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# Microseismic Monitoring of Solution Mining Cavities

M. GUARASCIO

*Department of Mine Design, University of Trieste, Italy*

Microseismic monitoring of mining areas is a developing technique, described here for the Belvedere Spinello Mine, southern Italy, where dissolution cavities in the mining area have proved problematic. The preliminary condition for locating seismic impulses has been found to be a reliable seismic ground model. Ground signals are continuously recorded by means of data from piezometric wells, for sinkhole data, and linked gephones, for microseismic data. A computer system has been implemented to collect, analyse and interpret the incoming signals. Consequently, identification and classification of hypocentres of activity is facilitated, with advantages in terms of safety, preventing harmful side-effects, including rock bursts, and for environmental conservation.

## Introduction

Subsidence and sinkholes are the surface effects of solution mining. Apart from damage to economic production, such events are now of environmental concern. The control of cavity evolution and its effect is thus a problem which requires serious examination.

In concept, when salt dissolution creates a cavity around the top stresses, fractures and falls can occur and consequently seismic impulses. The problem is to locate exactly in 3-dimensional space the position of the seismic impulse source, 'the hypocentre'. The present paper describes the basic concepts and operating techniques for continuous microseismic monitoring of the mining area. This technique can be of considerable advantage both in monitoring how the work is done and also preventing the onset of undesirable and at times negative phenomena.

The preliminary condition for determining the locations of sources of seismic impulses is the availability of a reliable seismic ground model. In the specific case described, a suitable model was constructed based on the available geological and geophysical information. This model relates to Belvedere Spinello Mine (Crotone, southern Italy) which is being operated by hydrodissolution.

In order to ensure maximum safety of mining operations, monitoring is performed on subsidence linked to an event (sinkhole) on the water table (using piezometric wells), and on microseismic activity (using a network of geophones).

A network of geophones has been designed for the continuous recording of ground signals generated by falls and/or stresses around the expanding cavities, and an appropriate hardware/software system has been implemented to allow the collection of the signals, their analysis and interpretation.

The main result is the classification and identification of the hypocentres according to the modifications of their locations in space and time. The mapping of the loci of the classified hypocentres in 3D space-time will be a useful tool for controlling cavity development for safety purposes.

## The case study

The Belvedere Spinello salt deposit in Italy is mined by the technique of hydrodissolution. Mining operations at the mine are carried on through coupled wells (injecting well plus flushing well) and single wells (injecting/flushing wells), though mining operations are essentially limited to the technique of coupled wells.

Figure 1 illustrates schematically the flow conditions achieved using this specific mining system, together with an indication of an average representative stratigraphic series. This series comprises:

- an upper complex (300 to 600 m thick) essentially formed by clayish layers, clay-sandy layers and marl rock that we can simplify as upper claystone layers and lower sand layers;
- a middle complex (90 to 120 m thick) situated above the salt minerals, formed by clayish and chalky layers that we can simplify as claystone layers;
- and a lower complex characterized by layers of salt minerals with inserted clay layers which are considered as waste in salt layers.

During mining operations, it is particularly important to monitor closely all changes in the cavities created as a result of the dissolution process. By recording the microseismic activity associated with the expansion of the cavi-

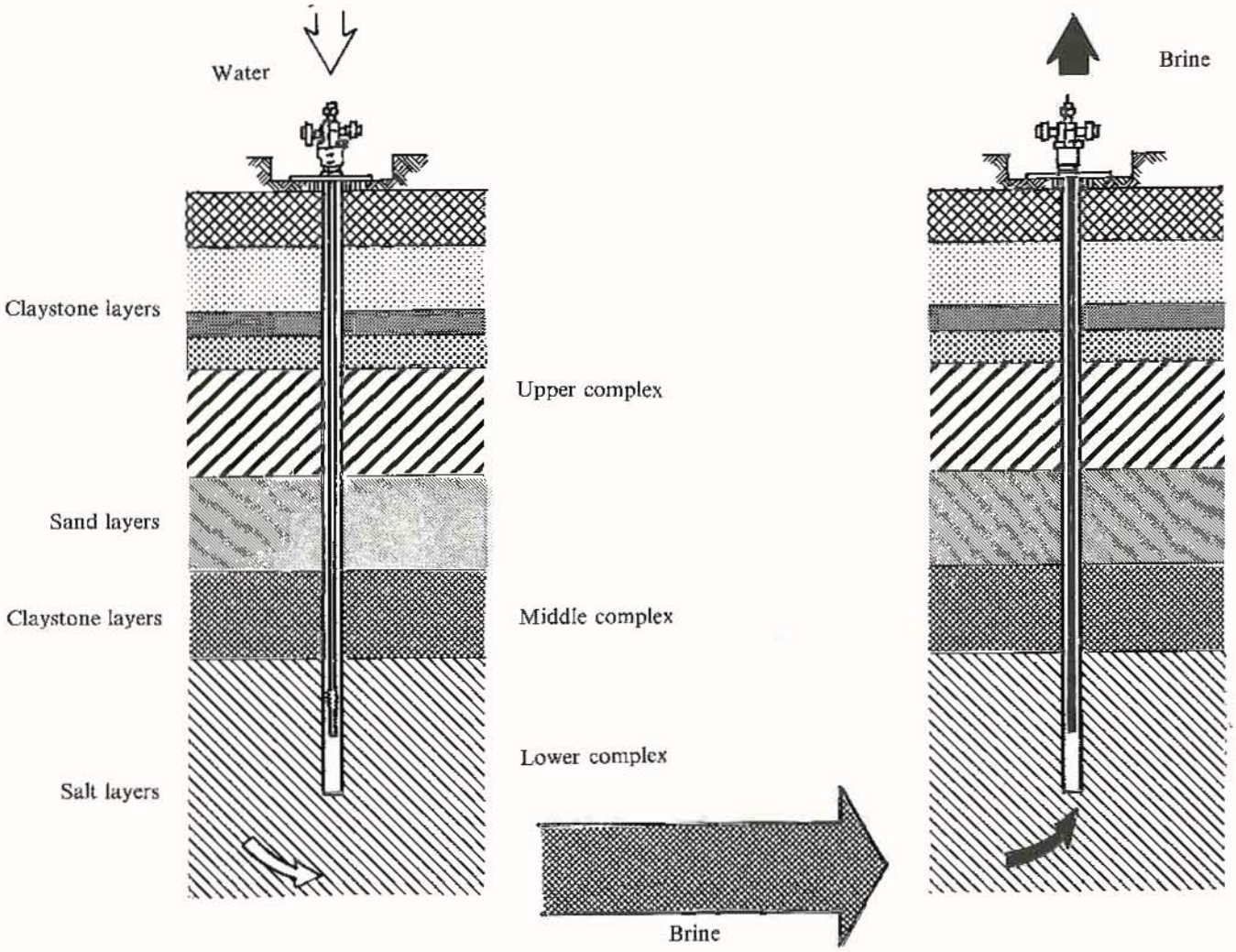


FIGURE 1. Mining technique using coupled wells

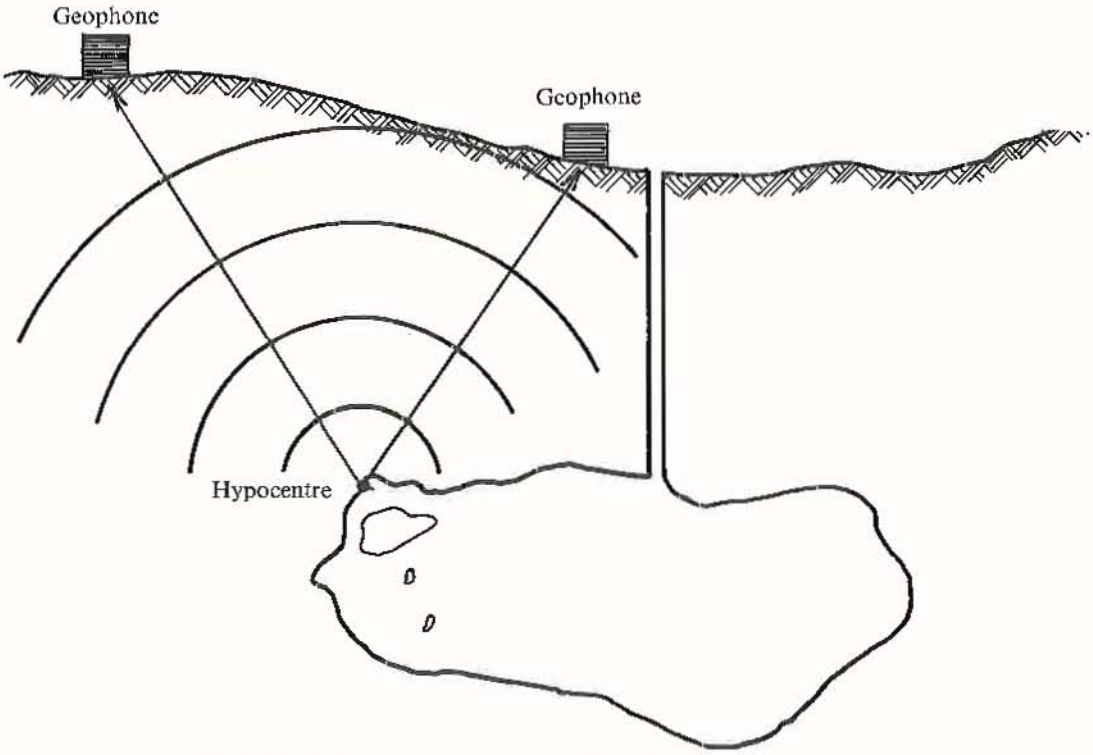


FIGURE 2. Geophones to record seismic impulses

ties, it is possible to identify the behavioural characteristics of the latter and hence note the appearance of any undesirable or negative phenomena as an accelerated subsidence and uncontrolled sinkholes.

## Microseismic activity and cavity evolution

The rocks surrounding a cavity created by dissolution, especially when heterogeneously layered, can present phenomena characterized by the liberation of elastic energy, possibly accompanied by more or less localized caving. In fact, the circumferential stresses of these rocks may exceed their mechanical strength at different points around the void, giving rise to dynamic phenomena that reveal themselves in the form of microseismic impulses.

In our particular case the quite uniform distribution of clay layers or waste units within the salt generates a systematic series of occurrences of microseismic emissions. Through the location of the sources of microseismic impulses the growth in space and time of the cavities can be monitored.

## Identification of hypocentre location

A network of geophones capable of recording underground vibrations is being installed at suitable positions on the surface, over the whole mining area. The aim is to identify the locations of the points (hypocentres) where the described dynamic phenomena occur.

As the positions of the geophones are known in terms of the three reference coordinates $x$, $y$, $z$, and having constructed a seismic model of the site, the problem is solved by directly determining the coordinates of the hypocentres.

The seismic velocities of the ground layers illustrated by the geostructural model of subsurface rocks can, however, also be considered to be unknown. Figure 2 is a schematic illustration of how a seismic impulse is generated and how the wave arrives at the geophones on the surface.

The computer program developed by MINING Italiana S.p.A. for determining the hypocentre of a seismic impulse is based on the Geiger method of resolving problems through successive approximations. The theoretical principles of this calculation are briefly discussed hereafter with reference to a homogeneous isotropic seismic model of underground conditions.

Assuming hypothetical starting points $x_o$, $y_o$, $z_o$ for the seismic source, the characteristics $v_o$ of the adopted model are used as the basis for calculating both the times of arrival of the impulse at each geophone of the network ($T_i$) and the time of emission of the impulse itself ($T_o$). Indicating by $t_i$ the corresponding arrival times actually recorded, an 'error function' ($R_i$) is obtained:

$$R_i = R_i(t, x, y, z, v) = T_i - t_i \qquad [1]$$

If $R_i$ is developed according to a Taylor series, one obtains

$$R_i(t, x, y, z, v) = dt + \frac{\delta t_i}{\delta_x} dx + \frac{\delta t_i}{\delta_y} dy + \frac{\delta t_i}{\delta_z} dz + \frac{\delta t_i}{\delta_v} dv + l_i \qquad [2]$$

where the $l_i$ represent the terms of higher order, i.e. the errors.

In practice, it is a question of finding the adjustment vectors ($d_t$, $d_x$, $d_y$, $d_z$, $d_v$) of the position ($x_o$, $y_o$, $z_o$) of the initial hypocentre such that the sum of the squared errors is a minimum:

$$\Sigma_i l_i^2 = \Sigma_i (R_i - dt - \frac{\delta t_i}{\delta_x} dx - \frac{\delta t_i}{\delta_y} dy - \frac{\delta t_i}{\delta_z} dz - \frac{\delta t_i}{\delta_v} dv)^2 \qquad [3]$$

Taking all derivatives for $d_t$, $d_x$, $d_y$, $d_z$, $d_v$ to be zero, one obtains the following system:

$$\begin{aligned}
&n dt + \Sigma a_i dx + \Sigma b_i dy + \Sigma c_i dz + \Sigma d_i dv = \Sigma R_i \\
&\Sigma a_i dt + \Sigma a_i^2 dx + \Sigma a_i b_i dy + \Sigma a_i c_i dz + \Sigma a_i d_i dv = \Sigma a_i R_i \\
&\Sigma b_i dt + \Sigma a_i b_i dx + \Sigma b_i^2 dy + \Sigma b_i c_i dz + \Sigma b_i d_i dv = \Sigma b_i R_i \\
&\Sigma c_i dt + \Sigma a_i c_i dx + \Sigma b_i c dy + \Sigma c_i^2 dz + \Sigma c_i d_i dv = \Sigma c_i R_i \\
&\Sigma d_i dt + \Sigma a_i d_i dx + \Sigma b_i d_i dy + \Sigma c_i d_i dz + \Sigma d_i^2 dv = \Sigma d_i R_i
\end{aligned} \qquad [4]$$

where $n$ = the number of geophones;
$a_i = \delta t_i / \delta x$;
$b_i = \delta t_i / \delta y$;
$c_i = \delta t_i / \delta z$;
$d_i = \delta t_i / \delta v$.

The solution of this system provides a first approximation of the values for $d_t$, $d_x$, $d_y$, $d_z$, $d_v$.

The subsequent parameters of the impulse will therefore be:

$$t_0 + d_t, (x_0 + d_x, y_0 + d_y, z_0 + d_z), V_0 + d_v \qquad [5]$$

and the procedure is iterated until the optimal solution is identified.

## Optimization of geophone grid

The precision with which the hypocentre of seismic impulses is determined depends essentially on the absence of bias in the hypotheses assumed for the ground model and on the positioning of the geophones on the surface. It is clear that once the characteristics of the seismic model have been defined, the results in terms of precision of identification of the hypocentres are improved by optimizing the positions of the geophones on the surface.

In fact, it is known that the positioning error in the calculation of the hypocentre ($D_r$) due to an erroneous evaluation of the entity DV of the seismic velocity (homogeneous isotropic ground model) is given by:

$$D_r = \frac{1/n\Sigma r_i - (r_o)}{1/n\Sigma\cos\theta_i - (\cos\theta_o)} - \frac{D_v}{v}$$

where: $n$ = the number of geophones used to determine the hypocentre; $\theta_o$ and $\theta_i$ are the angles that the error vector ($D_r$) forms with the point hypocentre/nearest geophone and with the point hypocentre/i-th geophone, respectively.

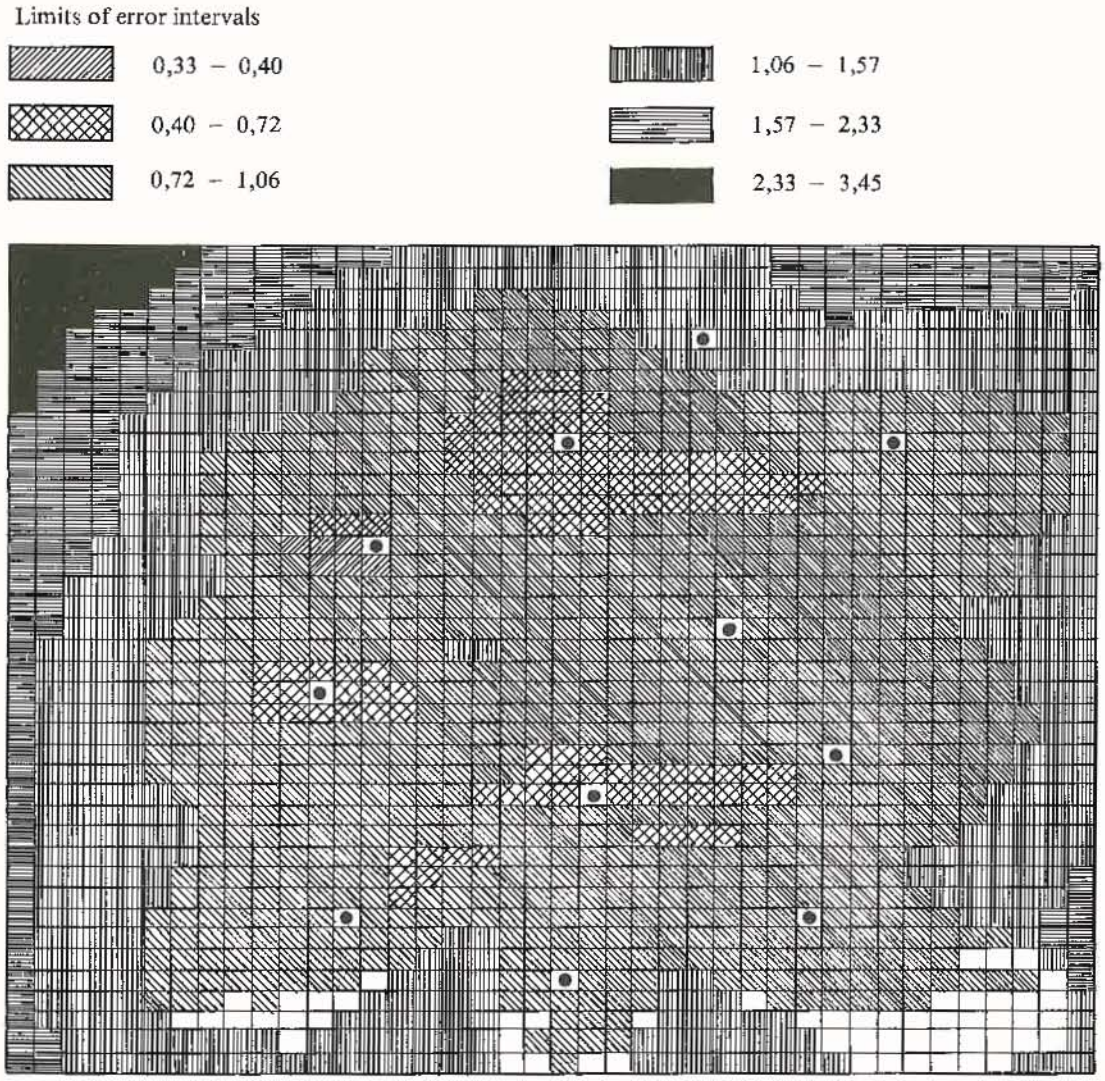


FIGURE 3. Graphic matrix of positioning errors of hypocentres

The above discussion shows that the most unfavourable situations are obtained when geophones are arranged in a row and/or located at too great a distance from the seismic source. The problem may be solved with the help of the computer using a mathematical model which takes account of both the subsurface and surface characteristics of the zone.

Operationally, the sources of the seismic impulses are assumed to be arranged on a flat surface the orientation of which is irrelevant, but corresponding to the nodes of a reference grid of pre-established size. For a given seismic ground model, and taking the positions assumed for the network of geophones, the program provides an evaluation of the precision with which the position of each hypocentre can be determined.

Figure 3 is an example of the graphic output of the aforementioned computer model, where the positioning error is divided into a discrete number of classes. In this way, it is possible to verify the monitoring potential of microseismic activity with the required precision in the areas of major interest. Clearly it is possible, by modifying the locations of the geophones on the surface, to obtain different configurations for the matrix of positioning errors.

By means of successive runs, it is possible to identify an optimal configuration for the network of geophones and also to evaluate the influence of the schematic assumptions on the basis of the analyses performed.

## Data recording and processing system

The system for recording and processing seismic impulse data consists essentially of a group of local units connected by radio to a data collection centre, connected in turn with a computer. Each local unit is equipped with a geophone, systems for storing and transmitting the signals and an autonomous power source operated by solar cells. The collecting centre is equipped with devices for receiving and treating the data inputs, and for controlled interconnections with a computer. Figure 4 illustrates a symbolic scheme of the path of a seismic signal from the hypocentre to the computer.

The seismic impulse originating underground reaches the geophone on the surface and generates an electrical impulse of determined characteristics in terms of amplitude, frequency and duration. The electronic devices with which the local unit is equipped perform a verification of the amplitude and the frequency band of the signal, preventing the latter from proceeding to the next stages

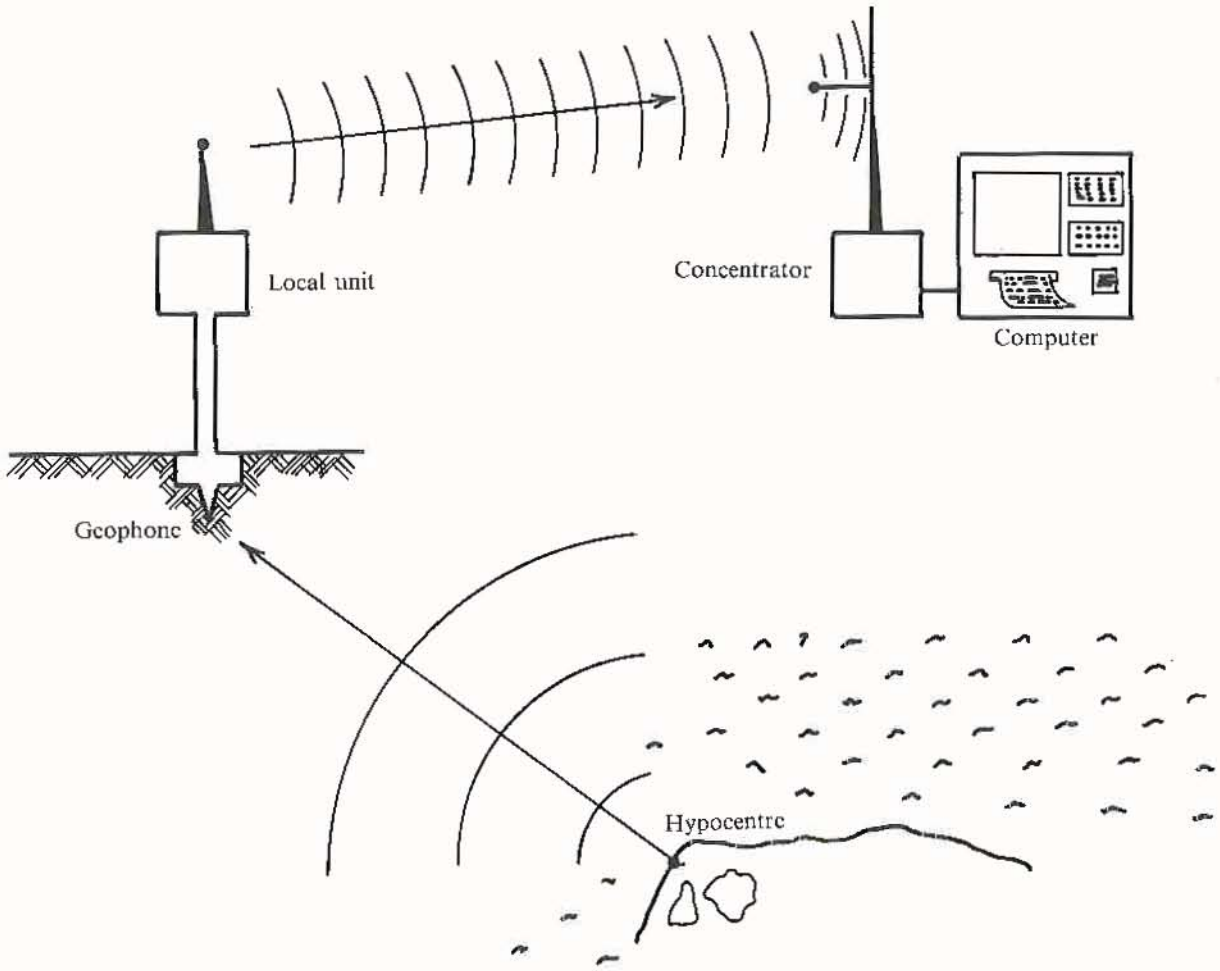


FIGURE 4. Configuration of the system of data collection and processing

if it presents inadequate characteristics.

In the cases where the system accepts the signal, still in analog form, a digital sampling of the same is performed using appropriate methods. The signal is then transmitted to the main memory of the local unit, the capacity of which is 512 Kbytes.

Each local unit activated by a given seismic impulse thus sends a warning signal to the concentrator and the latter activates a verification device to detect possible false alarms (e.g. accidental collisions with the local unit on the surface). If the event is recognized as valid, the concentrator proceeds with the collection of data from the different local units and activates the computer for the calculation of the hypocentre of the seismic impulse.

Figure 5 presents a general schematic illustration of the phases of work at the level of local units and concentrator, starting from a seismic impulse that reaches the surface geophones.

Figure 6 illustrates the locations of the hypocentres of microseismic activity in the area mined. This map makes it possible to infer the behaviour of the cavities formed by dissolution and to identify the onset of dangerous caving phenomena that could give rise to harmful events.

## General comments and conclusions

Using the operational hypotheses described in this paper, the proposed method for monitoring microseismic activity, occurring when dissolution cavities grow, provides important information on the ground conditions and hence can be a valid means for the prevention of harmful side-effects and for conserving the environment.

The same methodology can be usefully applied to monitoring underground mining operations where phenomena known as 'rock bursts' occur. In these cases, knowing the location of the hypocentres of the seismic impulses makes it possible to identify the zones of major concentration of mechanical stresses.

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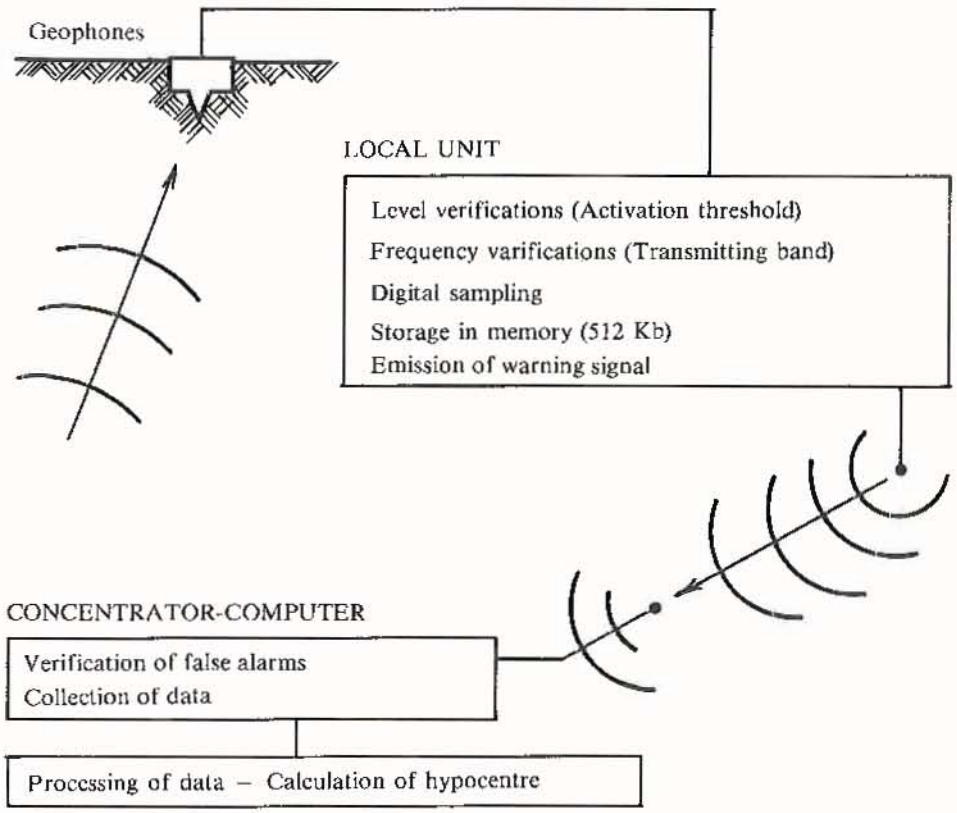


FIGURE 5. Operational characteristics of the data recording and processing system

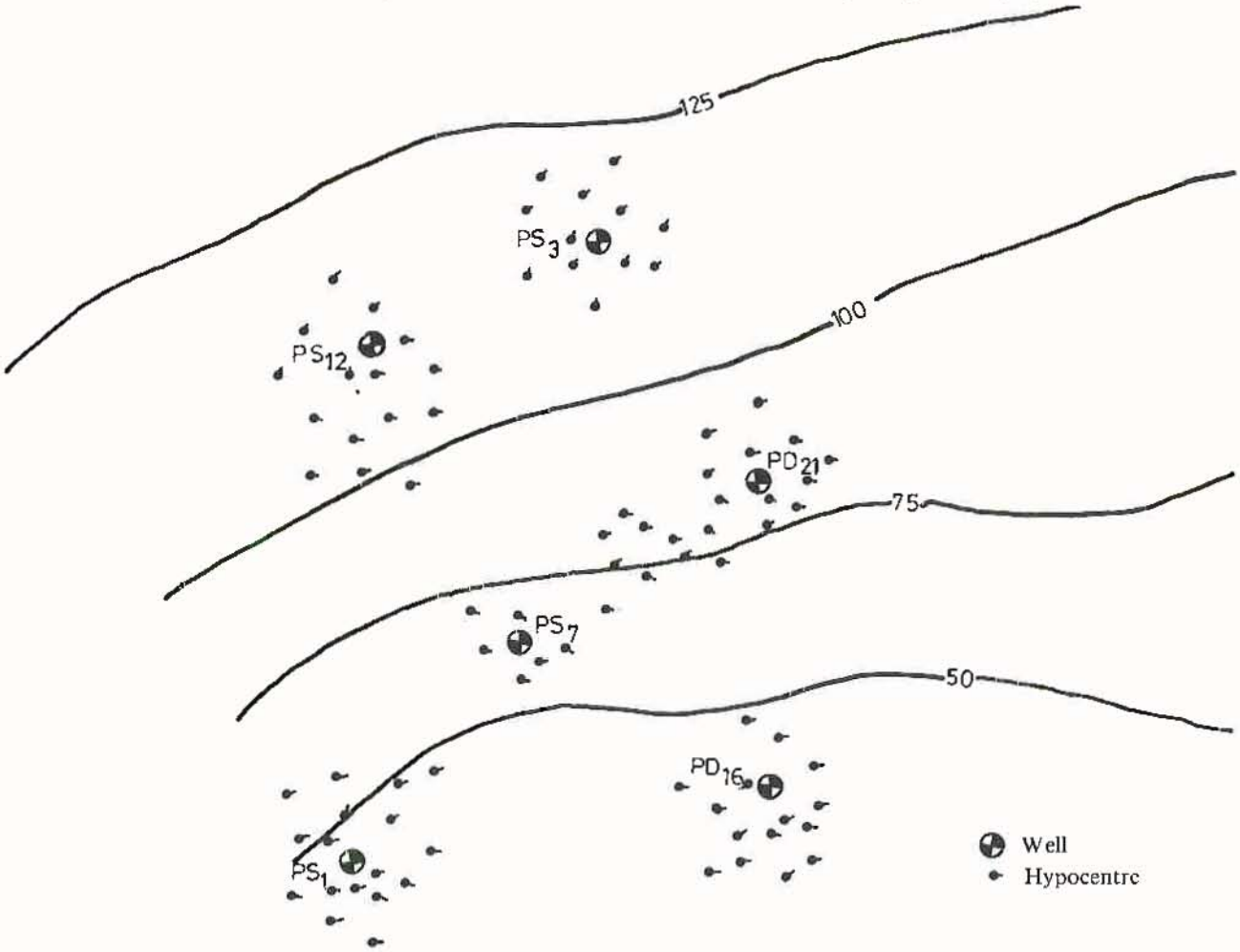


FIGURE 6. Microseismic activity – Map of hypocentres