H. H. Hobbs III

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Contents

COMPUTER REDUCTION OF SURVEY DATA

FLOW VELOCITY IN CAVE CONDUITS

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Deducing Flow Velocity in Cave Conduits from Scallops[*]

Rane L. Curl[**]

ABSTRACT

Flowing water in caves frequently forms dissolution patterns, called scallops, on limestone surfaces. It has long been known that scallops may be used to indicate past flow direction. More recently, it has been learned that information about flow velocity may also be obtained from them.

The basic hydrodynamic phenomena that control the characteristic dimensions of scallops have been deduced from experiments in their generation on soluble surfaces and are summarized here. Relations are developed for estimating the average flow rate in conduits, given certain dimensional information about scallops and about the conduit.

INTRODUCTION

In Fig. 1 is shown the form of flow markings, or scalloping, that develops in limestone caves and in caves in ice. Flow markings have been the subject of a number of recent studies (Curl, 1966; Allen, 1971; Goodchild and Ford, 1971; Blumberg, 1970; Blumberg and Curl, 1974) that have considered them from geological and hydrodynamic viewpoints. Because almost nothing about this cave phenomenon has appeared in the American speleological literature, the purpose of this paper is to review some recent theoretical and experimental findings and to extend them to practical use in deducing "paleo-hydrologic" conditions in cave systems.

THE SCALLOPING PROCESS

The basic setting for the production of scallops is the turbulent flow of a solvent over a soluble surface. In nature, this occurs most frequently with water dissolving limestone or with air "dissolving" ice (exaporation being completely analogous to the dissolution process). In either case, surface irregularity may lead to the flow situation shown in Fig. 2, in which Blumberg (1970) has observed the following features: At the crest of an irregularity (Point 1), the main flow *separates,* that is, it forms a "jet" above a region of slower, recirculating flow. Within a short distance, this jet flow becomes strongly irregular and itself becomes turbulent (Point 2). Because the turbulence thereby produced causes mixing between the fluid in the lee eddy (Point 3) and the jet, fluid is entrained out of the lee eddy, causing the jet to turn toward the surface and *reattach* at Point 4. Some of the fluid then enters the lee eddy region and the rest flows onward along the surface.

In the vicinity of reattachment (Point 4), where the turbulent jet flow impinges most directly upon the surface, the rate of solution (or evaporation) is the highest. One consequence of this is that the scallop pattern moves *downstream* as it is dissolved further into the wall. This has been observed in all experimental simulations of scallop development. The characteristic asymmetry of scallop profiles, from which the direction of flow may be deduced, is also indicated in Fig. 2.

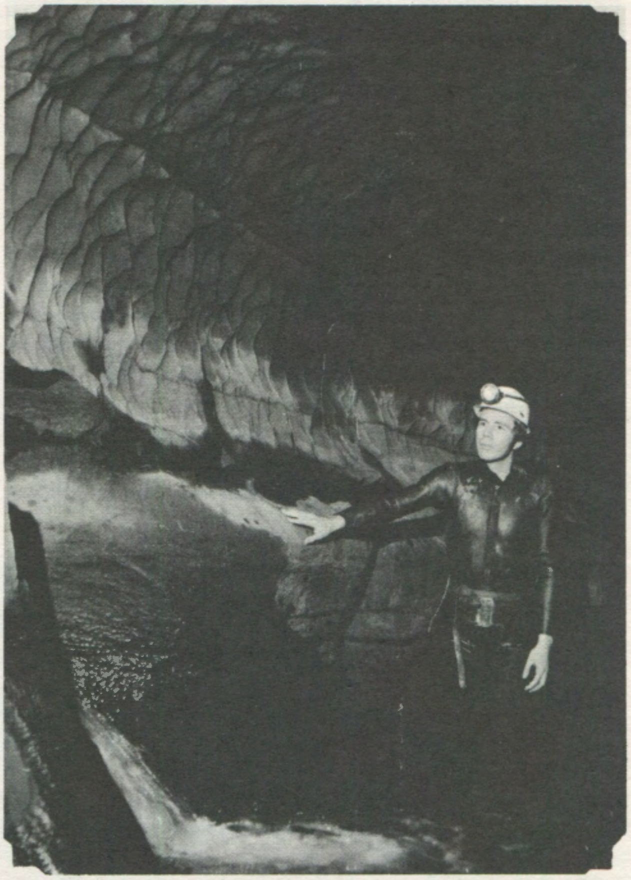

Fig. 1. Scalloping in Little Neath River Cave, South Wales. Photo by P. A. Standing.

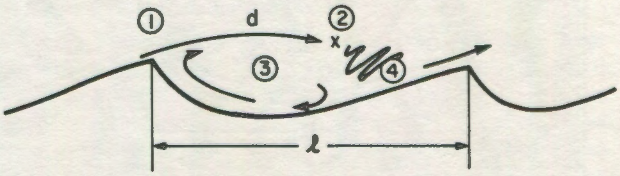

Fig. 2. Fluid motion in the vicinity of a scallop. Point 1: flow separation at crest. Point 2: transition of laminar shear layer to turbulence. Point 3: recirculating flow in lee eddy. Point 4: jet reattachment region.

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[**] Department of Chemical Engineering, The University of Michigan, Ann Arbor, Mich. 48104.

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The hydrodynamic processes in the vicinity of scallops are also responsible for the well-known inverse relationship between the size of scallops and the velocity of the flowing fluid (water or air) that produced them. This inverse relationship is produced by phenomena associated with the *free laminar shear layer* (between Points (1) and (2)) that separates the outer rapid turbulent flow from the slow, recirculating flow in the lee eddy (Point 3). It has been found that a free laminar shear layer undergoes transition to turbulence in a distance d that is determined by the density, ρ, viscosity μ, velocity U of the jet, and by the level of initial turbulence in the jet. This implies (see Blumberg and Curl, 1974) that there is a characteristic Reynolds Number for transition, $Re_t = \rho U d/\mu$ (See Table 1), which should depend only on the nature of the outer turbulent flow. Experiments with laminar jets producing a free laminar shear layer have given a value $Re_t = 30{,}000$. This value should be smaller when scalloping occurs and there is a turbulent outer flow.

The characteristic scaling of scallop size with the reciprocal of velocity is a consequence of the above phenomenon. If, for example, the scallop is too small (or the velocity too low for that scallop size), transition to turbulence (Point 2) will occur further along the scallop and reattachment will impinge on the next crest. The higher solution rate at that point will reduce that crest and, in effect, lengthen the scallop. On the other hand, if the scallop is too large (or the velocity too high for that scallop size), transition and reattachment will occur sooner. In this case, the distance between the reattachment (Point 4) and the next crest will be increased and an irregularity in this region could be the origin of a new scallop, thereby reducing the average scallop size.

There are two important consequences of this mechanism. First, because the characteristic scaling of scallop size is the result of a purely hydrodynamic mechanism, we do not expect the molecular diffusivity of the dissolving material to play an important role. Second, the scaling mechanism acts *longitudinally* (in the flow direction) and, therefore, scallop dimensions in that direction most directly reflect the scaling mechanism, as contrasted with scallop depth or width that are the consequence of secondary flow mechanisms. These aspects will be discussed in a more quantitative form in the following sections.

Various other features of scallop development and hydrodynamics, such as the rate of solution, the direction of propagation of the pattern (downstream, at about 60° into the wall), the wall friction, and the profile of individual depressions, are treated in detail in Blumberg and Curl (1974). Their experimentally developed scalloping is shown in Fig. 3. For our present purposes, we need only to review the nature of turbulent flow in the vicinity of the rough wall and the interaction of this with the roughness caused by dissolution of the surface.

TURBULENT FLOW NEAR A ROUGH WALL

Experiments on flow through artificially roughened conduits have shown that a moderately good approximation to the average velocity profile near such a rough wall is given by Prandtl's "universal velocity distribution law"

$$u/v^* = 2.5 \ln \frac{y}{L} + B_L \qquad (1)$$

(Schlichting, 1968), where u is the average flow velocity at distance y from the wall, L is some characteristic dimension of the roughness, and v^* is the friction velocity $\sqrt{\tau/\rho}$ where τ is the average shear stress at the wall and ρ the fluid density. The "roughness" constant B_L depends only on the nature (geometry) of the wall roughness.

Still following Prandtl (as presented by Schlichting, 1968), we assume that Equation (1) applies everywhere

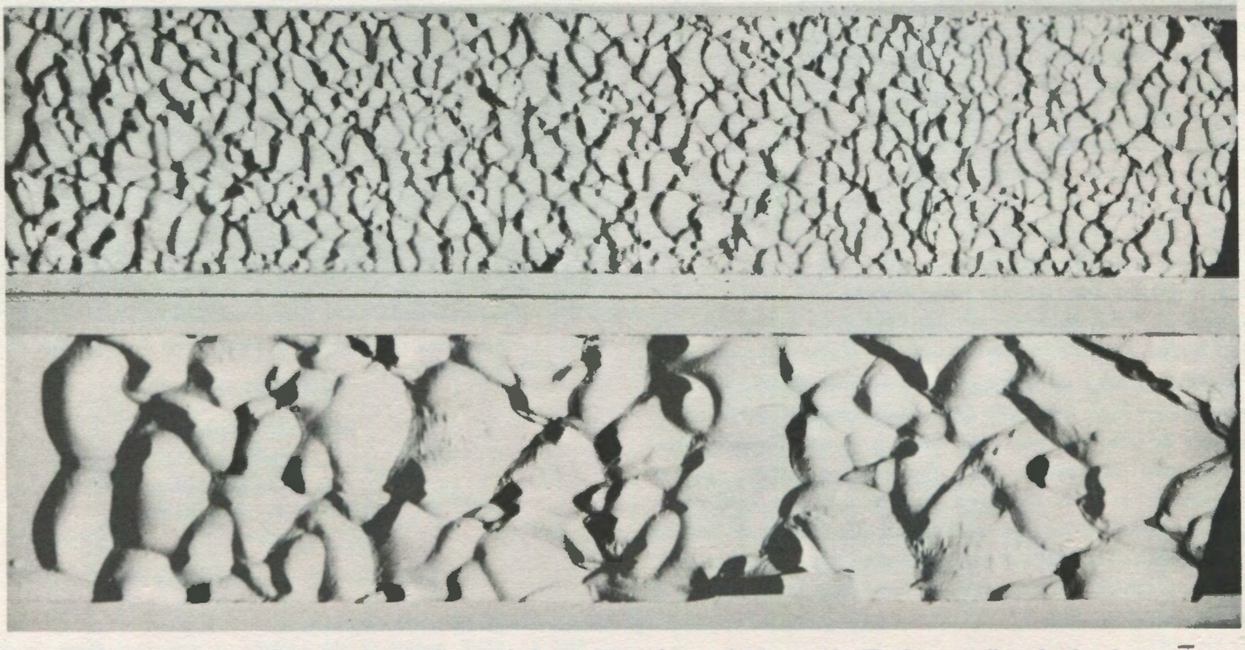

Fig. 3. Artificially produced scallops on plaster of paris, blocks are 76 cm long and 15 cm wide. The larger scallops developed at $u\,(\overline{L}_{32}) = 40$ cm/sec and 16°C., $\overline{L}_{32} = 6.0$ cm. The smaller scallops developed at $u\,(\overline{L}_{32}) = 90.7$ cm/sec and 33°C., $\overline{L}_{32} = 1.7$ cm. The values of Re_L are both close to 21,000. Flow (and illumination) was from left to right.

in a rough conduit and that we therefore may average u over the cross section of a conduit by appropriately integrating Equation (1) from the wall ($y=0$) to the center ($y=D/2$). D is the diameter of a circular conduit, or the width between two parallel walls. The result, for the *average velocity u,* is

$$\overline{u} = v^* \left[2.5 \left(\ln \frac{D}{2L} - 3/2 \right) + B_L \right] \tag{2}$$

for the circular conduit, and

$$\overline{u} = v^* \left[2.5 \left(\ln \frac{D}{2L} - 1 \right) + B_L \right] \tag{3}$$

for the parallel walls. It remains to relate v^*, L, and B_L to the scalloping phenomenon.

CHARACTERISTIC SCALLOP SIZE

The following section follows Blumberg and Curl (1974): Imagine that, in a soluble conduit, we impose a fixed pressure drop or, more particularly, an average wall shear stress τ. This is equivalent to imposing a value of the friction velocity v^*, given the fluid (water or air) with which we are dealing. It is the nature of turbulent flow near a wall that the velocity profile depends primarily upon the wall roughness and shear stress. That is, the flow near the wall is not "aware" of the conduit size except as it affects τ.

As the walls dissolve, scalloping will develop with some characteristic dimension L. This characteristic dimension will depend upon v^* and the fluid properties (density ρ and viscosity μ) and, possibly, upon the molecular diffusivity $\mathcal{D}$ of the solute (calcium bicarbonate or water vapor). We may express the dependence by writing

$$L = f\,(v^*, \rho, \mu, \mathcal{D}) \tag{4}$$

Nondimensionalizing this general statement, we conclude that

$$Re^* = \frac{L v^* \rho}{\mu} = f\left(\frac{\rho \mathcal{D}}{\mu}\right) \tag{5}$$

that is, that the Reynolds number based on the friction velocity and the scallop size Re^*, depends, at most, on the Schmidt number $Sc = \rho \mathcal{D} / \mu$.

Observations of the phenomenon in nature, the results of experiments, and the earlier comment on the role of molecular diffusivity all suggest that the dependence of Re^* on Sc is very weak (see also Wigley [1972]). If it is negligible, Re^* must be a universal constant.

In the above, it was not presumed which dimension (L) of scalloping was being considered. It may have been an average scallop length, or width, or depth, or any other composite dimension. Since all must scale according to Equation (5), ideal scalloping must also have a "universal shape" (albeit of the nature of a random-pattern), varying only in size with changing conditions. As turbulent velocity profiles have been found to be similar over similar roughness, we deduce that B_L is also a universal constant for scalloping.

The choice of a characteristic dimension L for a scallop pattern is rather arbitrary. Goodchild and Ford (1971) used the number-mean maximum length of each depression. They also provided evidence, however, that the average size of "scallops" depends to some extent on the material being dissolved—air bubbles (in plaster) and insoluble inclusions (such as fossils in limestone) creating the conditions for the development of smaller scalloping. In addition, scalloped surfaces exhibit a number of small depressions that appear to be related to the intersections of the rims of the depressions. Consequently, a better method of deriving the average size would suppress the importance of the smaller features, especially if comparison should be made with the regular, periodic, two-dimensional flow markings (flutes) that sometimes appear.

We will choose here the definition

$$\overline{L}_{32} = \frac{{}^{i}\sum}{{}^{i}\sum} \tag{6}$$

where l_i is the largest *longitudinal* (parallel to the flow) dimension of the *ith* scallop. (This average is called a "Sauter-mean".)

Using this definition for L in Equations (1) through (5), Blumberg and Curl (1974) found from their experiments $Re^* = 2200$ and $B_L = 9.4$. The product of these is (from Equations [1] and [5] $Re_L = \rho u\,(\overline{L}_{32})\,\overline{L}_{32}/\mu = 21{,}000$.

This is a Reynolds number based on the fluid velocity at a distance from the wall equal to the chosen characteristic dimension $L = \overline{L}_{32}$.

SCALLOP—CONDUIT REYNOLDS NUMBER

The Reynolds number based on mean scallop size and average fluid velocity in a conduit is

$$\overline{Re}_L = \frac{\rho \overline{u}\, \overline{L}_{32}}{\mu} \tag{7}$$

By multiplying Equations (2) and (3) by $\rho L/\mu$ and using $L = \overline{L}_{32}$, we obtain

$$\overline{Re}_L = Re^* \left[2.5 \left(\ln \frac{D}{2\overline{L}_{32}} - 3/2 \right) + B_L \right] \tag{8}$$

for the circular conduit and

$$\overline{Re}_L = Re^* \left[2.5 \left(\ln \frac{D}{2\overline{L}_{32}} - 1 \right) + B_L \right] \tag{9}$$

for the case of parallel walls.

If Re^* and B_L are known, and if D and $\overline{L}_{32}$ are measured for the particular situation, it is possible to calculate Re_L. Then, the average fluid velocity under which the scallops were developed may be found if values for μ/ρ are known or can be guessed (for water at 10°C, $\mu/\rho = 0.013$ cm^2/sec; for air at 0°C, $\mu/\rho = 0.132$ cm^2/sec).

Using the values for Re^* and B_L given earlier, Equations (8) and (9) are plotted in Fig. 4.

Fig. 4 shows that scalloping of a given size in a large conduit represents a larger mean flow velocity than it would in a small conduit. This is to be expected, once we accept the inverse relationship between scallop size and some near-wall velocity ($u[\overline{L}_{32}]$, say), as this velocity will be lower in the larger conduit for the same mean conduit velocity.

The accuracy of Fig. 4 for estimating prior flow conditions depends on several factors. It is useful to enumerate them here.

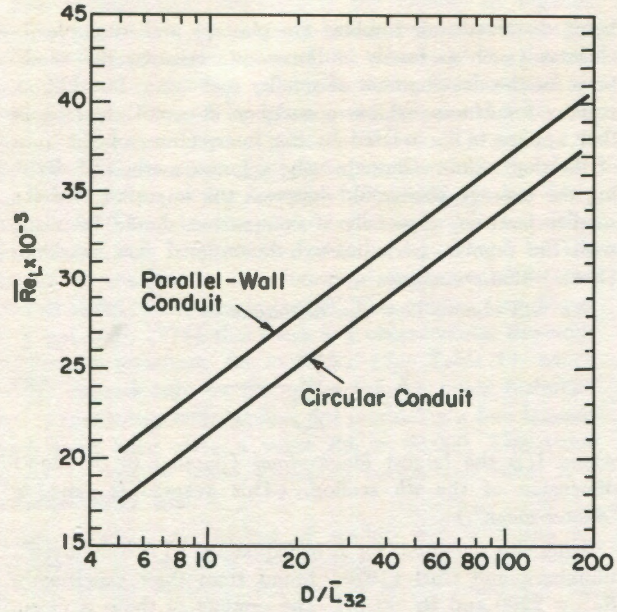

Fig. 4. The predicted relation between the (mean velocity in conduit) x (mean scallop size) Reynolds number ($\overline{Re}_L$) and the ratio of conduit diameter or width to mean scallop size ($D/\overline{L}_{32}$).

1. Equation (1) is an adequate approximation to the turbulent flow velocity profile across a rough conduit. There are alternative velocity profile expressions (see Schlichting, 1968) and some fussing has been done with the constants 2.5 and B_L (for various types of roughness). Given, however, other, greater, sources of error, Equation (1) should be adequate at high Reynolds numbers based on conduit diameter, $\overline{Re}_o = \rho\bar{u}D/\mu$. (See Table 1)

2. The constants Re^*_D and B_L that have been used here will be subject to some revision when experiments are conducted in longer conduits than anyone has as yet used. It is estimated, however, that they are now known with sufficient accuracy that Fig. 4 is correct within about ± 15%. The values used here differ considerably from an equivalent estimate made by Goodchild and Ford (1971). The exact reason for this is not yet known.

3. The conduit must be of regular cross section and must be sufficiently long and straight for almost fully developed flow to be established. The cross section need not be either circular or parallel-walled (the effect will be a relation lying between those for the circular and parallel-walled channels in Fig. 4), but it should be unchanging for some distance. In curving conduits, the velocity is greatest near the inner wall at the beginning of the turn and near the outer wall at the end of the turn (there also may be a reverse flow on the inner wall near the end of the turn). Therefore, Equations (2) and (3) are highly approximate in other than regular, straight conduits.

4. The flow must have been at a constant velocity (actually, at constant $\rho\bar{u}/\mu$) throughout the period of final development of the scallop pattern. This is unlikely to be true in any given case but, since scallop patterns develop most rapidly at high velocities, they tend to reflect the past history of the higher velocity flows in a given conduit.

5. The dissolution process should be dominated by diffusional mass-transfer, not by a chemical rate-limiting step at the surface. For pure calcite, it has been shown (Curl, 1968) that at low dissolution rates the process is controlled by the diffusional transfer of Ca++ (plus HCO_3-) between the surface and the bulk solution, while at high transfer rates it is controlled by the diffusional transfer of H_2CO_3 (not CO_2) to the surface. There was predicted to be very little effect of solvent motion on the rate of dissolution in an *intermediate calcite dissolution regime*. Is scalloping in this regime?

The intermediate regime may be defined approximately (and non-dimensionally) by

$$1 < \frac{1}{h}\sqrt{\mathcal{D} k_2} < 100 \qquad (10)$$

where h is the mass transfer coefficient for H_2CO_3, and k_2 the rate constant for the homogeneous reaction step $H_2CO_3 \rightarrow CO_2 + H_2O$. In addition, the mass transfer coefficient on a scalloped surface (measured by Blumberg [1970] and reported by Blumberg and Curl [1974]) is

$$\frac{h\overline{L}_{32}}{\mathcal{D}} = 112\ Sc^{1/3}. \qquad (11)$$

Eliminating h between Equations (10) and (11), we obtain

$$112\ Sc^{1/3}\sqrt{\frac{\mathcal{D}}{k_2}} < \overline{L}_{32} < 1.12 \times 10^4\ Sc^{1/3}\sqrt{\frac{\mathcal{D}}{k_2}}\ . \qquad (12)$$

At 10°C, $k_2 = 3.45\ \text{sec}^{-1}$, $\mathcal{D} = 1.43 \times 10^{-5}\ \text{cm}^2/\text{sec}$ and $Sc = 914$ (Curl, 1968). These give $2.2 < \overline{L}_{32} < 220$ cm. *This range includes most natural occurrences of scallops on limestone.*

It appears that, in turbulent (rapidly fluctuating) flows over microscopically rough surfaces, a flow velocity effect on the calcite dissolution rate is not fully suppressed. This problem has not been studied, but something can be said about its effect on scallop dimensions and geometry.

It was found by Blumberg (1970) that, although flutes of a dimension not matching (in terms of Re^*) the adjacent flow velocity still retained their *shape*, the direction of propagation was changed. As the velocity was doubled, the downstream propagation angle increased from 60° to 75° into the surface. The local average rate of dissolution remained consistent with the original geometry. It may be demonstrated that, if the actual local rate of dissolution were to vary as, say, $h^{0.5}$, due to kinetic phenomena, rather than being directly proportional to h (as would be the case outside the intermediate calcite dissolution regime, or if the substrate were gypsum), *the profile of a flute would show little change,* although the angle of propagation would steepen to near 75°. In addition, the characteristic dimension L (or $\overline{L}_{32}$ in particular) still should be determined mostly by hydrodynamics and, therefore, be largely independent of the additional kinetic phenomena.

This matter requires further study.

6. A multitude of factors that can modify or obscure scallop patterns have been omitted from the foregoing discussion. These have been discussed in some detail elsewhere (Curl, 1966) and include close jointing or fracturing, a heavy bed load, deposition of clay, and numerous insoluble inclusions in limestone.

ACKNOWLEDGEMENT

Measurements of the dimensions of the scallops in Fig. 3 were taken by Mr. Barry I. Hollander, as part of a senior research project in the Department of Chemical Engineering, University of Michigan.

Table 1. Definitions of Reynolds numbers

Characteristic length	Characteristic Velocities "Near wall" U	Friction v^*	At $y=\overline{L}_{32}$ $u(\overline{L}_{32})$	Average conduit, u
Distance to transition, d	Re_t	—	—	—
Average scallop size, L_{32}	—	Re^*	Re_L	$\overline{Re}_L$
Conduit diameter or width, D	—	—	—	$\overline{Re}_D$

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Goodchild, M.F. and D.C. Ford (1971)—Analysis of Scallop Patterns by Simulation under Controlled Conditions: *Jour. Geol.* 79:52-62.

Schlichting, H. (1968)—Boundary Layer Theory: NYC, McGraw-Hill, pp. 578-583.

Wigley, T.M.L. (1972)—Analysis of Scallop Patterns by Simulation under Controlled Conditions: A Discussion: *Jour. Geol.* 80:121-122.

Note added in proof:

An additional important general reference on flow markings is:

Allen, J.R.L. (1971)—Transverse Erosional Marks of Mud and Rock: Their Physical Basis and Geological Significance: *Sedimentary Geol.* 5:165-388.

The evolution of scalloping from an initially flat surface is treated in some detail. It was observed in experiments that the mean dimension of scalloping decreased with time and appeared to be approaching a limit. An estimate of the limiting value of Re_L(based on $\overline{L}_{32}$), is 25,000, although Allen did not measure $u(L_{32})$ or v^*. Of particular importance, however, is the demonstration that the average scallop size is evolutionary between equilibrium conditions and, therefore, the patterns observed in nature may not represent "steady" conditions. The patterns also evolve from defects, which can affect their shapes and average dimensions.

A recent analysis of ripples on the underside of ice covers on rivers is given by: Ashton, G.D. and J.F. Kennedy (1972): *Proc. Am. Soc. Civil Eng., Hydraulics Div.* 98 (HY9):1603-1624.

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Use of a Computer Program for Cave Survey Data Reduction

John M. Rutherford * **and Robert M. Amundson** **

ABSTRACT

A computer program for processing large quantities of cave survey data over an extended period was developed as an adjunct to the cartography program of the West Virginia Association for Cave Studies (WVACS). This program includes not only the ability to close loops and to prepare point plots in the standard WVACS cartographic grid system, it also includes in the printout cross-sectional data, descriptive comments, and the positions of permanent stations. Flexibility is represented by a highly versatile data card format, by the ability to run only a selected portion of a cave at one time, by optional cave rotation, and, especially, by the "two-way" data card—i.e., one which can be completely interpreted without reference to any other card in the data deck, and which therefore can be read either in the direction of the original survey or in the opposite direction. The procedure for assembling large decks of data cards was made as fool-proof as possible by using flags to monitor the reading of the data deck, by color-coding punch cards to facilitate organization of the deck, and by building-in a routine to avoid problems caused by most instances of card reading errors. Long-term use of the program indicates that its value lies neither in increased speed nor in greater accuracy in generating a map from survey data, but in the advantages of neat data summaries and improved record-keeping abilities, of the facile generation of fitted data for loop closures, and of the ease with which the cave maps can be redrawn at different scales or attitudes.

INTRODUCTION

The use of computers to process cave survey data is relatively common today. A large variety of computer programs to serve this purpose have come into being. These range from relatively simple, basic ones to highly complex ones utilizing x-y plotters to draw the cave map. Computer-generated, three-dimensional, stereographic line drawings, utilizing inks of different colors and special eye-glasses for viewing, have even been produced. It is virtually impossible to review the diverse activities in this field (see, for example, Wefer [1971]), since much of it has been the end product of whim and inspiration scattered throughout the caving community over the past 10 years and has gone unreported. Surprisingly, little seems to have been done to bring together workers in this field for the exchange of ideas and experiences.

In 1967, a symposium was held at the meeting of the Southeastern Regional Association of the National Speleological Society (NSS) to facilitate the exchange of ideas among workers in the field. Programming also has been discussed at recent NSS conventions, especially at the 1969 NSS convention (Lovell, Wyoming), where one session was devoted to data processing (NSS, 1970). At the latter, an *ad hoc* committee was formed to recommend a "standard" format for cave survey data cards, but it was not heard from subsequently and enthusiasm for organizing or coördinating the efforts of workers in the field waned.

Recently, NSS Computer Programs was organized (Pierce and Hosley, 1971) to accumulate and to publish a compilation of programs and algorithms as a survey of the current state of the speleological computer art. Most recently, a data-processing workshop was held during the 1971 NSS convention, at which time various experiences, techniques, and suggestions were shared by the participants. The purpose of this article is to describe the basic characteristics of a general-purpose computer program which WVACS has developed for cave-survey data reduction and to comment on some of WVACS' experiences in using this program through the years.

THE BASIC PROGRAM

The purpose of a cave-survey data-reduction program is to convert raw survey data taken in the field to *x,y,z* coördinates. The main reason WVACS decided to develop a program was to obtain the advantages accruing from an *x,y,z* coördinate system in closing survey loops smoothly and from drawing maps on a standard grid system. It should be kept in mind, however, that the current program is the result of several years of evolutionary change. Many of its present features were not even anticipated when the first prototype program was written in 1964.

Once the decision had been made to go to the computer, it became necessary to consider the kinds of data to be processed. Because of the large number of people involved in WVACS' field work, the raw survey data being obtained were highly variable. Distances were being measured both in English and in metric units and compass bearings were being taken both in quadrants and in 360° azimuths. Hence, a very general format for the data cards was needed.

The details of this format will be given later. One aspect of it, however, needs to be considered here. A very important characteristic of WVACS' survey data is that it frequently includes back-sights. It is not at all uncommon to find survey lines consisting of an unpredictable sequence of fore- and back-sights. Rather than trusting people to correct these back-sights, either when the data are recorded in the field or when they are punched onto computer cards, the decision was made to build this capability into the program. In order to do so, each data card has to have *two* survey stations punched on it: The first one (ST1) is the survey designation for the station where the compass was located

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* West Virginia Association for Cave Studies, 46 Cabot La., Kinnelon, N. J. 07405

** West Virginia Association for Cave Studies, 249 Mountain View, Bluefield, W. Va. 24701

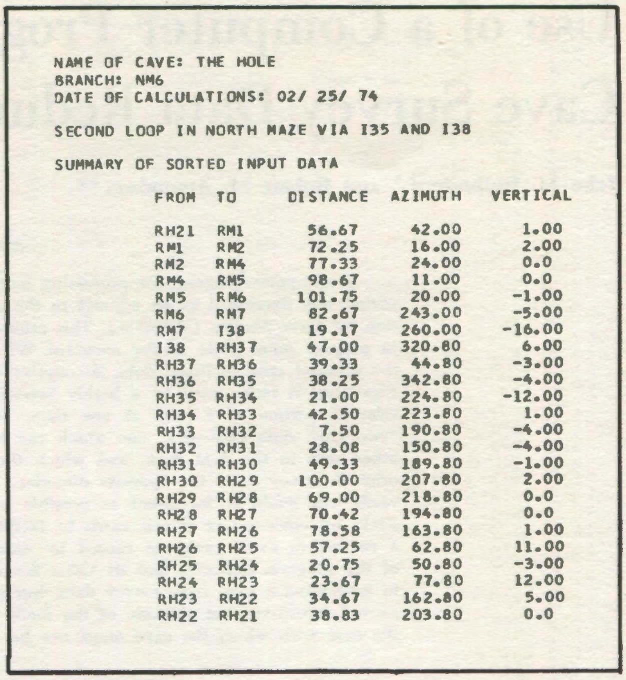
during that particular sighting; the second one (ST2) is the designation for the station toward which both the compass bearing and the vertical angle were measured (by convention, both the azimuth and the vertical angle at each station must be read while facing a single direction—i.e., from ST1 to ST2).

A *branch* is a sequence of data cards, each of which carries the information required to compute the coördinates of a new station from those of a station previously calculated. After the survey data have been punched onto data cards, the cards are assembled into one or more branches. The first card in each branch is called the "header" card. This card carries two essential pieces of information for the computer: (a) it indicates which of the two stations on the first data card in that branch is the starting station, and (b) it indicates whether the branch is a simple branch or whether it is a loop which must be force-fitted to close smoothly to a station the coördinates of which already have been calculated. The header card also may carry cross-sectional data for the first station in the branch. The second card in each branch is the branch "title" card. The title card may contain any type of descriptive material about the branch. Its contents are printed out in the heading of the output for that branch. The data cards follow the header and title cards.

The designations used to represent stations on the data cards can contain up to four characters selected from the numbers, letters, or various symbols and punctuation marks of the FORTRAN program language—i.e., they are "alphanumeric", in computer terminology. Many computer programs utilize specific systems for designating sequential stations in the data deck. These may indicate the precise position of the station in the branch, the branch to which the station belongs, or the connecting stations in a branched network. An example of this last usage would be designating as "A9.1", the first station of a new branch connected to a previously computed station designated "A9". In this program, such systems for designating stations are carefully avoided because those systems bring with them constraints on the way in which the data deck can be assembled. The sequence of station designations can be completely random. This characteristic of the program will be discussed later.

Branch by branch calculations are performed in the following manner: On reading each card, the computer first examines ST1. If it is "END", no more data cards are to be read for that branch. All calculations for that branch are then made, the results are printed out, and a new card is read. If the new card is not another header card, it means the end of the data deck and the final output of calculations for that cave is printed out.

On reading a data card whose ST1 is not "END", the computer determines whether or not ST1 is the same as the previously computed station (or, in the case of the first data card in the branch, the same as the station indicated on the header card). If the same, the data card carries measurements for a front-sight. The distance, bearing, and vertical measurements from ST1 to ST2 are then converted to a standard form (feet and tenths, decimal degrees azimuth and vertical), to be printed out as a summary of the sorted input data. If, instead of ST1, ST2 is the same as the previously computed station, a back-sight is involved. Before conversion to standard form, the bearing is changed by 180°, the sign of the vertical angle is changed, and any cross-sectional data are reversed.



```
NAME OF CAVE: THE HOLE
BRANCH: NM6
DATE OF CALCULATIONS: 02/ 25/ 74

SECOND LOOP IN NORTH MAZE VIA I35 AND I38

SUMMARY OF SORTED INPUT DATA

          FROM  TO      DISTANCE  AZIMUTH   VERTICAL

          RH21  RM1       56.67     42.00      1.00
          RM1   RM2       72.25     16.00      2.00
          RM2   RM4       77.33     24.00      0.0
          RM4   RM5       98.67     11.00      0.0
          RM5   RM6      101.75     20.00     -1.00
          RM6   RM7       82.67    243.00     -5.00
          RM7   I38       19.17    260.00    -16.00
          I38   RH37      47.00    320.80      6.00
          RH37  RH36      39.33     44.80     -3.00
          RH36  RH35      38.25    342.80     -4.00
          RH35  RH34      21.00    224.80    -12.00
          RH34  RH33      42.50    223.80      1.00
          RH33  RH32       7.50    190.80     -4.00
          RH32  RH31      28.08    150.80     -4.00
          RH31  RH30      49.33    189.80     -1.00
          RH30  RH29     100.00    207.80      2.00
          RH29  RH28      69.00    218.80      0.0
          RH28  RH27      70.42    194.80      0.0
          RH27  RH26      78.58    163.80      1.00
          RH26  RH25      57.25     62.80     11.00
          RH25  RH24      20.75     50.80     -3.00
          RH24  RH23      23.67     77.80     12.00
          RH23  RH22      34.67    162.80      5.00
          RH22  RH21      38.83    203.80      0.0
```

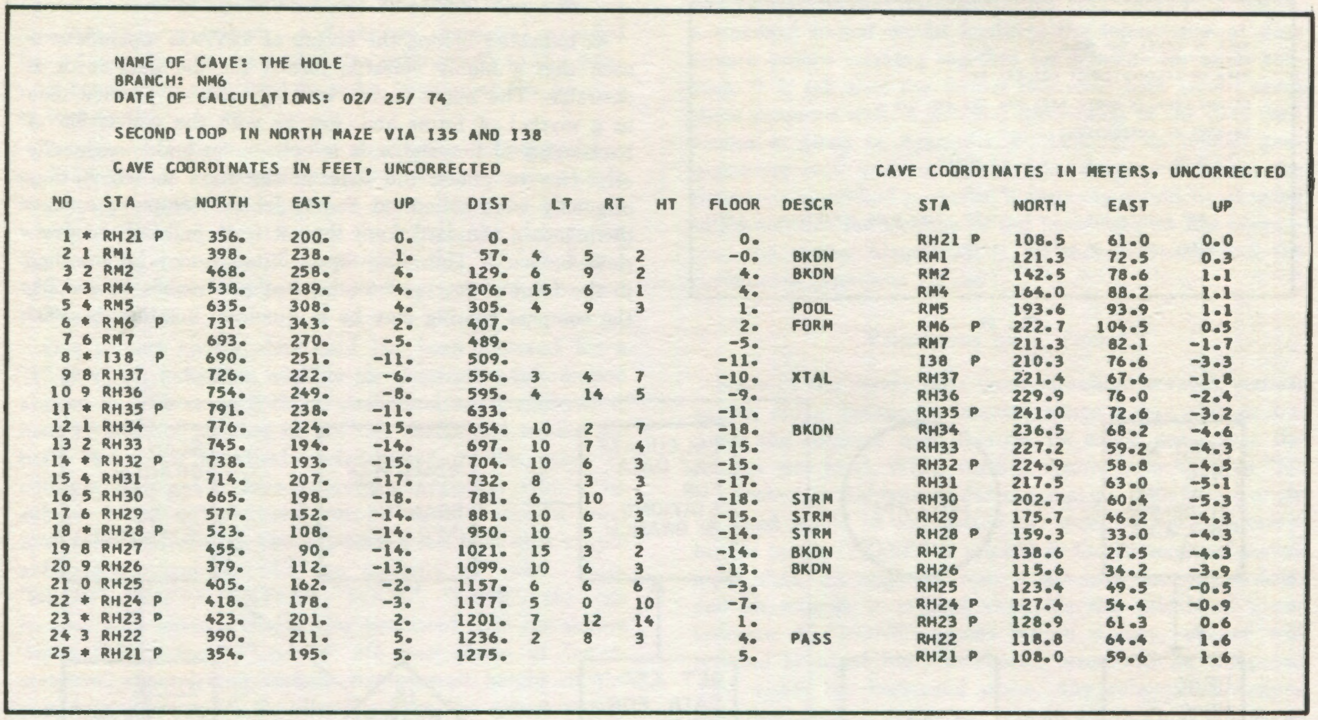
Fig. 1. Typical summary of standardized input data.

The sorted input data summary for a branch is printed out in standard form when the end of the data for that branch is reached, as shown in Fig. 1. An internal memory check is then made to find the *x,y,z* coördinates of the initial station in the branch. These may have been read in with the set-up cards at the start of the deck, or they may have been calculated in an earlier branch. From those values (or using 0,0,0, if none are found), coördinates then are calculated for each new station and printed out (see Fig. 2). If the branch has been identified on the header card as a loop, the memory is searched for the coördinates of the final station in the branch, a new set of force-fitted coördinates is calculated and printed out for the "closed" loop, and the closure error is calculated and printed out (see Fig. 3). Coördinates are then stored in the memory for any station in the new branch which was included in a list of stations to be remembered read in at the beginning of the data card deck. The computer then proceeds to the next branch. A generalized flow chart of the program is shown in Fig. 4.

The algorithm used for closing loops is not an especially sophisticated one. It simply computes the error in each vector direction and applies a correction to each coördinate of each station proportional to the length of the survey shot used to reach that station. That is,

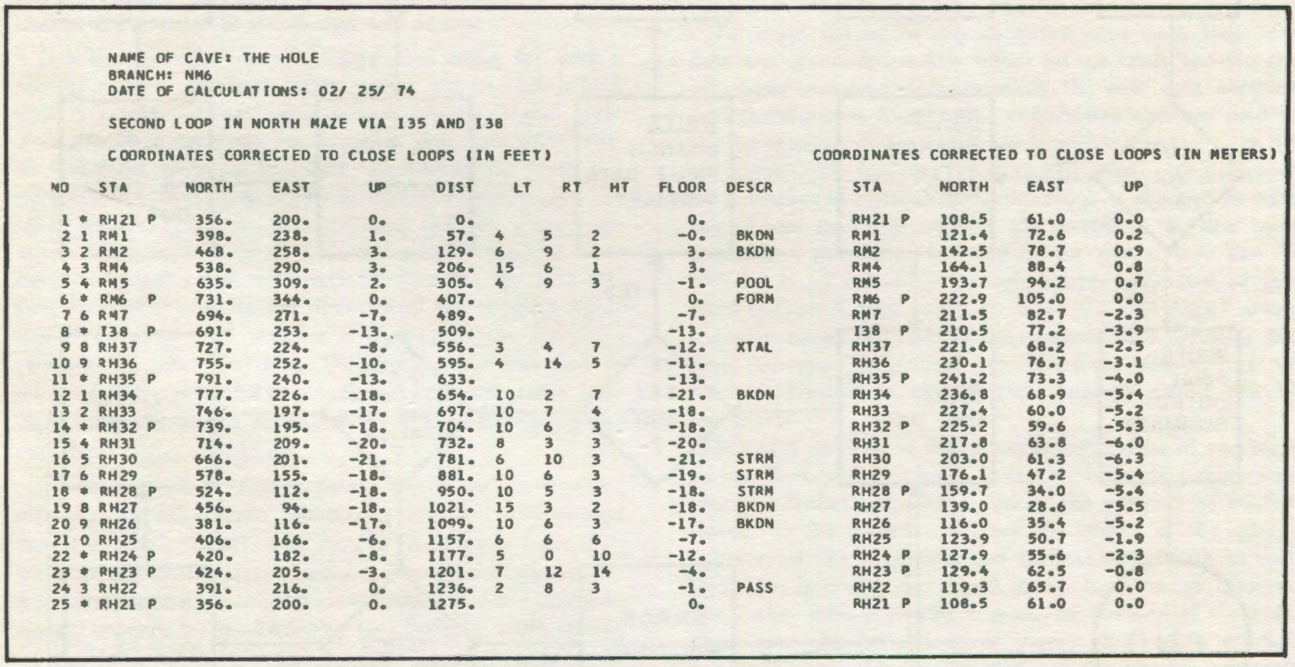
$X_i = x_i + (\triangle x)\ (D_i)/T$, where

X_i = the closed x coördinate of the i^{th} station in the branch,
x_i = the uncorrected x coördinate of the i^{th} station in the branch,
$\triangle x$ = the total closure error (positive or negative) for the whole branch in the x direction,
D_i = the cumulative taped distance to the i^{th} station along the branch,
T = the total taped distance of the branch.



```
     NAME OF CAVE: THE HOLE
     BRANCH: NM6
     DATE OF CALCULATIONS: 02/ 25/ 74

     SECOND LOOP IN NORTH MAZE VIA I35 AND I38

     CAVE COORDINATES IN FEET, UNCORRECTED                 CAVE COORDINATES IN METERS, UNCORRECTED

NO   STA     NORTH   EAST    UP    DIST  LT   RT   HT  FLOOR DESCR    STA     NORTH    EAST     UP

 1 * RH21 P   356.   200.    0.      0.                   0.          RH21 P   108.5   61.0    0.0
 2 1 RM1      398.   238.    1.     57.  4    5    2     -0. BKDN     RM1      121.3   72.5    0.3
 3 2 RM2      468.   258.    4.    129.  6    9    2      4. BKDN     RM2      142.5   78.6    1.1
 4 3 RM4      538.   289.    4.    206.  15   6    1      4.          RM4      164.0   88.2    1.1
 5 4 RM5      635.   308.    4.    305.  4    9    3      1. POOL     RM5      193.6   93.9    1.1
 6 * RM6  P   731.   343.    2.    407.                   2. FORM     RM6  P   222.7  104.5    0.5
 7 6 RM7      693.   270.   -5.    489.                  -5.          RM7      211.3   82.1   -1.7
 8 * I38  P   690.   251.  -11.    509.                 -11.          I38  P   210.3   76.6   -3.3
 9 8 RH37     726.   222.   -6.    556.  3    4    7    -10. XTAL     RH37     221.4   67.6   -1.8
10 9 RH36     754.   249.   -8.    595.  4    14   5     -9.          RH36     229.9   76.0   -2.4
11 * RH35 P   791.   238.  -11.    633.                 -11.          RH35 P   241.0   72.6   -3.2
12 1 RH34     776.   224.  -15.    654.  10   2    7    -18. BKDN     RH34     236.5   68.2   -4.6
13 2 RH33     745.   194.  -14.    697.  10   7    4    -15.          RH33     227.2   59.2   -4.3
14 * RH32 P   738.   193.  -15.    704.  10   6    3    -15.          RH32 P   224.9   58.8   -4.5
15 4 RH31     714.   207.  -17.    732.  8    3    3    -17.          RH31     217.5   63.0   -5.1
16 5 RH30     665.   198.  -18.    781.  6    10   3    -18. STRM     RH30     202.7   60.4   -5.3
17 6 RH29     577.   152.  -14.    881.  10   6    3    -15. STRM     RH29     175.7   46.2   -4.3
18 * RH28 P   523.   108.  -14.    950.  10   5    3    -14. STRM     RH28 P   159.3   33.0   -4.3
19 8 RH27     455.    90.  -14.   1021.  15   3    2    -14. BKDN     RH27     138.6   27.5   -4.3
20 9 RH26     379.   112.  -13.   1099.  10   6    3    -13. BKDN     RH26     115.6   34.2   -3.9
21 0 RH25     405.   162.   -2.   1157.  6    6    6     -3.          RH25     123.4   49.5   -0.5
22 * RH24 P   418.   178.   -3.   1177.  5    0    10    -7.          RH24 P   127.4   54.4   -0.9
23 * RH23 P   423.   201.    2.   1201.  7    12   14     1.          RH23 P   128.9   61.3    0.6
24 3 RH22     390.   211.    5.   1236.  2    8    3      4. PASS     RH22     118.8   64.4    1.6
25 * RH21 P   354.   195.    5.   1275.                   5.          RH21 P   108.0   59.6    1.6
```

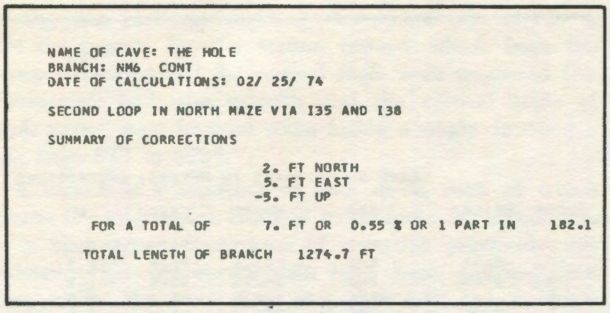
Fig. 2. Typical uncorrected output, in feet and meters.



```
     NAME OF CAVE: THE HOLE
     BRANCH: NM6
     DATE OF CALCULATIONS: 02/ 25/ 74

     SECOND LOOP IN NORTH MAZE VIA I35 AND I38

     COORDINATES CORRECTED TO CLOSE LOOPS (IN FEET)    COORDINATES CORRECTED TO CLOSE LOOPS (IN METERS)

NO   STA     NORTH   EAST    UP    DIST  LT   RT   HT  FLOOR DESCR    STA     NORTH    EAST     UP

 1 * RH21 P   356.   200.    0.      0.                   0.          RH21 P   108.5   61.0    0.0
 2 1 RM1      398.   238.    1.     57.  4    5    2     -0. BKDN     RM1      121.4   72.6    0.2
 3 2 RM2      468.   258.    3.    129.  6    9    2      3. BKDN     RM2      142.5   78.7    0.9
 4 3 RM4      538.   290.    3.    206.  15   6    1      3.          RM4      164.1   88.4    0.8
 5 4 RM5      635.   309.    2.    305.  4    9    3     -1. POOL     RM5      193.7   94.2    0.7
 6 * RM6  P   731.   344.    0.    407.                   0. FORM     RM6  P   222.9  105.0    0.0
 7 6 RM7      694.   271.   -7.    489.                  -7.          RM7      211.5   82.7   -2.3
 8 * I38  P   691.   253.  -13.    509.                 -13.          I38  P   210.5   77.2   -3.9
 9 8 RH37     727.   224.   -8.    556.  3    4    7    -12. XTAL     RH37     221.6   68.2   -2.5
10 9 RH36     755.   252.  -10.    595.  4    14   5    -11.          RH36     230.1   76.7   -3.1
11 * RH35 P   791.   240.  -13.    633.                 -13.          RH35 P   241.2   73.3   -4.0
12 1 RH34     777.   226.  -18.    654.  10   2    7    -21. BKDN     RH34     236.8   68.9   -5.4
13 2 RH33     746.   197.  -17.    697.  10   7    4    -18.          RH33     227.4   60.0   -5.2
14 * RH32 P   739.   195.  -18.    704.  10   6    3    -18.          RH32 P   225.2   59.6   -5.3
15 4 RH31     714.   209.  -20.    732.  8    3    3    -20.          RH31     217.8   63.8   -6.0
16 5 RH30     666.   201.  -21.    781.  6    10   3    -21. STRM     RH30     203.0   61.3   -6.3
17 6 RH29     578.   155.  -18.    881.  10   6    3    -19. STRM     RH29     176.1   47.2   -5.4
18 * RH28 P   524.   112.  -18.    950.  10   5    3    -18. STRM     RH28 P   159.7   34.0   -5.4
19 8 RH27     456.    94.  -18.   1021.  15   3    2    -18. BKDN     RH27     139.0   28.6   -5.5
20 9 RH26     381.   116.  -17.   1099.  10   6    3    -17. BKDN     RH26     116.0   35.4   -5.2
21 0 RH25     406.   166.   -6.   1157.  6    6    6     -7.          RH25     123.9   50.7   -1.9
22 * RH24 P   420.   182.   -8.   1177.  5    0    10   -12.          RH24 P   127.9   55.6   -2.3
23 * RH23 P   424.   205.   -3.   1201.  7    12   14    -4.          RH23 P   129.4   62.5   -0.8
24 3 RH22     391.   216.    0.   1236.  2    8    3     -1. PASS     RH22     119.3   65.7    0.0
25 * RH21 P   356.   200.    0.   1275.                   0.          RH21 P   108.5   61.0    0.0
```

Fig. 3a. Typical "closed" output, with error message.

An argument can be made on theoretical grounds for more complex closure techniques. The probability distribution of random errors in compass-and-tape surveys is such that the most probable error in a branch is proportional to the average shot length of that branch (Schwinge, 1962). Examination of a large number of WVACS closure errors, however, indicated that they do not conform to the predicted pattern. The observed errors generally are larger than predicted and seem to be independent of the average shot length in the branch. This discrepancy between predicted and observed errors almost surely arises because errors of a different kind predominate (i.e., blunders in reading the compass and/or in recording the data). Accordingly, there seems to be little point in adopting a more elaborate closure technique. The theoretical basis for it is belied by the data on hand.



```
NAME OF CAVE: THE HOLE
BRANCH: NM6   CONT
DATE OF CALCULATIONS: 02/ 25/ 74

SECOND LOOP IN NORTH MAZE VIA I35 AND I38

SUMMARY OF CORRECTIONS

                             2. FT NORTH
                             5. FT EAST
                            -5. FT UP

    FOR A TOTAL OF        7. FT OR  0.55 % OR 1 PART IN    182.1

   TOTAL LENGTH OF BRANCH   1274.7 FT
```

Fig. 3b.

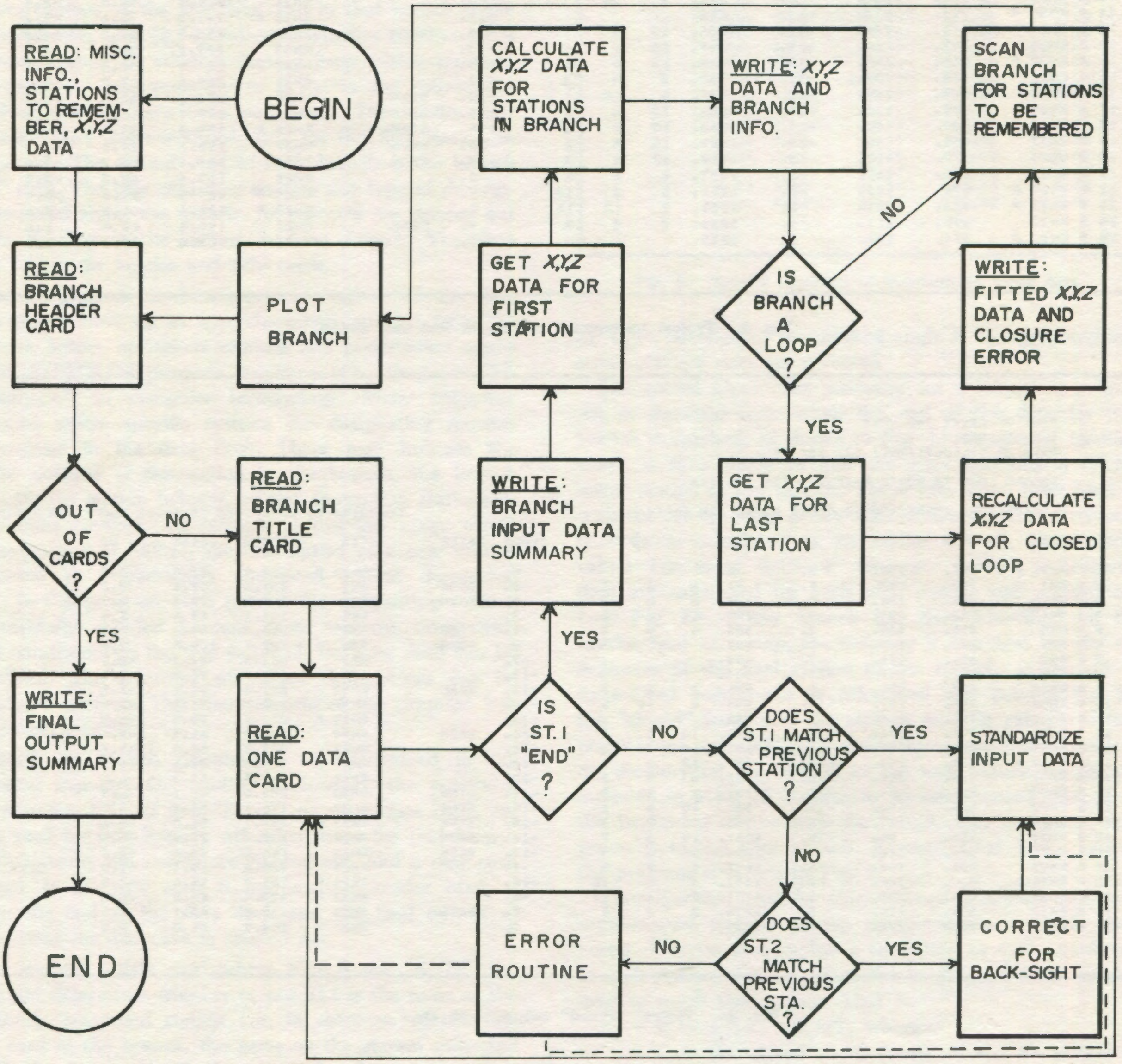


Fig. 4. Generalized flow diagram for data reduction program.

A Versatile Data Card Format

As indicated before, the nature of WVACS' operations is such that a highly versatile format for the data cards is desirable. The many cavers working with us provide data in a myriad of forms and, just as with the conversion of back-sights to fore-sights, it is both easier and more nearly error-free to punch the data in the form in which they originally were submitted and to let the computer convert them into a standard form than it is to make the conversions by hand. Thus, the taped distance may be punched in the form of feet and tenths, feet and inches, or meters; the compass bearing may be in quadrant notation, in 360° azimuth, or in mils; vertical angles may be in decimal degrees, in degrees and minutes, in mils, or in per cent grade. In order to conserve space for each of the three kinds of data, the actual numbers always are punched in the same locations on the data card, with an additional column (or with two additional, in the case of bearings) containing a sentinel to indicate which forms of distance, bearing, and vertical data are being carried by the card. Many different compasses were used to collect WVACS' data, some of which were set for the local magnetic declination and others of which were not. To permit these different data sets to be processed in a single run, space was provided for a "correction" to be added (or subtracted) to the compass bearing on each card in order to convert the bearing to true north.

Provision has been made for descriptive information on each card. Two considerations are important here: (a) to avoid any possible ambiguity, it must be made clear to which station (of the two on the card) the description applies; (b) it must be clear which is the "left" wall and which is the "right" wall in a mixed sequence of fore- and back-sights.

One column on the data card has been reserved for a "1" or a "2", indicating whether the descriptive information applies to ST1 or to ST2. A one-character "comment" is used to indicate whether or not this designated station actually has been inscribed and labelled in the cave. In addition, there is a four-character description which, by suitable encoding techniques, can be made to carry a great amount of information. Our experience has been that simple abbreviations can describe the majority of cases. Thus, "BKDN", "WF30", "XTLS", "POOL", "GYPS", etc. can be used with obvious effect. Also associated with the station designated by the "1" or "2" are four pieces of "cross-sectional" data. These include the over-all height of the passage at that point, the distance from the actual station to the bottom of the passage (to facilitate drawing profile views of the passage), and measurements or estimates or any other details pertaining to the left wall and to the right wall in the vicinity of the designated station.

It is here that the second consideration arises, for, with a mixture of fore- and back-sights, it may not be clear which wall is meant by "left" wall and which by "right" wall. This has been resolved by adopting the convention that all left/right data on the data card must be from the perspective of the *designated* station, as though facing the other station. Thus, the cross-sectional data on a card can apply either to ST1 or to ST2; the general practice is to have each card carry cross-sectional data for the new station, without regard for the direction of the compass sighting. If the data card contains a back-sight, the computer reverses the left/right data. The guiding consideration in adopting this particular convention for handling the left/right data was that it preserved the option of reading the card from either direction.

Three of the four cross-sectional "fields" on the card are not used for calculations but merely are read and printed out. The "left", "right", and "height" data fields have been made alphanumeric, so that a limited amount of descriptive information can be encoded here in addition to the measurements. If a side passage were to be present in the left wall 12 feet from the station, for example, the "left" field could be punched "12 P". Or, "25 + B" could be punched in the "height" field to indicate a 25 ft high passage on top of breakdown, with the real floor hidden somewhere beneath. Again, "5/3W" could represent "height above water" over "water depth". Etc. The only real limitation here is one's ingenuity at uniquely reducing the information to four characters.

Were a standard data card format for cave survey data reduction programs to be generally adopted, cave survey data from all parts of the country might some day be filed in a central location provided by the NSS. More realistically, a standard format would facilitate the interchange of data among groups working together for scientific or other reasons. It is felt that the format discussed here would serve these purposes well. A detailed description of the data card format is given in Appendix A. Although individual programmers may wish to modify the data card format for their own individual purposes, it certainly would be of value to standardize the location of the basic data on the caves—viz., the station identifications, all measurements, and the declination correction (if any).

Variations on a Theme

Some of the survey data were submitted without vertical angles, either because a lensatic compass was used or because the compass man thought he could guess that the passage was level. When vertical control is lacking, an "N" is punched in the column for the sign of the vertical angle (a blank would be interpreted as "zero" by the computer). In this event, "NONE" is printed in the summary of sorted input data, an angle of zero is assumed for calculations, and an asterisk is printed alongside the calculated z coördinate. If "NONE" occurs within a loop, closure will proceed as usual but the closure error will be computed only within the horizontal plane. Any subsequent stations calculated from a station carrying an asterisk also will be so labelled, calling attention to the fact that there may be more than the usual amount of error associated with the vertical coördinate for these stations.

To avoid having to run an entire cave each time new data are accumulated, the initial set-up cards include the previously surveyed distance. Only the new data need be run, therefore, as long as the coördinates also are read in for the starting stations of those branches connected to the old survey. To facilitate such partial runs, coördinates of all remembered stations are printed out at the end of each run. These normally include all tie-points, so that most coördinates needed to be read in for partial runs can be found without searching through a large collection of previous output. A final summary sheet (or title page) giving the cave name, the date of calculations, and the total distance surveyed is printed out when the calculations are finished. Up-to-date output and summary sheets can be produced.

WVACS' interest in the possible correlation of raw cave survey data with geologic structure, especially with joint control (Rutherford, 1967), led to the addition of another feature to the program. During the course of the normal calculations, the horizontal and vertical components of each shot are cumulatively stored as a function of compass orientation from 0 to 180 degrees. At the end of the computer run, the percentage of survey data taken at each orientation and the average slope of the passage segments are printed out by one degree increments. Although this is a somewhat specialized refinement and originally was done by a separate program, it soon became apparent that most of the required calculations already were being performed by the survey program and this feature was incorporated into it.

A plotting routine [1] for use on the line printer is tailored to the standard cartographic system used by WVACS. It

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[1] Plotting routines have been discussed by others, e.g., by Frater (1969).

employs a standard grid system 1000 feet north-south by 700 feet east-west and normally plots the survey at a scale of 100 feet to the inch. A more detailed description of this plotting routine is given in Appendix B. In essence, it plots each station at the nearest print position, which permits accuracy to within five feet east-west and eight feet north-south (at the usual scale). Although the plot is not quite exact, because of the limitations imposed by print positions, there is no cumulative error.

Successive stations are represented by a running sequence of the 10 digits, to assist in identifying the stations. The plotting symbols are shown in the main output for the branch. When more than one station falls in the same print position, an "M", indicating a multiple station, is plotted in place of a digit. An asterisk is used as the plotting symbol for all permanently inscribed stations. It takes precedence over the "M", in the event of a conflict. For a typical point plot, see Fig. 5. Originally added to facilitate map drawing, this point plot has the additional advantage of allowing rapid recognition of some survey blunders. More than once, examination of these plots has revealed gross errors in the bearing—where the wrong end of the compass needle was read or where the wrong quadrant was recorded.

The capability of rotating the cave was added by the simple expedient of including in the set-up cards an angle which may be added by the computer to each compass bearing. Rotation of the survey permits one of the vector directions to be made coincident with the strike of the rocks. In this way, geologically significant cross-section maps can be prepared more easily. If desired, rotation also could be employed to obtain the optimum fit of a cave map to a rectangular grid.

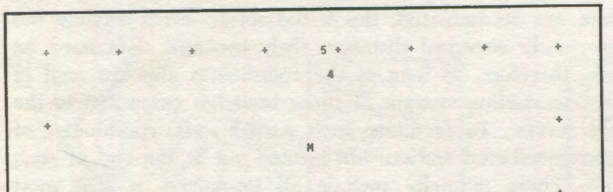

Fig. 5. Typical point plot, from the line printer, of part of one branch. McClungs Cave: N= 0, E = −700 at lower right corner. Passage enters quadrangle from right margin, exits and re-enters from left margin, and finally exits from top margin.

While a scale of 100 ft to the inch was adopted as being the optimum for generating working maps, the "finished" maps of major caves are better rendered at a smaller scale. A second set of station coördinates, in meters, also is printed out, in order to facilitate the drawing of these maps on an analogous grid system. Complete versatility regarding scales for the output data is achieved by adding to the program a single card which multiplies the taped distance by a scaling factor after it has been converted into standard form. In this manner, both the coördinates and the point plot can be obtained at any scale desired.

PROGRAM EVOLUTION AND MISCELLANEOUS EXPERIENCES

This program is the product of a long, evolutionary sequence of false starts and periodic modifications. Although some additional changes no doubt will be made (a sophisticated routine for the CALCOMP plotter has nearly been completed), the program probably is close to its "final" form. The prototype, written by Jean Cropley, was a program so versatile that it could handle a data deck which had been shuffled before being run. His program was an intellectual triumph but, because it required tremendous memory and long running times, a practical failure. It did get WVACS off on the right foot, however, in that it required a self-explanatory, "two-way", data card. John Fisher later took over the programming chores and, among other improvements, added loop closing, data sorting by orientation, and plotting. Today, it is a highly complex program, written in FORTRAN IV with a nine-page listing. Nonetheless, it is reasonably efficient, requiring only about one minute of running time for 10 miles of data on an IBM 360/65 computer.

Many ideas were seized upon during the evolution of this program. Many were discarded, also. For the consideration of others interested in the subject, the following experiences may be pertinent. Since several miles of data were being computed in a single run during later stages of program development, modifications had to be made in the program to make it as foolproof as possible with regard to "reading errors". Too many times, mistakes were being made in the assembly of the thousands of cards in the data deck, with the result that alphabetic characters would appear on a card where the computer had been instructed to find numerical data. Execution of the program would terminate automatically whenever such a reading error occurred, because the computer is unable to process alphabetic data like it processes numerical data. Originally, the computer recognized the end of each branch by reading the specific number of data cards which were indicated on the branch header card. Unfortunately, to err is human and, too many times, the count punched on the header card did not match the number of data cards in that branch. This circumstance was by far the most frequent cause of reading errors and, in order to minimize them, the use of a station count to monitor the reading of data cards was discontinued in favor of the use of a "flag"—i.e., a card carrying the letters "END" in its first three columns—at the end of each branch. The computer now reads data cards until it encounters one with "END" as the first station.

The same potential for error also occurs, though less frequently, at the beginning of the data deck, when the starting coördinates for key stations and the list of stations to be remembered are being read in. Here, too, the use of counting as a monitor was replaced by flags.

Other problems arose when the computer could not match either of the stations on a new data card with the station previously calculated. These usually resulted from keypunch errors. Sometimes, if the keypunch operator noticed an error while punching a card, a new card was punched immediately but the incorrect one absent-mindedly was left in the deck. At other times, a card was improperly "justified". Station designations in this program have four digits. These can be either alphabetic or numeric in character. Because the blank ("b̸") is a legitimate alphabetic character, "A15b̸" as a station designation looks different to the computer than does "b̸A15". This can be a special problem when several different people help to punch the survey data. The convention of left-justifying all station designations was therefore adopted because left-justification is easier for the keypunch operator.

In order to minimize problems associated with an apparent mis-match of stations from one card to the next, an error routine was built into the program which tries to determine if the mis-match was caused by a wrong punch or by an extra data card. After performing the error routine, the machine prints a warning and continues. It has been about 75% successful in correcting such errors.

The program was designed, initially, to handle any number of caves in a single run, with flags at the end of each cave and a different, "final", flag at the end of the last cave. However, a reading error would stop the run and none of the subsequent caves in that run would be calculated. Introducing the error routine was a help in this regard, but multi-cave capability later was achieved in a much more efficient manner by the use of Job Control Language (JCL). Under this procedure, the program was modified to compute only one cave at a time and JCL cards preceding the program instruct the machine to store the compiled program at the end of execution just in case it is needed again. For multi-cave runs, additional JCL cards are inserted between the different data decks. These recall the previously compiled program, even when reading errors have occurred in one or more caves encountered earlier in the run.

It also is important that care be taken to minimize instances in which the same station designation is used more than once in the same cave. Unless the identical stations are adjacent, the program will run properly. But, if it is a designation to be remembered, or one with read-in coördinates, problems can arise. The computer always will store the most recently calculated set of coördinates for any such designation, so, by judicious sequencing of the branch data, the proper computations usually can still be obtained. However, WVACS' standard procedure in such instances has been to change duplicated station designations if they are tie points and, hence, likely to be remembered; one character in one of the duplicated stations is replaced by an asterisk, a symbol never originally assigned for station designations. A duplicated "AC16", thus, might become "A*16" and, on seeing the asterisk in the output, the reader is alerted to the fact that the station is differently marked in the survey notes and in the cave. A somewhat related problem arises when two different survey lines assign different designations to a single station. A single designation must be selected for use in the computer. Both of these problems usually can be clarified in the four character comment field, because "X23A" or "AC16" is not likely to be misinterpreted as a passage feature.

To help prevent errors while assembling decks, colored cards are used for flags and for header cards, while all data cards are manila. The use of drum control cards on the Model 29 IBM keypunch machine helps both to speed the task and to minimize the errors during keypunching of the survey data. In addition to reducing decimal-point errors, drum control cards help to prevent the punching of alphabetic characters in numeric fields.

After the distressing experience of having three full boxes of data cards discarded inadvertently, WVACS began punching all cards in duplicate and maintaining a duplicate deck for each cave. Such is easily arranged using the dual drum control cards available on the Model 29 keypunch. One set of control card instructions includes information for punching the data. The second set of instructions duplicates a data card. Thus, after punching a data card, a second card is fed in under the other set of instructions and is duplicated automatically.

The interchange of left and right cross-sectional data at a station was another error which occurred with sufficient frequency to require a remedy. Note takers, data transcribers, or keypunchers sometimes would record strings of data with the left and right data in reverse order, because of the frequent alternation of fore- and back-sights. Accordingly, the program was modified so that, by adding an "R" to such cards, the computer is instructed to compensate for the error.

To help guard against data cards from one cave becoming mixed with those from another, the last three columns of all data cards are reserved for a three-letter code identifying the cave to which the data refer. All cards from McClungs Cave carry "MCL" in the last three columns, "GBC" is Greenbrier Caverns, etc. This information normally is not used by the computer, but it is of considerable help to the persons involved in storing, manipulating, and assembling the decks. It is especially helpful to WVACS, which has well over 100 miles of survey data stored on cards (Rutherford, 1971).

Another principle guiding the evolution of this program was convenience and utility in selecting and arranging the output. Computer output is printed on 11 in. by 17 in. sheets. An inch-thick pile of such sheets, bound together accordian style, is cumbersome to handle, at best. Accordingly, the output has been arranged so that the individual sheets can be separated, torn or cut down to 8½in. by 11 in. in size, punched to fit a standard binder, and stored in book form. To prevent possible confusion after the output has been separated, each sheet is labelled as to cave, run date, and branch number for ready identification. In the original plotting routine, the entire cave was plotted on a single grid system after the calculations were completed.

Three different sets of running print symbols originally were used to help the reader identify individual branches on the final plot. Nonetheless, complex or multi-level caves still were very confusing, and a policy of plotting by individual branches was adopted rather than of plotting the entire cave on one sheet.

The most recent option added is that of selecting precisely the form of output desired from a particular run. Sorted input data, passage distribution by compass orientation, unclosed (or closed) loop data, or the point plot all can be deleted from the output by placing suitable instructions on the set-up cards at the beginning of the deck.

Inasmuch as the main motive for developing the program was to facilitate the drawing of maps, the form of the output has been tailored to suit WVACS' own needs. The 100 feet-per-inch working maps can be drawn directly from the output, and the point plot has been scaled so that it can be laid on a light box and traced directly. To further simplify the process, the symbols used on the point plot are reproduced alongside the station designations in the output. The overall passage height at each station, rather than ceiling and floor distances from the station, is printed out, because this is of more interest to cartographers. The vertical coördinate of the floor at each station also is printed out and, by comparison with the vertical coördinate for the station, the height of the station above the floor can be reconstructed when desired. This simplifies drawing profiles.

An elaborate encoding system at one time was devised for each of the four columns of the four-character "comment" associated with each station. Intended to describe (1) cave fill, (2) speleothems, (3) amount of water (or degree of agony), and (4) geologic features at each station, this, again, was something of an intellectual triumph but turned out to be a practical failure. Most note takers on survey parties are not interested in such tedious details and long practice would be required to master the four encoding systems before they could be used efficiently. The potential of this comment field came, instead, to be used mainly to signal the presence of some feature in the passage.

Coördinates for stations in a loop are indellibly fixed once that loop has been closed, at least for the duration of the particular computer run. For large, complex caves with concatenated loops, two problems sometimes arise. The first is that, in force-fitting a *portion* of a loop to tie-points already fixed, any error in the previously fitted (and hence fixed) section is relayed onto the new loop segment. The second is that, because different loop segments contain different intrinsic errors, it becomes important to consider the sequence in which the interlocking loops are closed. The most accurate segments, naturally, should be closed first. The question of optimal closure of concatenated loops is a complex subject in its own right (Schmidt and Schelleng, 1970) and is beyond the scope of this paper. One thing which has been very helpful to WVACS in dealing with this problem superficially has been to have the "raw", uncorrected, coördinates printed out for all branches that are closed, in addition to the force-fitted coördinates. It frequently was found that relatively casual study of the raw data would disclose a superior sequence of loop closures.

One of the convictions that has grown in those who have had intimate contact with this program during its evolution is the considerable value which accrues from the self-contained, two-way data card—that is to say, a data card which can be fully interpreted without reference to any of the other cards in the data deck and which can be read from either direction along a branch without modification either of the card or of the program, without insertion of a flag in the deck. The complete freedom which two-way cards allow in rearranging decks to accommodate new interconnections in the cave or in changing the sequence of loop closures to minimize errors is a very real blessing when handling large amounts of data. In addition, it is sometimes simpler to institute program changes when all data cards are self-explanatory. These considerations are difficult to document ***but can hardly be over emphasized.***

ADVANTAGES OF USING THE COMPUTER

Despite years of experience in using computers to process cave survey data, the impression persists that many of their oft-touted advantages are merely the rationalizations of avid computer programmers. Just where do the advantages lie, assuming that the proper function of a computer program is to translate a set of survey notes into a cave map?

One reason, frequently cited by advocates of the computer, is that it eliminates plotting inaccuracies. Plotting errors arising from the thickness of the drawn line or from dimensional changes in the paper are at least an order of magnitude smaller than is the margin of error associated with decent (?) survey data and, hence, are relatively inconsequential as regards the accuracy of the map *when compared to the real cave.*

It certainly is true that the computer can (and does) eliminate plotting blunders, for it calculates with flawless precision and never mistakes 235 degrees for 325 degrees, as might the cartographer with his drafting machine. Oddly, experience indicates that computer processing increases the likelihood that other blunders will occur. Keypunching the data introduces an additional step in data handling and it is here that undetected blunders can very easily occur. Additional people, usually people who were not present when the survey was done, also have been added to the process. Thus, the computer approach to cartography is rather more than less likely to result in inaccurate maps. What can go wrong, will.

Mistakes in the program also are possible. The computer follows its programmed instructions flawlessly but, if programmed to calculate something incorrectly, it will do so with one-hundred per cent efficiency. Programming errors have been known to go undetected for years, when the errors generated are small; to make matters worse, such errors tend to be systematic and cumulative. The argument for increased accuracy via the computer does not hold up.

A second argument advanced in defense of the computer is that it more rapidly bridges the gap between raw survey data and the drawn map. This argument also fails in the real world, for the person with the drafting machine (plus electronic calculator with trigonometric functions, when verticals are involved) usually will beat the person with the keypunch machine and the computer.

If the arguments for accuracy and for speed lack factual bases, the question naturally arises: Just why do people keep going to the machine, if the computer does not deliver these advantages?

Part of the reason people keep going to the computer probably lies in the satisfactions they gain from developing a program and in attendant feelings that they are being thoroughly modern and progressive by utilizing the latest technology. However, a few practical advantages do result from the use of the computer. One is the simple fact that, once all the data have been punched on cards, neat, concise data summaries can readily be prepared. This information is printed out automatically, whereas it otherwise probably would remain scattered on the muddy pages of diverse survey notebooks. Admittedly something of a fringe benefit, the advantages of such summaries nonetheless are very real.

An advantage sometimes not recognized at the outset is that going to the computer almost forces one to use an *x,y,z,* coördinate system. This not only paves the way for the adoption of a grid, or quadrangle, system of cartography, which is advantageous when dealing with large caves because "roll maps" can become terribly unwieldy, it also makes extremely simple the preparation of supplementary maps at different scales. For manual plotting, all that is required is a change in the scale of the graph paper on which the map is drawn. Point plots can be obtained at other scales by making a minor adjustment in the program.

A third area where the computer shows to advantage is loop closures. In a sense, loop closing could be considered a special case of redrawing, because it could be done by replotting with a scale factor for each distance and a correction to be added (or subtracted) to each compass bearing. However, loop closing is required so often and is so much more involved than is redrawing to a different scale that the ability to achieve facile loop closures is probably the single most important advantage accruing from use of the computer. After all, maps *can* be plotted by bearing and range on graph paper in order to obtain *x,y,z,* coördinates, and they *can* be photographically reproduced at different scales, but no other method of forcing closures is as rapid and accurate as is this.

A substantial advantage of going to the computer is the flexibility that may be achieved in handling large amounts of data after the data have been placed on cards. When caves have large numbers of interconnected loops, two-way data cards permit the problem of closing multiple loops to be solved by trial-and-error variation of the closure sequences. Computer data handling also introduces the possibility of extracting information in addition to *x,y,z,* coördinates by resort to data-processing techniques. WVACS' efforts at correlating survey data with geologic structure is one such example.

Finally, the data cards, the computer print-out, and the maps drawn on grid systems are of standardized shapes and sizes and are durable. They can be stored systematically, according to their geographic area or other classification, much more easily than can maps of different sizes and field and working notes of various dimensions and deteriorating physical condition.

The "advantages" of going to the computer for processing cave survey data do tend to accrue only when one is dealing with large amounts of data. This should not be too surprising, for it was primarily to manipulate large amounts of data (or to perform very lengthy calculations) that computers were developed.

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(We regret that, due to the loss of the original illustrations, publication of this paper was delayed.)

APPENDIX A

Data Card Format

Column Number	Field Designation	Remarks
1–4	A4	Designation (letters or numbers) of station where compass was located.
6–9	A4	Designation (letters or numbers) of station toward which measurements were made.
12	I1	Number of station (first or second) to which cross-sectional data apply.
13	A1	One character "comment" (letter or number), usually indicates that the station (column 12) is permanent.
18–22	F5.2	Taped distance, in decimal feet or meters, with decimal assumed between columns 20 and 21.
23	A1	"M", if taped distance is in meters; otherwise, left blank.
24–25	F2.0	The inches portion, if any, of the taped distance.
32	A1	"N" or "S" for quadrant bearings; otherwise, left blank.
33–36	F4.1	Bearing, to the nearest 0.1 degree (decimal assumed between columns 35 and 36) or in mils.
37	A1	"E" or "W" for quadrant bearings, "M" if bearing is in mils; otherwise, left blank. (Note: quadrant bearings due east or west must be punched N(S)90E(W), for, if column 32 is blank, this program assumes that the bearing is not in quadrant notation.)
38–39	F2.0	"Minutes" portion, if any, of bearing.
41–42	F2.0	"Minutes" portion, if any, of vertical angle.
43	A1	"N" for unmeasured angles, "—" for negative angles, and "+" or left blank for positive angles.
44–47	F4.2	Vertical angle, to the nearest .01 degree (decimal assumed between columns 45 and 46) or in mils.
48	A1	"M" if vertical angle is in mils, "G" if in per cent grade; otherwise, left blank.
49–52	A4	Four character "comment" (letters or numbers).
54–56	F3.1	Declination correction (positive or negative), decimal assumed between columns 55 and 56, to be added to the bearing to change it to true north.
57	A1	Normally left blank. A "W" (west) here changes the sign of the declination correction. (Because the computer reads unsigned numbers as positive [east], and because of space limitations in the preceeding field, this is the only way to make rare, negative [west] corrections greater than 10°).
60	A1	"R" if left and right cross-sectional data should be reversed; otherwise, left blank.
61–64	A4	Cross-sectional descriptive information (letters or numbers) for the left wall.
65–68	A4	Cross-sectional descriptive information (letters or numbers) for the right wall.
69–72	A4	Cross-sectional descriptive information (letters or numbers) for the passage height.
73–76	F4.0	Distance (in feet) from the station to the lowest part of the floor, decimal assumed after column 76.
(77–80)	(A4)	Cave-identification code, using up to four letters.

APPENDIX B

Plotting Routine for the Line Printer

The plotting routine relies heavily on the use of integer arithmetic to locate for each station: (a) the proper quadrangle in the 1000 ft N-S by 700 ft E-W grid system and (b) the closest print position within that quadrangle. The individual stations cannot be printed as they are being calculated, because the line printer only prints downward one line at a time. Since later stations may be found to fall on the same line, and since the branch may wander back and forth between two or more quadrangles, printing of all quadrangles must be deferred until the print positions of all stations in the branch have been determined. Therefore, the necessary printing information for each station is stored in an integer array, called "PAGE", which contains 61 times 71 storage location. These correspond to the 61 lines (six per inch) north-south, plus one for the margins and 71 print positions (10 per inch) east-west, plus one for the margins.

Actually, that is a slight simplification, because a different PAGE will be required to store the printing information for each quadrangle occupied by the branch. A three-dimensional array, "BOOK", is required. Such an array, comprised of 61 times 71 times 25 storage locations, is appropriately imagined to be a book containing 25 pages, each page being capable of holding the information required to print one quadrangle. In addition, some sort of indexing system is needed to keep track of which quadrangles are to be printed. The Hollerith symbols to be printed include the 10 digits (stored in a 10 element integer array, "SYMBOL") and the "+", the "b̸",—the "*", and the "M".

After all other branch calculations have been completed, the plotting routine is executed as follows, From the *x,y* coördinates of each station, the proper quadrangle is determined first. A check then is made to determine if this is a new quadrangle. If so, a new PAGE must be prepared. Because it may contain point-plotting information from a previous branch, the new PAGE must be filled with blanks and, around the border, rimmed with plus marks at one-inch intervals to indicate the 100 ft per inch scale. A record also is made in the index, identifying the location of this particular quadrangle in the BOOK, so that subsequent entries may be made in it and so that it may be printed at the end of the routine. The position within the quadrangle is next determined to the nearest line (six lines per hundred feet north-south) and print position (10 print positions per hundred feet east-west), using integer arithmetic and suitable round-off procedures. The proper print symbol then is stored in that element of the PAGE array.

Three kinds of symbols are used to represent stations in the point plot: the 10 digits (0-9), which, for the *n*th station along the branch, are the last digit of *n*-1; the "M", which indicates that more than one station is located in that print position; and the "*", which indicates that a permanent station is located in that print position. The "*" is given highest priority and, therefore, when the final plot is rendered, it can be interpreted as follows: The "*" indicates that one or more stations fall within that print position, one or more of which is permanent; the "M" indicates that two or more stations fall within that print position, none of which is permanent; the digit indicates which single, non-permanent station falls within that print position. In deciding which print symbol to store, the program first determines if "*" already is stored there. If so, it procedes to the next station. If not, it replaces whatever already is stored there with: (a) an "*", if the new station is permanent, (b) an "M", if a digit already is stored there, or (c) *n*-1 if neither of the preceeding is found. If the print position is on a border of the quadrangle, then the same symbol must be entered in the appropriate location in the adjacent quadrangle PAGE(s), following the basic procedure of checking the index for the location of the extant PAGE or, if it is a new one, preparing the new PAGE and entering the new symbol in it.

After printing instructions for the last station in the branch have been stored, the contents of each PAGE are printed out as quadrangles in their indexed order. The coördinates and branch number of each quadrangle are printed in its lower right-hand corner. A sample quadrangle (with labels deleted) is show in Fig. 5; a simplified flow diagram for the plotting routine is shown in Fig. 6.

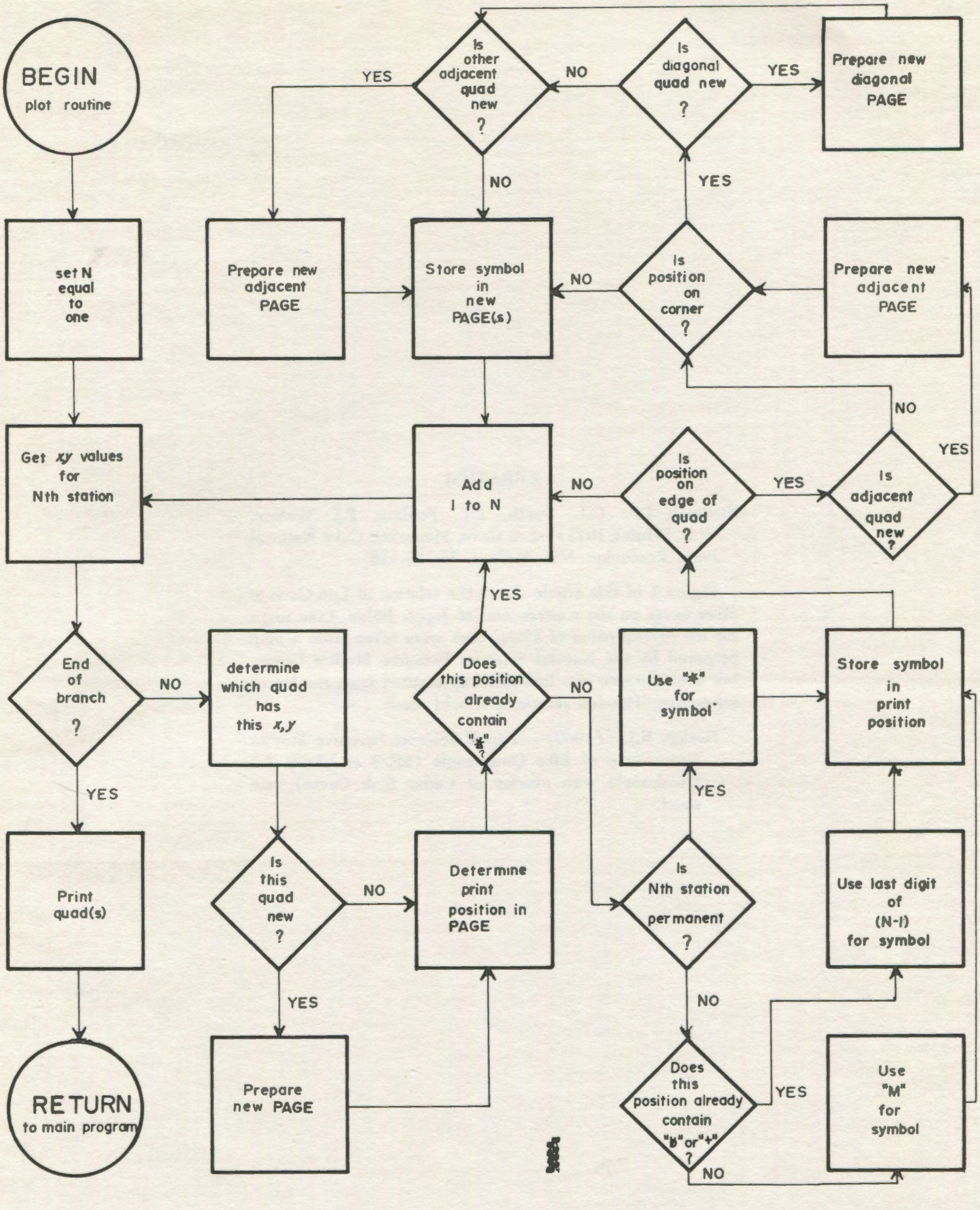

Fig. 6. Simplified flow diagram for point plotting routine.

ERRATUM

Freeman, J.P., G.L. Smith, T.L. Poulson, P.J. Watson, W.B. White(1973)—Lee Cave, Mammoth Cave National Park, Kentucky: *NSS Bulletin* 35:109-126.

Figure 1 of this article shows the relation of Lee Cave to other caves on the western end of Joppa Ridge. Line maps for the several caves of Cedar Sink were taken from a map prepared by the Natural Sciences Resource Studies Group, but the reference was inadvertently omitted from the list of references. The full reference should read:

Hosley, R.J. (1969)—Natural Sciences Resource Studies Group map of Elko Quadrangle (SE/9 of Rhoda 7.5 Quadrangle with overlay of Cedar Sink Caves), one sheet.

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Office Address:

NATIONAL SPELEOLOGICAL SOCIETY
CAVE AVENUE
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