have been a very dense network of passages in this area, so closely spaced that very extensive collapse took place, leaving a roomy cavity roofed by the base of the massive sandstone which here overlies the limestone. Sections of the former joint network can still be recognised amongst the tumbled boulder of the floor.

Passages lead off from Carlisle Cavern to the west, south and east: the south and east passages are narrow rifts with few side branches, the latter communicating with high level mined passages which drop down into Clay Vein Passage. The main complex of passages, however, is west of Carlisle Cavern.

A small hole behind a boulder near the north end of the west wall of the Cavern quickly enlarges into an impressive 12 ft. high by 5 ft wide passage, opening onto Nineways Junction, where name indicates the complexity of the area.

The "hub" of the maze of passages west of Carlisle Cavern is a second collapse chamber, at an earlier stage in its development to the latter. This is Creaking Boulder Cavern, formed (or forming — the area is very unstable and boulder movements are still taking place) at the intersection of several major passages. Steep and loose boulder slopes lead up into this chamber, which shows the same flat sandstone roof as Carlisle Cavern, although on a smaller scale. The massive boulder ruckle forming the floor of Creaking Boulder Cavern is of the order of 40 feet in depth, and must extend virtually to the base of the limestone.

The complexities of the series of passages radiating out from the maze area between Creaking Boulder and Carlisle Caverns can best be understood from the survey. To the north, the passages generally terminate too tight or choked: two are impassably small draughting tubes which cannot be any great distance from the hush (an artificial ravine on the surface, produced by the miners' opencast working of a vein, debris being removed by "flushing" with water from a diverted surface stream) which marks the line of the fault, which terminates the block of limestone containing the caverns to the north. To the south, most of the major passages end in unsafe boulder ruckles, or (in the south east area of passages) simply pinch out into impassably narrow rifts.

Passage development, on a smaller scale, does appear to extend further south than the current limits of exploration in the main area of caverns. By following the mine level for a further 160 ft. from the base of the Second Rise, the Third Rise is reached (shortly beyond this the level ends in a roof fall), and a 20 ft climb up leads into a mined sub-level a little over 400 ft. long. Parts of this appear to be enlarged natural passage, and natural passages do open off it at several points, but all become too tight or choked within a few feet.

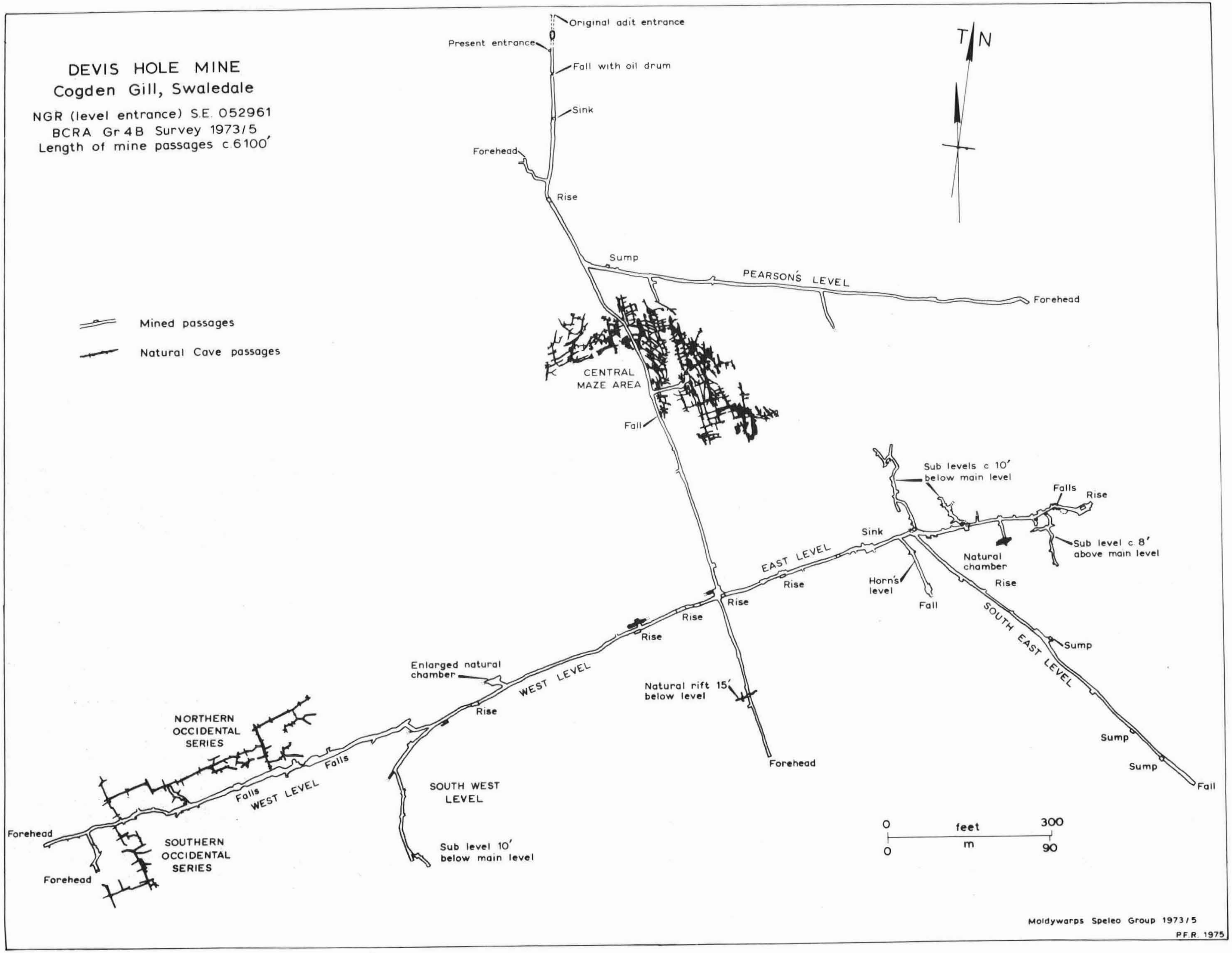
One tantalising piece of evidence to suggest that cave development does in fact extend much further south is seen in the small cave known as Damocles Hole, which lies about half a mile to the south of Windegg Level entrance, on the plateau above Little Windegg Scar. Here a collapse allows access to a short section of a major phreatic rift passage, very like those seen around Nineways Junction in the heart of the Windegg complex. A second collapse a few yards further south seals off the passage again — digging might be possible, but the whole cave is very unstable, and falls have taken place recently in the second collapse chamber.

Hazards of Exploration

Any visitors to Windegg Mine Caverns (if the entrance is again re-opened) should bear in mind that this is one of the most hazardous cave systems in the Northern Dales, many of the boulder piles and ruckles in the cave being very unstable; several rather frightening incidents occurred whilst MSG members were working in the system. The Creaking Boulder Cavern area, in particular, should be avoided. The old mine workings through which the natural system is approached are themselves hazardous in parts, and the old timbers in the area of the Second Rise should be treated with the greatest caution.

DEVIS HOLE MINE CAVE

The re-opening of Devis Hole Mine in 1973 allowed access to, and study of, an extensive phreatic network cave of rather less hazardous, and more comfortable, nature than Windegg Mine Caverns (Fig. 3).


DEVIS HOLE MINE
Cogden Gill, Swaledale
NGR (level entrance) S.E. 052961
BCRA Gr 4B Survey 1973/5
Length of mine passages c.6100′
Mined passages
Natural Cave passages
T N
Original adit entrance
Present entrance
Fall with oil drum
Sink
Forehead
Rise
Sump
PEARSON'S LEVEL
Forehead
CENTRAL
MAZE AREA
Fall
Sub levels c 10′
below main level
Falls
Rise
Sub level c 8′
above main level
Sink
Natural
chamber
EAST LEVEL
Rise
Horn's
level
Fall
Rise
SOUTH EAST LEVEL
Rise
Rise
Rise
Sump
Enlarged natural
chamber
WEST LEVEL
Natural rift 15′
below level
Rise
NORTHERN
OCCIDENTAL
SERIES
Sump
Sump
Forehead
Fall
Falls
Falls
WEST LEVEL
SOUTH WEST
LEVEL
0
feet
300
m
0
90
Forehead
SOUTHERN
OCCIDENTAL
SERIES
Forehead
Sub level 10′
below main level
Moldywarps Speleo Group 1973/5
P.F.R. 1975

Situation

Devis Hole Mine is situated in Cogden Gill, about 1½ miles south of Grinton in Swaledale, and 6½ miles south-south-east of Windegg Mine Caverns. The cave system is again in the Main Limestone a few hundred feet from its surface outcrop, but at a rather lower altitude (about 1150 ft. O.D.) than Windegg, and in a valley bottom rather than a valley side/plateau edge situation.

The level entrance (SE 052961) is found by following the Gill up (southward) from the impressive 18th century Grinton Smelt Mill, for about quarter of a mile, to an extensive old spoil heap which virtually blocks the valley. The level entrance, again a timbered shaft some 50 ft. from the original portal, is a few yards up the western of the two valleys which continue up beyond the tip.

History of Exploration

Devis Hole is one of the earliest major lead mines in Swaledale, much of the workings dating from the second half of the 18th century. The name "Devis Hole" is perhaps a corruption of "Devil's Hole", ascribed to the mine because of the presence of natural cavities, about which the miners were intensely superstitious.

The level remained open until comparatively recently, until, probably in 1964, a roof fall blocked the passage 90 feet from the entrance. Following this, the initial section of level rapidly became silted up, almost to the roof, due to the surface stream, which in flood used to flow into the level to sink in the floor about 100 feet in, backing up at the fall.

In 1971 MSG members, finding the level silted virtually to the roof, and thinking the roof fall to be much nearer the entrance than it actually was, dug the present entrance shaft hoping to drop into the level beyond the fall. EMRG members then took over the dig, and entered the badly silted level 40 feet short of the collapse. However, they cleared the level to crawlable dimensions, and dug through the roof fall, stabilising the route through this with timbering and two oil drums, their ends cut out, forming a tube through the unstable section. Beyond the fall they entered the level, open and unsilted, and found virtually the whole of the old mine workings still accessible, although in places of dubious stability. Once again, the main interest of EMRG was in the old mine itself, and it was left to MSG members, who arrived on the scene a few weeks later, to commence exploring and surveying the natural passages (Ryder, 1974, p.3-6).

Description

The natural passages intersected by the workings of Devis Hole Mine fall into three main groups:—

(i) The Central Maze Area — a very complex area of passages, totalling 5,150 feet, in all, contained in an area roughly 400 feet by 150 feet, and cut through by the mine level between 500 and 600 feet from its entrance (Fig. 4).

(ii) The East-West Level — this follows the line of a major lead vein, which for a considerable distance has been followed by a natural passage, now modified by the miners.

(iii) Occidental Series — near the far west end of the East-West Level, another series of natural passages have been intersected, in length a little over 1,500 feet (Fig. 5).

The present entrance to the mine level, a 10 feet timbered shaft, drops into the mine 30 feet from its original entrance. The initial section of the level is silted to within 2 feet of its roof, being a muddy crawl for 40 feet to the roof fall, now passed by squeezing through two oildrums — the second, smaller one has a diameter of 15 inches and may prove awkward to larger cavers.

Once through the fall, the level is easy walking, with one or two minor roof falls, passing Pearson's Level branching off on the left, to the point at which the mine breaks into the Central Maze area of natural passages.

This area is too complex to allow a detailed description, other than in the form of notes to be used alongside the survey. The Central Maze can conveniently be divided into four sub-areas, on the right (west) of the level, the Near West and the Far West, and on the left (east) the Near and Far East.

The Near East is the most complex part of the system, being a network of passages developed on three major joint directions, aligned roughly on 68°, 118° and 156°. There are some small collapse chambers, but generally the passages have suffered little modification from their original solutional form. Typically the passages are 5-10 ft. high and about 12 ft. wide, often widening slightly in the upper part of their cross sections. The roof section is generally square cut, due to minor collapse in a blocky mudstone band, and below this (locally absent in some partsof the Central Maze) is a band of fossil corals, the corallites left standing proud of the walls by the solution which produced the passages. The passage floors are generally clay, sometimes covered by a layer of calcite.

To the east all passages but one (cross section 'c' on survey) terminate in a linear belt of collapses, often highly calcited. This north-south belt of collapse serves to separate the Near East area from the Far East.

In the passages of the Far East, the 118° joint direction is less in evidence, thus a much more rectilinear grid plan results. To the east and south the various passages all end too low or choked — there does seem to be a fairly definite limit of development. In the southern part of the area the passages are generally higher than elsewhere in the Central Maze, the clay floors lying at a lower level. The miners, in sinking the Branch Level Sump (25 ft. deep) in the centre of the area, sectioned one of the major passages on the 156° orientation, showing that the clay fill extends to a considerable depth. This may be the case throughout the Central Maze, with 20 feet or more of fill lying beneath the passage floors.

The Near and Far West are less extensive areas of network than those on the opposite side of the

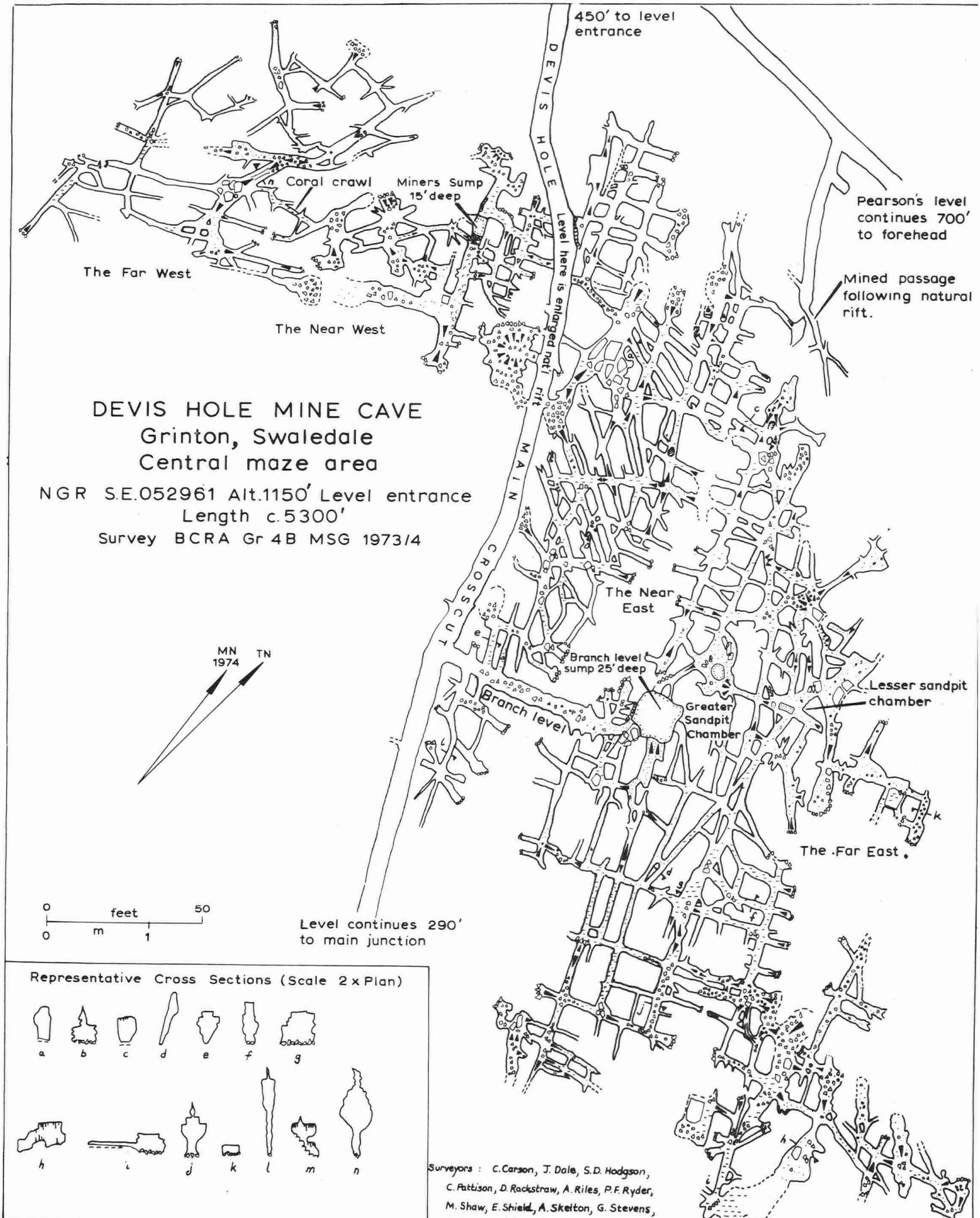

DEVIS HOLE MINE CAVE
Grinton, Swaledale
Central maze area
NGR S.E.052961 Alt.1150′ Level entrance
Length c.5300′
Survey BCRA Gr 4B MSG 1973/4
450′ to level entrance
DEVIS HOLE
Level here is enlarged natl rift
MAIN CROSSCUT
Pearson's level continues 700′ to forehead
Mined passage following natural rift.
Coral crawl
Miners Sump 15′ deep
The Far West
The Near West
The Near East
Branch level sump 25′ deep
Branch level
Greater Sandpit Chamber
Lesser sandpit chamber
The Far East
MN 1974
TN
feet
0
50
m
0
1
Level continues 290′ to main junction
Representative Cross Sections (Scale 2 x Plan)
a b c d e f g
h i j k l m n
Surveyors : C.Carson, J. Dale, S.D. Hodgson, C. Pattison, D. Rackstraw, A. Riles, P.F. Ryder, M. Shaw, E. Shield, A. Skelton, G. Stevens, M. Stockwell, A. Younger.
PFR 74

Fig. 4

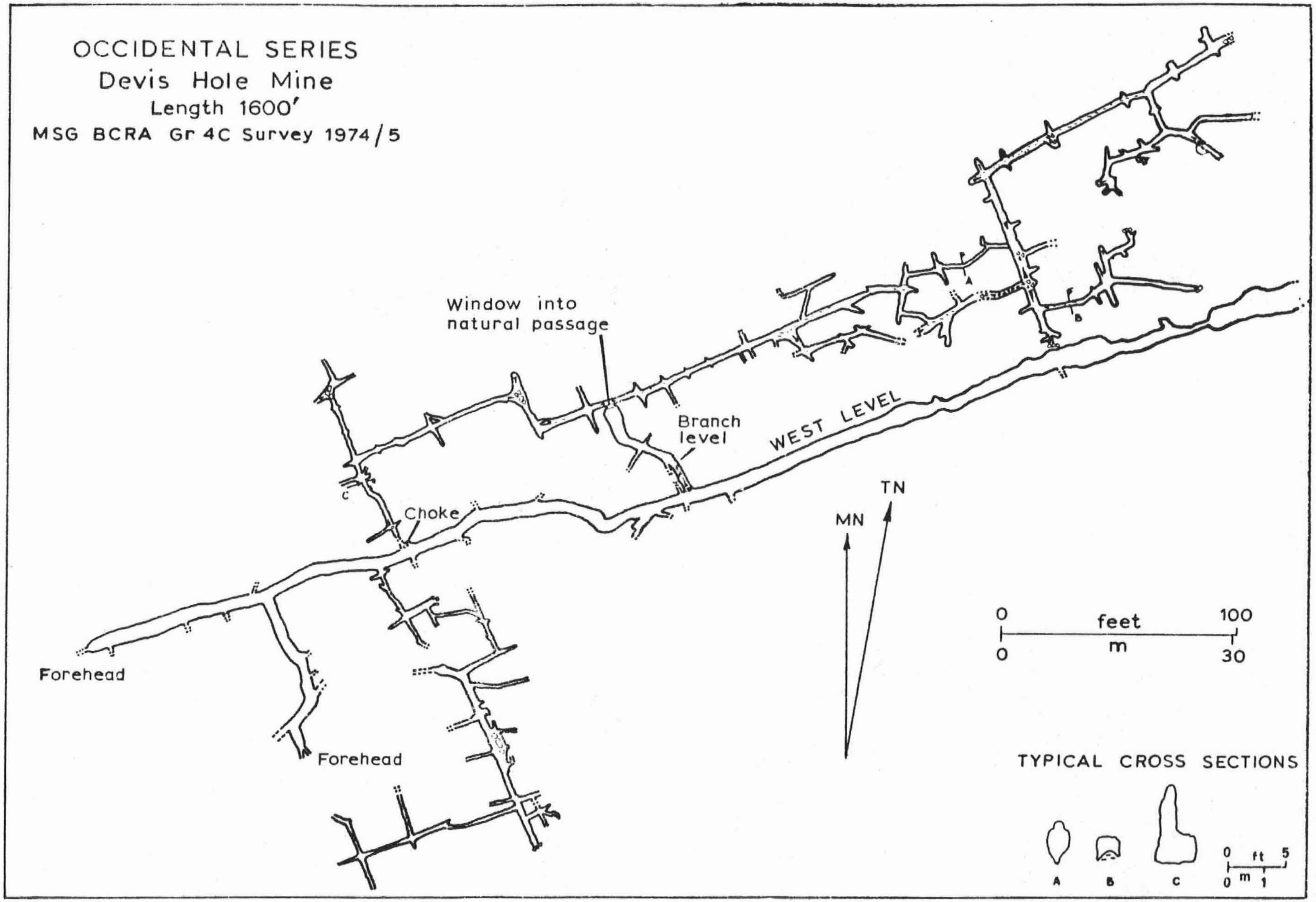

OCCIDENTAL SERIES
Devis Hole Mine
Length 1600′
MSG BCRA Gr 4C Survey 1974/5
Window into natural passage
Branch level
WEST LEVEL
Choke
C
Forehead
Forehead
MN
TN
0 feet 100
0 m 30
TYPICAL CROSS SECTIONS
A
B
C
0 ft 5
0 m 1

Fig. 5

mine level, the only connecting link between the two western areas being the constricted Coral Crawl, a narrow and low passage developed entirely in the coral band, here exceptionally thick.

The Near West contains one fairly sizeable collapse modified passage running parallel with the mine level, the degree of calciting again suggesting that these collapses are of some age (there are some small collapse chambers adjacent to the mine level, which appear much more recent in origin).

In the Far West the predominant passage orientations change markedly, the preferred joints being on approximately 20° and 68°. At the far end of the tortuous Coral Crawl one emerges into a short but impressive section of passage (cross section 'n' on survey) which is the largest unmodified (by collapse or mining) passage in the Central Maze. However, this large gallery soon terminates in chokes, and the remainder of the passages in this area are relatively constricted rifts, all terminating choked or too tight.

Beyond the Central Maze area, the main mine level continues, through one unstable-looking section, for 384 feet to a junction with the main vein workings, the East-West Level. The entrance crosscut continues beyond the East-West Level, for a further 307 feet, passing a small rise and a 15 feet deep hole in the floor (leading into a few yards of narrow natural passage) and ending in a forehead.

The East-West Level, to both east and west of the junction with the entrance crosscut, is in places a little modified natural passage. Plentiful evidence of the original nature of the passage (in most places at least one natural waterworn wall) remains in the first hundred yards or so of passages east of the junction, and along the level west of the junction as far as the collapses beyond the junction with South West Level.

Turning along the level to the west from the entrance crosscut, sections are passed where vein workings extend to a considerable height above the passage, and a stone arched roof has been inserted below these stopes, whilst the original natural walls of the passage remain unaltered. A few small branch passages are evident on both sides of the level, mostly totally clay choked within a few feet. Three small branches on the north side of West Level are more interesting, opening into sections of what is apparently a parallel passage to the level, now almost entirely clay filled. The first section of this parallel passage is seen at the junction with the entrance crosscut, and the second 150 feet along West Level. The third section, 280 feet further along West Level, is a more sizeable chamber which has been modified by mining, but appears to be on the same alignment as the other sections of passage.

South West Level is again an only slightly modified natural passage in its initial stages, ending in a drop of 10 feet into a short mined sub-level. In the region of the West Level/South West Level junction are several small clay-filled branch passages, some of which show well developed anastomoses in their roofs, a few inches above the top of the clay fill. These only occur in relatively small passages, and may have existed elsewhere but have been destroyed by the collapse which gives the typical squarecut roof section to many of the larger natural passages in the system. These anastomoses may perhaps be due to a period of solution following the deposition of the majority of the clay fill.

A few yards beyond the junction with South West Level, West Level runs into a series of massive collapses. At the commencement of these the natural passage which the level has been following appears to split into two, one branch, totally clay filled, running into the left wall, the other disappearing under the first of the collapses. The collapsed section continues for several hundred feet, all evidence of natural passage being lost in a series of precarious boulder ruckles and roomy collapse chamber. Eventually more solid ground is met again, and a branch level on the right, stacked with miners "deads" to within 18 inches of its roof, is the route into the northern section of Occidental Series.

The southern section of Occidental Series opens in the left wall of West Level 150 feet further along. The level, now again apparently following a natural fissure, but one only a few inches wide (and visible in the roof only), continues for a further 150 feet to end in a forehead, with natural rifts too narrow to enter leading off. A short branch level on the left a few yards before the end terminates in a similar manner.

The natural system of Occidental Series appears to consist basically of a single passage which splits into two or three branches at its east end. The present entry, into the northern part of the series, from the branch level, opens into a passage running parallel with the mine level (i.e. east to west). To the east the passage continues for several hundred feet, with some short side branches and small areas of network development, and one roomy passage-cum-chamber, quite well decorated, running north-south (and probably formerly connecting with the mine level, but now terminating in a boulder choke beneath one of the massive collapses in the level). Beyond the chamber two or three passages resume the eastward trend of this part of the series, before ending choked or too low.

Turning left (west) at the entry into Occidental Series from the branch level, a narrow passage continues, turning left for about 200 feet to end in a choke a few feet from West Level, in the opposite wall to the entrance to the southern part of the Series.

The southern part of Occidental Series consists of a series of generally narrow rift passages, trending south and then west again before ending too tight.

The passages of Occidental Series are generally similar to those of the Near East area of the Central Maze, often showing a slightly tubular cross section, narrowing downwards. There is, however, no evidence of the great depth of fill observed in the Central Maze. Some sections of passage are quite well endowed with formations, especially some small grottos near the eastern extremities of the northern passages. Northern Occidental Series contains a little over 1,000 feet of passage, Southern 510 feet.

At the time of writing, Devis Hole Mine remains open, although unless further work is undertaken to maintain access, the condition of the oil drums in the first roof fall will slowly deteriorate. In very wet weather the surface stream still flows into the level, and the initial crawl may be impassable for a short time when this happens. The mine levels and workings giving access to the Central Maze and East-West Level

Level present no serious hazards other than occasional unstable sections, but visits to Occidental Series are not really advisable, due to the dangerous condition of sections of West Level beyond its junction with South West Level.

A COMPARISON OF WINDEGG AND DEVIS HOLE MINE CAVERNS

The two main contrasts between the Windegg and Devis Hole systems are seen in the density of passage within the joint network, and actual passage size.

The greatest passage density is seen in the Near East area of the Central Maze in Devis Hole Mine Cave, a network based on three rather than two predominant joints, with over a quarter of a mile of passage crammed into an area about 150 by 65 feet.

The main network of Windegg Mine Caverns is developed on two joints only, but these meet at a more acute angle than any of those in the Devis Hole system, and much more collapse at passage intersections has resulted (although this is probably not the only factor responsible for the greater frequency of collapses in Windegg Mine Caverns, as will be explained later). The passages in the Windegg system are often much larger than those seen in Devis Hole, this being partly due to the greater amount of clay fill in the latter, and partly due to actual passage dimensions.

Several interesting points arise from a comparison of the two major phreatic networks in Swaledale with the now inaccessible Silverband Mine Caverns (see above). The Silverband system, or the parts of it accessible when surveyed by Myers (1967) included two series of sizeable passages and chambers, with some areas of joint network, nowhere as closely packed or complex as in the two more recently surveyed systems.

The occurence of passages of different cross sections on different joints, commented on in the description of Windegg Mine Caverns above, has not been noted in the Devis Hole system. However, this phenomenon is apparently paralleled in Silverband Mine Caverns; Myers, in his description of the joint network section, stated that the north-south passages showed most height, whilst the east-west short linking passages were more tubular. This situation is virtually identical with that in parts of the Windegg complex. In the Central Maze area of Devis Hole Mine Cave, there generally seems to be an approximately equal degree of development on each joint.

An interesting parallel can be seen however, between two other features, in Devis Hole Mine Cave and in Silverband Caverns. The long stretch of natural passage which has been enlarged by the miners to form the East-West Level in Devis Hole Mine appears to be a quite different type of passage to those seen in the Central Maze, a few hundred feet away. This feature, of a long linear passage, not seen in Windegg Mine Caverns, is paralleled by Lords Level or No.1 Crosscut in the Silverband Mine. This passage, several hundred feet away from the main area of natural caverns, is a continuous natural rift passage, only slightly modified by the miners, and over 2,000 feet in length. Sections of the original floor of the passage had been preserved, being composed of sand and fine gravel, and Myers suggested that in its later stages of development a stream from a surface sink fed this passage. There is no such evidence for a vadose phase in the Devis Hole passage, which may well have been choked by its original clay fill until cleared by the miners.

Both the Windegg and Silverband systems showed frequent massive phreatic scalloping on the passage wall,s where unmodified by collapse. Very little scalloping has been noted in Devis Hole Mine Cave.

THE GEOMORPHOLOGICAL HISTORY AND DEVELOPMENT OF THE SYSTEMS

WINDEGG MINE CAVERNS

Both Windegg Mine Caverns and the Central Maze area of Devis Hole Mine Cave are complex network systems which appear to result from slow solution in a well jointed limestone beneath the water table, which may have been locally impounded by faults and mineral veins.

In the case of Windegg Mine Caverns, some evidence of directional flow, probably of low velocity, can be seen in the occurrence of passages of different cross sections on different joints, especially in the southwest area of the Caverns. From this one can presume a water flow along the major rift passages (e.g. Durham Rift, Crystal Rift) in a south to north direction, following the local dip of the strata.

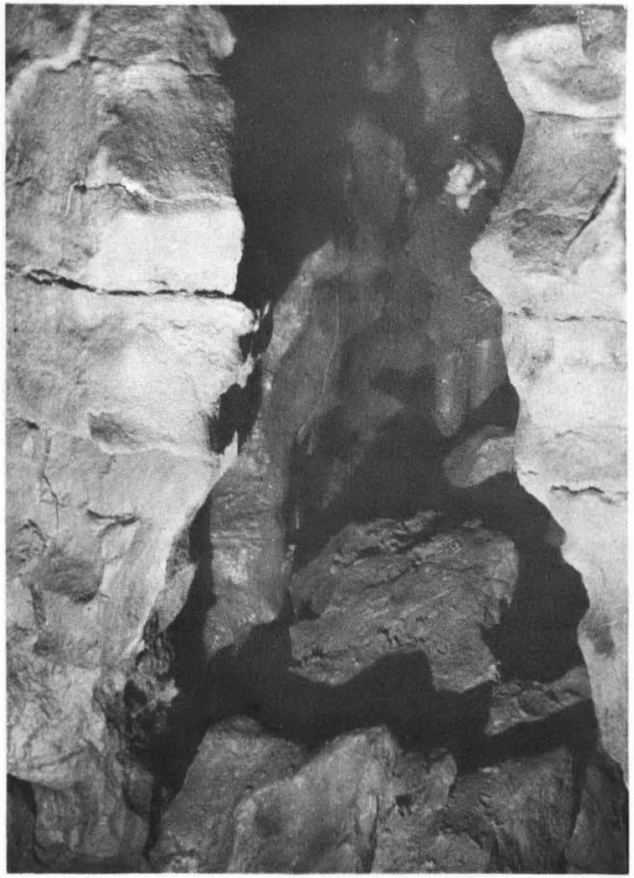
Following initial solution, there seems to have been a phase of clay deposition, as is commonly the case with phreatic caves. In the case of the Windegg system, this phase may have been fairly brief, there being no deposits of fill on the scale of those seen in the Central Maze of the Devis Hole system. Similarly, there is little evidence of any calcite deposition on any scale, beyond some flowstone cascades on the walls of Durham Rift. The apparent brevity of these post-solutional phases of development raises the question of the date of the cessation of phreatic conditions, and the initial drainage of the system.

Certain sections of Silverband Mine Caverns are reported to have been full of water when first tapped by the miners (Dunham, 1948, p.113). At first sight, this appears rather unlikely to have been the case at Windegg, since the Windegg system, unlike Silverband, is situated relatively close to the surface outcrop of the limestone, which is well-jointed and fissured throughout, and seems likely to have been drained at a rather more distant period.

However, a closer inspection of some of the actual features of Windegg Mine Caverns — the evidence of a phase of collapse modification still continuing, and the thin mud deposits on much of the passage walls — suggests that the phreatic phase did persist until more recently than the relationship of the cave to present topography would suggest. The surface features of the area have in fact been very much altered by lead mining activities during the 18th and 19th centuries, and the cutting of the deep 'hush' along the line of the northern of the two faults which terminate the block of limestone in which the cave system is developed

Plate 1

WINDEGG MINE CAVERNS

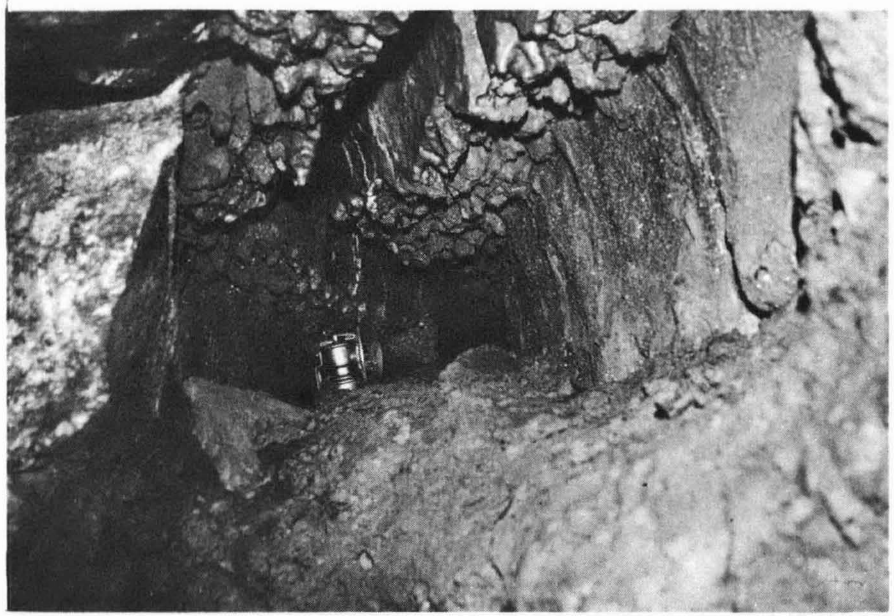


Nineways Junction.
Large phreatic passage with collapse and scalloping (photo: C. Carson)

Transverse Rift Series
(photo: G. M. Davies)

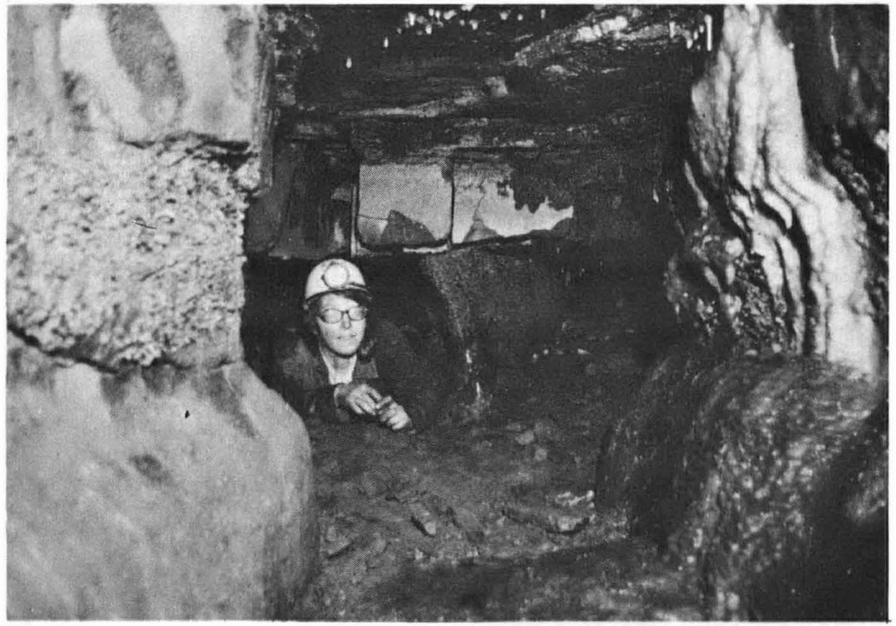
Transverse Rift Series
(photo: G. M. Davies)

Entrance through oil drum
(photo: P. F. Ryder)



Side passage in West Level with roof anastomosis
above clay fill (Photo: P. Ryder)

Central Maze area in the Near West Series
with collapsed blocks and stalactites
(photo: P. F. Ryder)



Central maze area in the Near East - a junction showing
a coral band in the walls and a square-cut roof due to
collapse of a mudstone bed (photo: P. F. Ryder).

may have resulted in the drainage of a considerable body of groundwater, previously contained by the two faults throwing the limestone against impermeable strata. This would account for the caverns having been drained, albeit recently, when broken into by the miners working Windegg Level in the mid 19th century.

DEVIS HOLE MINE CAVE

In considering the development of this system, the Central Maze area and the East-West Level/ Occidental Series passages can most conveniently be dealt with separately.

The Central Maze Area

This complex network shows little evidence of directional flow, either in the form of scalloping or of differential passage widths. Solution must have been under virtually static water conditions.

The great thickness of clay deposits suggests a lengthy depositional phase, and perhaps a gradual rather than a sudden cessation of phreatic conditions. Drainage may have resulted from valley deepening during a Glacial phase, and a consequent fall in base level on deglaciation. Certainly, it appears extremely unlikely that any part of the system held water when first broken into by the miners.

The collapse modification that has occurred in parts of the Central Maze area seems to be mostly of considerable age, in placed predating clay deposition (i.e. in some chambers obviously enlarged by collapse, no debris is present above the clay fill). The major phase of collapse modification in this, and similar systems, is probably at the time of the initial drainage of the system. Collapse debris is visible above fill level in some areas (e.g. the chokes separating the Near East and Far East), but this is much calcited over, again suggesting that the collapses are here of some age. A series of chokes in the Far East may be of more recent origin, as is the collapse that has occurred in the immediate vicinity of the mine levels.

The East-West Level and Occidental Series

The natural passage utilised by the miners as the East-West Level, and the passages of Occidental Series, may have originally formed virtually linear system running east-west for over 1550 feet. The natural passage followed by the East-West Level is admittedly lost beneath the massive collapses in West Level, but it seems quite probable that it originally connected with one at least of the passages at the east end of Occidental Series.

This series of passages seems to have developed quite separately from those in the Central Maze area, along the line of a mineral vein (which is probably a fault of limited throw). There is some evidence to suggest an original direction of water flow from west to east, namely, the presence of a sink (now fed by small streams draining the eastern mine workings) in the floor of East Level a little less than 300 ft. from its junction with the entrance crosscut, and the bifurcation and narrowing down of the passages at their western extremities. The dip of the limestone in this area also appears to favour a west to east flow direction, and it is possible (see later) that an active hydrological system with flow in this direction exists today, at a lower horizon in the limestone.

A phreatic conduit system thus seems to have existed in relatively close proximity to a joint network cave developing under almost static water conditions, the relationship between the two not being understood as yet. There is no obvious connecting link between the two systems, although one of the eastern passages of Occidental Series, now choked to within a few inches of the roof with fill, could perhaps be heading north-east rather than east, and if this trend continued for four or five hundred feet, the terminal chokes of the passages of the Far West area of the Central Maze might be reached. It is hoped that some further exploration may be possible here.

One factor suggesting that the East-West Level passages and Occidental Series may not in fact be part of the same system, is that there seems to be only small amounts of clay fill in Occidental Series, whereas the East-West Level and associated passages appear to have been almost completely filled.

PRESENT DAY HYDROLOGY OF THE CAVE SYSTEMS AND ASSOCIATED MINE WORKINGS

Windegg Mine Caverns

There is little present water flow in Windegg Mine, apart from drainage into the entrance level, which in wet weather becomes ponded against the entrance collapse making the level a waist deep rather than a knee deep wade. A small stream which enters the workings in wet weather from the First Rise is probably easily accounted for by small sinks on the surface directly above. More interesting is a small stream briefly seen in a fissure a few inches wide at the base of the large rift beyond Eyehole Crawl: its source and its destination are unknown, and it does not appear to enter the main mine workings.

The hydrology of the Windegg area as almost certainly been very much affected by the mine workings, as suggested above. There are surface indications of several other mine levels and trials in the hushes above Windegg Level entrance, and these, now inaccessible, may well have intersected drainage routes in the limestone.

Devis Hole Mine

Whilst the areas of network cave in Devis Hole Mine are now completely dry, the drainage of the mine workings themselves poses some problems, no water tracing having been carried out as yet.

There are two stream sinks in the mine, that of the drainage from the East and South East levels in a choked hole in the floor of East Level, and that from the Entrance crosscut in a natural rift in the floor a few yards into the level from the roof fall 70 feet from the original entrance. In very wet weather the surface stream flows into the mine entrance to this sink. Digging in this sink has revealed a 5 feet drop to a small phreatic tube, taking the water, but choked by boulders.

There are several miners sumps — shafts dropping below the level of the main mine workings — in Devis Hole Mine, and these have not yet been fully investigated. Those which have been descended are either choked or lead into further old mine workings of limited extent, without any drainage of significance.

It seems likely that the two streams sinking in the mine drop into a natural drainage system, which may also be fed by a stream sink on the surface a few hundred feet to the east of the level entrance, above the mine tips.

There are two sizeable risings in the Cogden Gill valley below Devis Hole Mine. The higher of these is situated on the west side of the valley just above Grinton Smelt Mill, and only 50 ft. in level below the mine entrance. This rising appears to be artificial, and may be nothing more than the lower end of a conduit carrying the surface stream which in normal conditions flows past Devis Hole mine entrance and sinks in a marshy area in the extensive mine tips.

A more interesting rising is found a third of a mile lower down the valley, in the form of a quite sizeable stream flowing from an old mine level (SE 050970, altitude about 900 ft. O.D.), a few feet from the east bank of the Gill. Unfortunately this level is blocked by a massive fall about 900 ft. in.

Myers suggested that the stream flowing from this level (Cogden Gill Level) is in fact derived from sinks in the Main Limestone in Apedale, 2½ miles to the south-west and 450 feet higher in altitude (Myers, 1963, p.50), the level thus being the resurgence end of a major hydrological system cutting beneath the surface Wensleydale/Swaledale watershed. This suggested system has not as yet been verified by water tracing.

If this suggestion is correct, the original resurgence of this system may have been in Cogden Gill somewhere between Cogden Gill Level and the top of the Main Limestone — the horizon at which Devis Hole Mine is driven. The possibility that the cave system in Devis Hole Mine is associated with an inter-dale hydrological system thus arises.

The natural passages so far explored in the mine have apparently not passed through any vadose phase, but are all developed very near the top of the limestone, which is probably about 80 feet thick. A lower series of phreatic cavities may exist, occupied by a stream which is either a post-solutional invasion, or a vadose descendent of the phreatic water flow which formed the known Devis Hole Mine Cave. It is unlikely that phreatic conditions persist in the lower horizons of the limestone, although they may have done so until the driving of Cogden Gill Level.

This picture is of necessity conjectural, and further work in the fields of water tracing, examination of geological structure, and direct exploration is required. It is interesting to note that natural caverns in the Main Limestone were broken into by Harker Level in Apedale (Myers, 1963, p.49). These caverns were apparently never explored, and their exact location is unknown, the level now being choked by a major collapse just over 1,000 feet from the entrance. Harker Level formerly extended to within half a mile of the end of West Level in Devis Hole Mine, and it is possible that the natural caverns encountered may have been only a few hundred yards away from, and undip of, the end of Occidental Series.

Obviously much work remains to be done, but it does seem quite probable that a very extensive series of phreatic cavities exist in the gently dipping Main Limestone between Apedale and Cogden Gill, and that the presence of these may have been responsible for the initiation of an inter-dale hydrological system.

OTHER PHREATIC NETWORK CAVES IN THE SWALEDALE AREA

Several smaller caves in the Swaledale area show sections of joint controlled network development, often now exposed as a result of later vadose invasion.

East Gill Cave II (NGR NY 897020 Alt. 1275 ft.)

A small network system, with a little less than 500 ft. of passage, with the main development on a parallel series of north-west to south-east trending rifts, connected by generally smaller and lower passages at right angles to them, which now carry a small stream through the system in flood conditions. Although only associated with a minor hydrological system today (part of East Gill sinks and rises again a few hundred yards downstream), this cave is situated only quarter of a mile from the resurgence of a hydrological system in the Main Limestone connecting Swinnergill and East Gill. This resurgence, and East Gill Cave II are admittedly on opposite sides of the Gill, but the comparative proximity of a network cave and a major system may be more than coincidence.

Lovergill Caves (NGR SD 882961 Alt. 1700 ft.)

These show two small sections of a roomy network system, now separated by a deeply incised gorge and modified by later vadose action. The larger of the two caves (Lovergill West Cave) takes the stream in wet weather, which drops through lofty cross rift passages into a tight twisting vadose "drainpipe", apparently a secondary development.

Sod Hole Gill Caves (NGR SD 868937 Alt. 1675 ft.)

Situated just over the Wensleydale/Swaledale watershed from, and two miles south of Lovergill Caves, these very interesting caves show several sections of an apparently extensive phreatic joint network. The passages all end in chokes of clay fill, and are only open where the fill has been washed out by small surface streams which have invaded the system, from sinks at the rear of the limestone plateau. The passages are often of impressive dimensions, often having a "keyhole" section, 20 ft. high and 8 ft. wide. The small streams which now enter the caves sink into ludicrously small vadose passages where they leave the phreatic tunnels.

Sloat Hole Mine Cave, Faggergill (NGR NY 983070 Alt. 1400 ft.)

Entered via a small mine level incongruously driven in the side of a shakehole in which a sizeable stream sinks (the stream is not seen in the mine), Sloat Hole Mine consists of a rectilinear network of mine passages, which have apparently been produced by the miners enlarging a joint network of small natural passages, sections of which remain. There is no evidence of vadose action in any of these passages, although the stream which sinks beside the mine entrance is a feeder of another major hydrological system, resurging at Roughton Keld over a mile away to the west. Lead miners in Faggergill are reported to have broken into a large cave system through which the Roughton Keld stream ran (Geol Survey Memoir, 1891, p.197), but this is now lost, and it seems unlikely that the entrance to this was in Sloat Hole Mine.

The especial interest of Sod Hole Gill and Lovergill Caves is that they occur in close proximity to one of the major proven inter-dale hydrological systems, that of Cliff Force. Similarly, as described above, the Sloat Hole network cave is in close proximity to the Roughton Keld hydrological system.

In the case of the Cliff Force system, the major Cliff Force resurgence is situated only a few hundred yards to the south-west of Lovergill Caves, and Sod Hole Gill Caves are only a few hundred feet from the sink of Sod Hole Gill, which may feed into the system.

All four phreatic network caves, or groups of caves, listed above, along with the two major networks of Windegg and Devis Hole, are situated in the upper beds of the Main Limestone, and all, with the notable exception of Windegg Mine Caverns, appear to be situated within a few hundred yards of a major hydrological system, and active cave passages in the lower beds of the limestone (the East Gill and Cliff Force risings are both approximately at the base of the Main Limestone). This is all further evidence for the theory that the presence of pre-existing phreatic network caves has been an important factor in the initiation of the long distance and inter-dale hydrological systems of the Northern Dales.

ACKNOWLEDGEMENTS

The writer would like to acknowledge his debt to Dr. J.O. Myers, of Leeds University, in the fields of both published material and personal communications. He is also indebted to Dave Carlisle, and the Earby Mine Research Group, who reopened both Windegg and Devis Hole mine levels, allowing access to the natural cave systems. Members of the Moldywarps Speleological Group have put in many hours of work in the exploration and surveying of the caves, Dr. Graham Stevens probably being the prime worker in this field. He would also like to thank the staff of the Drawing Office, of the Geography Department of the University of Hull, for their work in preparing the maps and surveys in this article for publication.

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M.S. Received 24th November, 1975

Peter F. Ryder,
Geography Dept.,
University of Hull,
Hull. HU6 7RX.

POSTSCRIPT

Since the above article was submitted for publication, a paper on 'The Origin of Maze Caves' by A.N. Palmer (National Speleological Society Bulleton, 1975, Vol. 37 (3), pp.56-76) has come to my notice. Palmer classifies maze caves (the term being defined as "a network or irregular pattern of solution passages containing numerous closed loops of contemporaneous origin") into three types, network mazes, anastomatic mazes and spongework mazes. Devis Hole Mine Cave and Windegg Caverns fit well into his classification of a network maze, as "an angular grid of intersecting fissures formed by the solutional widening of nearly all major joints to roughly the same size, within a given area of soluble rock".

Of the 155 maze caves in the United States which Palmer examined, 59 were overlain by insoluble strata, and all but 2 of these exhibited a joint controlled network pattern. 49 of these network caves were closely overlain by a sandstone, and most were situated very near the limestone/sandstone contact.

The two Northern Pennine systems described above are both situated in the upper parts of the Main Limestone, directly beneath the contact between the limestone and the overlying insoluble beds. In the case of Windegg Mine Caverns, a massive sandstone directly overlies the limestone, and is exposed in several parts of the system. The beds directly overlying the area of limestone in which Devis Hole Mine Cave is developed appear to be mudstones and shales, but it is highly probable (following the usual cyclothemic nature of the Yoredale strata) that sandstones overlie these, within a relatively short vertical distance.

Whilst joint network caves had previously been interpreted as the result of artesian flow beneath an impermeable stratum, Palmer suggests that the sandstone-capped mazes result from water being transmitted downwards through a permeable sandstone into the limestone, the permeable nature of the insoluble caprock ensuring a more or less uniform supply of water to each major joint in the underlying limestone.

In the normal pattern of the Yoredale cyclothems, the limestone member is overlain by shales and siltstones which grade upwards into sandstones and grits. However, frequent local unconformities have been recognised, and the situation of a sandstone directly overlying a limestone is by no means uncommon. The Yoredale measures of the Northern Pennine Dales thus present a lithological environment more amenable to the development of joint network cave systems than is to be found in the "classic" karst regions elsewhere in the British Isles. It seems likely that continued exploration will reveal further phreatic network cave systems in this area.

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