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DEFORMATION AROUND A MINE SHAFT IN SALT

K. BARRON AND N.A. TOEWS

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DEFORMATION AROUND A MINE SHAFT IN SALT*

*K. Barron and N. A. Toews***

ABSTRACT

The recovery of potash from the vast deposits in Saskatchewan has presented conditions unique in Canadian mining history. Recognizing this, The International Minerals and Chemical Corporation (Canada) Ltd. proposed that research be initiated, in both the potash and the overlying salt, to obtain information pertinent to mine design, stability, safety and economy. This resulted in a cooperative research program involving the company, Dr. S. Serata, consultant, and the Mines Branch, Dept. of Mines and Technical Surveys, Ottawa.

Initial studies were made in the unlined portion of the shaft in the salt above the potash beds. Measurements were made of displacements, relative to the shaft axis, of points on the surface of the shaft and within the solid surrounding the shaft. A diametral extensometer and an extensometer to measure the longitudinal deformation of boreholes around the shaft were used.

The objective of these measurements was to obtain data on the creep (or deformation as a function of time) of salt around a simple opening and to correlate this data with theoretical ideas on the behaviour of the material.

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A successful correlation would contribute considerably to a better understanding of material behaviour and of loading conditions and thus aid the solution of the problems in the design of openings in salt. A further objective was to investigate whether such data might be used as an indication of shaft stability; this is particularly important in relation to both safety and maintenance.

This paper presents the measurements obtained and the approach taken to their interpretation by the Mines Branch. It is shown that the radial displacement, U_r, for a point in the solid at a radius r from the shaft axis may be expressed in the form: $U_r = -pB(a^2/r)\log_{10}(1 + bt)$ where B and b are constants, a is the shaft radius, t is the time and p is the pressure. In particular, the results obtained for points at depths of 4, 7 and 10 feet in the walls of the 18-foot diameter shaft are represented by: $U_r = -7.7\text{x}10^{-3}(a^2/r)\log_{10}\{1+(t/2.70)\}$ where U_r, a and r are in inches and t is the time in days. Surface points do not conform to the 1/r proportionality, but the time function is the same.

The form of the above results suggests that this type of measurement may be used to determine the shear creep function of the material in situ. This is important in correlating laboratory and field studies.

The divergence of the surface data from the general relationship at depth in the shaft wall indicates the possibility that a change in material properties has occured between the surface and 4-foot depth. There is insufficient data available to pronounce on shaft stability in this case other than to say that there is no evidence of a loss of stability owing to excessive deformation during the time of measurement. It appears, however, that a method might be developed, based on measurements of this type, for monitoring shaft stability with respect to the effects of excessive deformation.

On the basis of certain assumptions, a possible method of estimating stress from deformation measurements is proposed. The assumptions are, in part, substantiated by the data available. Additional measurements are suggested that are needed to confirm the above results.

With further work it should be possible to provide analytical data to assist in the judgment of shaft stability and in the design of excavations in salt.

INTRODUCTION

The sinking of the Yarbo No. 1 shaft at Esterhazy, Saskatchewan, to the potash deposits at greater than 3,000 feet below ground was an engineering feat unprecedented in Canadian mining history. The International Minerals and Chemical Corporation (Canada) Ltd., recognizing that the unique conditions surrounding the new undertaking might lead to unusual problems, proposed that research be initiated in both the potash and the overlying salt in order to obtain, at an early stage, information pertinent to mine design, stability, safety and economy. In consequence, a cooperative research program was conducted by the company, Dr. S. Serata, consultant, and the Mines Branch.

Initial studies were made in the unlined portion of the shaft in the salt above the potash beds. Measurements were made of displacements relative to the shaft axis, of points in the surface of the shaft wall and within the solid surrounding the shaft. Two types of observation were made to obtain this information, namely;

(i) Changes in the shaft diameter with time, using a diametral extensometer, and

(ii) Longitudinal deformation with time of various length boreholes in the shaft wall using a borehole extensometer.

The objective of these measurements was to obtain data on the creep (or deformation as a function of time) of salt around a simple opening and to correlate this data with theoretical ideas on the behaviour of the material. A successful correlation would contribute considerably to a better understanding of the material behaviour and of loading conditions and thus would aid the solution of the problems in the design of openings in salt. This shaft presented a unique opportunity to make such a study. A further objective was to determine whether such data might be used as an indication of shaft stability; this is particularly important in relation to both safety and maintenance.

The paper presents the measurements obtained from this initial program and discusses the approach taken to their interpretation by the Mines Branch.

METHOD OF MEASUREMENT AND RESULTS

A horizon in the 18-foot diameter shaft at a depth of 3,079 feet was ohosen as the observation site. Four measuring stations on this horizon were selected and numbered 1, 2, 3 and 4 in the north, east, south, and west walls respectively (Figure 1). At every station individual boreholes were drilled to take anchors at depths of 6 inches, 4 feet, 7 feet and 10 feet, respectively. Diametral deformations of the shaft were measured between stations 1 and 2 and between stations 3 and 4, using the anchors at 6-inch depths. At each station the longitudinal deformations of the 4-foot, 7-foot and 10-foot boreholes were measured between the surface of the shaft wall and the corresponding anchors.

All results were plotted as displacement, relative to a fixed shaft axis, against time. It was assumed that the surface (6-inch) anchors had both moved towards the shaft axis by equal amounts, dy/2. Hence, if an elongation, dx, of a borehole were measured, the displacement of the borehole anchor relative to the shaft axis would be dx - (dy/2).

Continuity of measurements was interrupted on two occasions, once by a break in the tape of the diametral extensometer and once by a break of a wire in a borehole. Repairs were made as quickly as possible and the gap in readings was bridged by extrapolation from the changes measured before and after the breaks. Thus, continuous graphs of displacement versus time were plotted. Figures 2, 3, 4 and 5 show the displacement relative to the shaft axis, with time for the surface, the 4-foot, the 7-foot and the 10-foot anchors respectively at each measuring station.

It may be seen from the graphs that all anchors converge towards the shaft axis and that the rate of displacement diminishes with time and with increasing radius from the shaft axis. At any particular radius there is relatively little spread between the readings from the four stations. This is consistent with the assumption that the changes in the diameter of the shaft are divided equally between opposite walls. It is also an indication that the salt body is homogeneous and isotropic and that the lateral compressive stress is uniform all round the shaft.

Since the agreement between corresponding measurements at different stations is reasonably close, it was decided that the average of these readings should be taken to provide mean displacement curves upon which the analysis would be based. Figure 6 shows the mean displacement curves.

ANALYSIS OF DATA

The radial displacement, U_r, of a point is a function of the radius, r, of that point and of the time, t. Assume that this function may be written as:

$$U_r = -A(r)\ \psi(t)$$

Now the creep of materials is due primarily to the change of shape and not of volume, instantaneous elastic effects being disregarded. Thus, with a cylindrial opening, U_r would be expected to be approximately proportional to $1/r$. (see Appendix I). U_r. r was therefore plotted against time as shown in Figure 7. It is seen from this figure that the U_r. r values for the 4-foot, 7-foot and 10-foot points are in good agreement, confirming the $1/r$ dependence of U_r. The surface points do not agree with this relationship; the significance of this fact is discussed later.

Empirical expressions of various forms may be used to approximate the time dependence of creep data of the type shown in Figure 7. Polynomial, exponential, or functional expressions could be used. Of the possible functional expressions for approximating creep data, the function -K log (1 + bt) has previously been applied successfully to initial (transient) creep in salt. This function does, of course, tend to infinity as t tends to infinity and so can only be used to represent experimental observations within a limited time range. It does, however, provide a conveniently simple expression for the data. Further, when the creep data is expressed in this manner the "true creep curve" can be estimated from zero time if the time interval between creation of the opening and start of measurements is known.

The expression $U_r r = -A \log (1 + bt)$ was therefore used to fit the creep data. Good fits were obtained both for the collective data representing the interior points and for the data representing the surface points. The same b value applies in both cases and only the A values differ.

The expression for the creep data from the 4-foot, 7-foot and 10-foot points is:

$$U_r r = -90.8 \log_{10} \{1 + (t/2.70)\}$$

and for the surface points:

$$U_r r = 76.6 \log_{10} \{1 + (t/2.70)\}$$

where U_r is the displacement in inches, r is the radius in inches, t is the time in days from start of measurement. The extent to which these expressions fit the data is shown in Figure 7, where the curves represent the expressions and the points are the observations.

DISCUSSION OF RESULTS AND THEIR SIGNIFICANCE

(a) In Relation to Theoretical Ideas on Material Behaviour

On the basis of the experimental results it is plausible to assume that the salt body is homogeneous and isotropic, and that $U_r r$ is independent of the polar angle θ. Further, because the salt creeps readily, it is reasonable to assume that the stress existing prior to the creation of the opening is uniform all round compression. If the above assumptions are made it can be shown (see Appendix II) that:

(i) The measured creep is proportional to the shear creep of the material.

(ii) The stress-strain relation of the material in shear creep is a linear function of the stress in the limited range of stress encountered.

(iii) The shaft radius, a, may be introduced into the creep expression to give,

$$U_r = -(a^2/r)pB \log (1 + bt)$$

where p is the initial pressure and B is a constant. Thus, introducing a into the expression for the 4-foot, 7-foot and 10-foot points gives:

$$U_r = -7.7 \times 10^{-3}(a^2/r)\log_{10} \{1 + (t/2.70)\}.$$

There is insufficient data to separate p and B in this expression.

Now the mechanical properties of an isotropic material are completely defined by the instantaneous elastic constants (compressibility and shear modulus), the shear creep function, and the dilatational creep function. The results indicate that the dilatational creep is negligible (otherwise the 1/r dependence would not hold) and the measurements exclude the instantaneous elastic response. Thus, as a consequence of (i) above, the deformation measurements in cylindrical shafts under all-round compression might provide a method of measuring the shear creep function in situ (or at least a function related to it by an arbitrary multiplication constant.) The ability to measure the shear creep function of the salt in situ would be valuable since it would provide a means of correlating laboratory and field creep studies.

It is apparent that the data obtained is limited in two ways:

(i) The measurements needed are insufficient to determine the ultimate behaviour of the displacements with increasing time. It would be useful to know whether or not the displacements approach limiting values. Further information could be obtained by resuming measurements when access to the shaft wall is again possible.

(ii) It is impossible to start measurements immediately on creation of the opening. Further, it is impossible to define the time between creation of the opening and the start of measurements, t_o, accurately. Since the strain rate at the start of measurements is quite high, an inaccuracy in t_o can give a large error in the estimation of the deformation, U_o, that has occurred prior to the start of measurements. It has been shown that, for the period of observation, the deformation can be accurately represented by the function $-K \log (1 + \alpha t)$. If this function is true for the initial part of the curve, i.e., $U_r = -K \log (1 + \alpha t_i)$ where t_i is the time from creation of the opening and measurements are started at a time t_o later, then the measured creep curve would be:

$$-K \log \{ (1 + \alpha t)/(i + \alpha t_o) \}$$

From the measurements it is known that:

$$\alpha/(1 + \alpha t_o) = 1/2.7$$

i.e., $t_o = 2.7 - (1/\alpha)$, but α is greater than zero; therefore t_o must be less than 2.7 days. However, since no record was made of t_o, there is no means of checking this conclusion, i.e., there is no means of checking whether this function is true for the initial part of the creep curve.

The results also suggest another possible method of measuring the whole of the shear creep curve in situ. Application of an all-round pressure in a borehole and simultaneous measurements of deformation would enable the entire creep curve to be determined in situ.

(b) *In Relation to Shaft Stability*

It is interesting to consider whether creep data of the type described here could be used to detect a condition of dangerous instability in the shaft walls. The most likely source of instability would seem to lie in the development of a zone of material, seriously weakened by excessive creep, surrounding the shaft. Such a zone could become unstable under its own weight as occurs in cases of slope instability.

Do the results indicate the existence of, or progressive growth of such a weakened zone? The fact that creep proceeds without change of volume between the 4-foot and 10-foot points indicates that, during the period of observation, there is no significant change in the material properties of the salt between these two depths. It is extremely unlikely that the material properties at the 10-foot depth are effected by creep, thus this means that the material properties at the 4-foot depth are also unaffected . In particular, there is no evidence of fracturing or loss of cohesion beyond the 4-foot depth.

The surface measurements, however, do diverge from the general relation, indicating that a change of material properties occurs between the surface and the 4-foot depth. Whether this is a gradual change or a sudden discontinuity cannot be determined from the data available. In the writers' opinion, the cause of this changed zone is more likely to be the result of blasting during excavation than the result of excessive creep. It is interesting to note that the surface displacement corresponds to that which would be expected at a depth of approximately two feet if there were no change in properties; i. e., the rate of displacement at the surface is less than would be expected for creep at constant volume when referred to deeper measuring points. It appears, therefore, that a surface layer of thickness something less than 4 feet was actually compacting.

Since the limiting deformation, if it occurs, had not been reached when measurements were discontinued and since no measurements were taken between the surface and 4-foot deep points, it is not known whether this changed zone is growing.

It can, therefore, be concluded that this type of measurement can potentially be used to obtain an indication of shaft stability with respect to the effects of excessive creep provided that measurements are continued until a limiting state of deformation is reached and that at least one more measuring point is installed in the surface to 4-foot zone. In this particular case there is insufficient data to pronounce on shaft stability other than to say that there is no evidence to indicate that the shaft has suffered a loss of stability owing to excessive creep during the period of observation.

A POSSIBLE METHOD OF ESTIMATING STRESS USING DEFORMATION MEASUREMENTS

The equation $U_r = -(a^2/r)\,p.\,B\,\psi(t)$ gives the deformation of a cylindrical shaft of radius a in a material with a shear creep function ψ (t) under uniform all-round compression p. B may be a function of p but is approximately constant over a range of p. A knowledge of B would, therefore, enable the stress to be estimated from deformation measurements. The best way of determining B is probably by a laboratory study. However, it may be possible to obtain an approximate value of B in the field, as follows:

Suppose that, over a relatively short length of shaft, the material remains homogeneous and that B is constant over the range of p represented by this short length of shaft. Also assume that the pressure difference between two levels defined by this length of shaft is given by the weight of the intervening material. If p_o is the pressure at one level, then the pressure at a level h feet below it is given by:

$$p_h = p_o + \rho g h$$

where ρ is the density of the intervening material and g the gravitational acceleration.

Then, if these assumptions are justified, the deformations are:

$$U_o = -p_o B(a^2/r)\,\psi(t)$$

and

$$U_h = -(p_o + \rho\,gh)(a^2/r)\,\psi(t)$$

i.e.

$$U_o - U_h = B\,\rho\,gh\,(a^2/r)\,\psi(t)$$

Hence B could be estimated from measurements at two levels h feet apart, and thus an estimate of p could be obtained.

Even if B is unknown, it is possible to compare the all-round pressure at one level with that at another level.

i.e.

$$U_o = -p_o(a^2/r)\,B\,\psi(t)$$

and

$$U_h = -p_h(a^2/r)\,B\psi(t)$$

therefore:

$$(p_o/p_h) = (U_o/U_h)$$

All the above considerations assume that uniform all-round pressure exists round the shaft. Therefore, such measurements should be made in a section of shaft where there is no possibility of the stress field being disturbed by the influence of other mine workings.

Under certain conditions it may be possible to consider the effects of disturbance due to mine workings in the vicinity. Assume that a shaft has been created in the material and has been left sufficiently long so that an approximate equilibrium condition has been attained. Suppose that a uniaxial stress field $\sigma(t)$ is then applied to it by virtue of mining in the vicinity and that while this stress field can vary in magnitude it does not vary in direction. In such a case it is possible, by the method indicated in Appendix III, to relate the resulting deformation to this uniaxial stress due to mining provided that the shear creep and volume creep functions as well as the instantaneous elastic moduli of the material are known. Further, it is possible to extend this method to the superposition of a biaxial stress field on the shaft due to mining activity, again assuming that the applied stress field does not vary in direction.

CONCLUSIONS

There is insufficient data available to draw anything but the most tentative conclusions and inferences from the results. These may be summarized as follows:

(1) All anchors converge towards the shaft axis and the rate of displacement diminishes with time and with increasing radius from the shaft axis.

(2) At any particular radius there is relatively little spread between displacement measured at each of the four stations. This is not inconsistent with the assumption that the shaft is subject to a uniform all-round compression.

Assuming that this type of stress field exists and that the radial displacement, Ur, at a radius r is some function of r and of time t, (i.e. $U_r = -A(r) \psi(t)$), then it can be shown that the displacement would be expected to be proportional to 1/r.

(3) The experimental results from the 4-foot, 7-foot and 10-foot points agree with this 1/r dependency. The results from the surface points do not agree with this relation.

(4) It is possible to fit the time dependency (creep function) by several expressions; one of the form $\psi(t) = -K \log(1 + bt)$ is convenient.

(5) For the 4-foot, 7-foot and 10-foot points the results can be expressed as a function of time, t, and radius, r, as:

$$U_r = -(90.8/r)\log_{10}\{1 + (t/2.70)\}$$

and, for the surface points:

$$U_r = -(70.6/r)\log_{10}\{(1 + (t/2.70)\}$$

i.e. 'b' is a constant for all results.

By assuming that compression is uniform all-round on the shaft and that the material is initially homogeneous and isotropic it can be shown that:

(6) The measured creep is solely due to shear creep of the material.

(7) The stress-strain relationship for the salt is linear with stress, at least in the range of stress involved in the experiment.

(8) The shaft radius, a, may be introduced into the creep expression:

$$U_r = -(a^2/r)\,p.\,B\log(1 + bt)$$

where p is the initial pressure and B is a constant.
For the 4-foot, 7-foot and 10-foot points this expression is:

$$U_r = -7.7 \times 10^{-3}\,(a^2/r)\log_{10}\{1 + (t/2.70)\}$$

(9) As a consequence of the agreement between the supposed 1/r dependence and the results, and as a consequence of (6) above, displacement measurements of this type provide a means of measuring in situ the shear creep function of salt. This is important in correlating laboratory and field creep studies.

(10) Measurements of the type made in this study have a potential use in indicating shaft stability with respect to the effects of excessive creep, provided that such measurements are continued until a limiting state of deformation is reached and that at least one more measuring point on the surface to 4-foot zone is installed.

(11) The divergence of the surface data from the data at depth suggests that a change of material properties has occured between the surface and the 4-foot depth. It is thought that this is more likely to be due to the effects of blasting during excavation rather

than to excessive creep.

(12) In this study there is insufficient data to pronounce on shaft stability other than to say that there is no evidence to indicate that the shaft has suffered a loss in stability due to excessive creep.

(13) The agreement obtained between measured data and assumptions made in theory suggests a possible method of using deformation measurements to estimate field stress.

In view of the tentative nature of many of the above points, it is thought that much could be learned from further measurements under similar conditions. For this reason it is recommended that during the sinking of a second shaft at Esterhazy, Saskatchewan, advantage should be taken to obtain additional information in the following ways:

(a) The measurements should be continued until it can be safely assumed that the displacement is approaching an asymptote.

(b) Additional measuring points should be installed at depths less than 4 feet from the surface.

(c) Note should be made of the shaft-sinking timetable in an effort to define t_o, the time between the creation of the opening and the start of measurement.

(d) Laboratory studies should be made on samples of salt from the study area in an attempt to define the constant B.

(e) Measurements should be made on at least two horizons a known distance apart in an attempt to estimate the field stress.

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APPENDIX I

1/r dependence of the deformation U_r

For most materials, the volume creep is insignificant when compared to the shear creep. That is, as the material creeps the volume of the material remains constant. Suppose that the displacement of the salt surrounding the shaft is U_1 at a radius of r_1 and is U_2 at radius r_2. Then the volume of material displaced across r_1 is $2\pi r_1 U_1$ and the volume of material displaced across r_2 is $2\pi r_2 U_2$ (where unit thickness is considered). Then since there is no change in volume:

$$2\pi r_1 U_1 = 2\pi r_2 U_2$$

i.e., $rU_r = A$ where A is a constant independent of r. Thus it is reasonable to expect that if the volume creep of the salt is relatively small compared to the shear creep, then U_r will be proportional to $1/r$.

APPENDIX II

Linearity of shear creep with stress

In the following it will be shown that, using experimental results and certain reasonable assumptions, the strain-stress-time relation for the salt undergoing shear creep is linear with the stress.

It is assumed that the salt is homogeneous and isotropic. In addition, it is considered as confirmed experimentally that the creep of the material surrounding the shaft can be represented by:

$$\left.\begin{aligned} U_r &= -(K/r)\psi(t) \\ U_\theta &= 0 \end{aligned}\right\} \qquad (1)$$

i.e., the displacement of the material at a given time is radial and varies inversely with the radius from the shaft axis. Implicit in the above expression is also the assumption that the deformation is independent of the polar coordinate θ. This is made plausible by the experimental fact that the creep in two perpendicular directions is the same.

From equation (1) the strains can be evaluated:

$$\left.\begin{aligned} E_r &= (\delta U_r/\delta r) = (K/r)\ \psi(t) \\ E_o &= (U/r) = -(K/r^2)\ \psi(t) \\ E_{r\theta} &= 0 \end{aligned}\right) \qquad (2)$$

Equation (2) shows that r, θ are the principal axes of strain and that a simple shear strain condition exists in the material surrounding the shaft.

A common assumption in rheology is that the shear and dilatational behaviour of a material can be separated. Assuming this, a general expression (not necessarily linear with stress) may be written for the material undergoing creep:

$$E_r + E_\theta = (\sigma_r + \sigma_\theta)\ f(\sigma_r + \sigma_\theta)\ g(t) \qquad (3)$$

$$\left.\begin{aligned} E^1_r &= \sigma^1_r\ k(\sigma^1_r)\ h(t) \\ E^1_\theta &= \sigma^1_\theta\ k(\sigma^1_\theta)\ h(t) \\ E^1_{r\theta} &= \sigma^1_{r\theta}\ k(\sigma^1_{r\theta})\ h(t) \end{aligned}\right) \qquad (4)$$

where g(t) and h(t) are the dilatational creep and shear creep functions and

$$E^1_r = E_r - (1/2)(E_r + E_\theta)$$

$$E^1_\theta = E_\theta - (1/2)(E_r + E_\theta)$$

From (2) $E_r + E_\theta = 0$

Therefore:

$$\left.\begin{aligned} E^1_r &= E_r \\ E^1_\theta &= E_\theta \end{aligned}\right) \qquad (5)$$

Hence, from (3) $\sigma_r + \sigma_\theta = 0$ i.e. $\sigma_r = -\sigma_\theta$

Therefore:

$$\sigma_r^1 = \sigma_r - (1/2)(\sigma_r + \sigma_\theta) = \sigma_r$$

$$\sigma_\theta^1 = \sigma_\theta - (1/2)(\sigma_r + \sigma_\theta) = \sigma_\theta \qquad (6)$$

Using the fact that $\sigma_\theta = -\sigma_r$ the equation of equilibrium of the material surrounding the shaft can be integrated. That is, from considerations of statics, for any material (linear or non linear):

$$(d\sigma_r/dr) + \{(\sigma_r - \sigma_\theta)/r\} = (d\sigma_r/dr) + (2\sigma_r/r) = 0$$

which gives on integration

$\sigma_r = -\sigma_\theta = (B/r^2)$ where B is an arbitrary constant. To evaluate B another assumption is made, namely that the stress existing prior to excavating the shaft is a uniform all-round compression, -p. For a material that creeps as readily as salt and that has had geological time to attain equilibrium, this is a reasonable assumption. The creation of the shaft is then equivalent to suddenly applying a tension at the circumference r = a of the shaft. Using this condition gives:

$$B = pa^2$$

$$\text{or } \sigma_r = -\sigma_\theta = pa^2/r \qquad (7)$$

Note: σ_r and σ_θ as given here are the changes in stress produced by the opening. To obtain absolute stresses - p must be added) substituting (7) into (4) and using (5) and (6) gives:

$$E_r = (pa^2/r)\ k(\sigma_r)\,h(t)$$

$$E_\theta = -(pa^2/r)\ k(\sigma_\theta)\,h(t) \qquad (8)$$

Thus, from (2) and (8):

$$E_r = (K/r^2)\ \psi(t) = (pa^2/r)\ k(\sigma_r)\ h(t)$$

$$E_\theta = -(K/r^2)\ \psi(t) = -(pa^2/r)\ k(\sigma_\theta)\ h(t)$$

Thus $k(\sigma_r)$ and $k(\sigma_\theta)$ are equal and, since p and a are constants, they are constant. Furthermore $\psi(t)$ must be proportioned to h(t) the creep function.

Since $k(\sigma_r)$ and $k(\sigma_\theta)$ are constants it follows from (4) that the stress-strain relation for the material in shear creep is linear with stress, at least in the range of stress occurring during the course of measurements.

If a value of 3000 psi is assumed for p, then the change in stress at the 10-foot and 4-foot points caused by excavating the shaft is approximately 700 and 1500 psi respectively; that is, the stress-strain relationship for the salt undergoing creep under simple shear is linear with the stress in a range 700 to 1500 psi during the time of measurement.

APPENDIX III

Superposition of a stress field due to mining in the vicinity of a borehole

It is assumed that a borehole has stood for sufficient time that a condition of approximate equilibrium has been obtained in the material surrounding it. It is also assumed that $\psi_s(t)$ and $\psi_v(t)$ the shear and dilatational creep functions of the material are known from laboratory measurements or from a combination of laboratory and field measurements.

Suppose that, due to mining in the vicinity, a uniaxial stress field $\sigma(t)$ normal to the axis of the borehole is superimposed on the original stress field existing in the material and that while $\sigma(t)$ can vary in magnitude it does not vary in direction. If $u(t)$ is the wall displacement, due to $\sigma(t)$, measured in the direction of $\sigma(t)$, then it can be shown that the following relation holds good between the Laplace transform of $\sigma(t)$ and the Laplace transforms of $u(t)$, $\psi_s(t)$ and $\psi_v(t)$:

$$\overline{\sigma(s)} = \frac{\overline{u(s)}}{a\ s\ \left[2\overline{\psi_s(s)} + \overline{\psi_v(s)}\right]}$$

Where the bars indicate the Laplace transforms and a is the borehole radius, all the Laplace transforms on the right hand side of the equation can be calculated from the known functions and thus $\overline{\sigma(s)}$ can be derived. Since $\sigma(t)$ is the inverse transform of $\overline{\sigma(s)}$, $\sigma(t)$ can be obtained. This method can be extended to a biaxial stress field by superposition provided that the direction of the applied stress field does not change with time.

Practical application of this method might prove difficult in the case of a shaft owing to the requirement that load direction does not vary. It might prove difficult to determine whether load direction is constant or slowly varying. The method might prove more useful with boreholes in pillars where an assumption of constant load direction may be more justified and perhaps more easily verified.

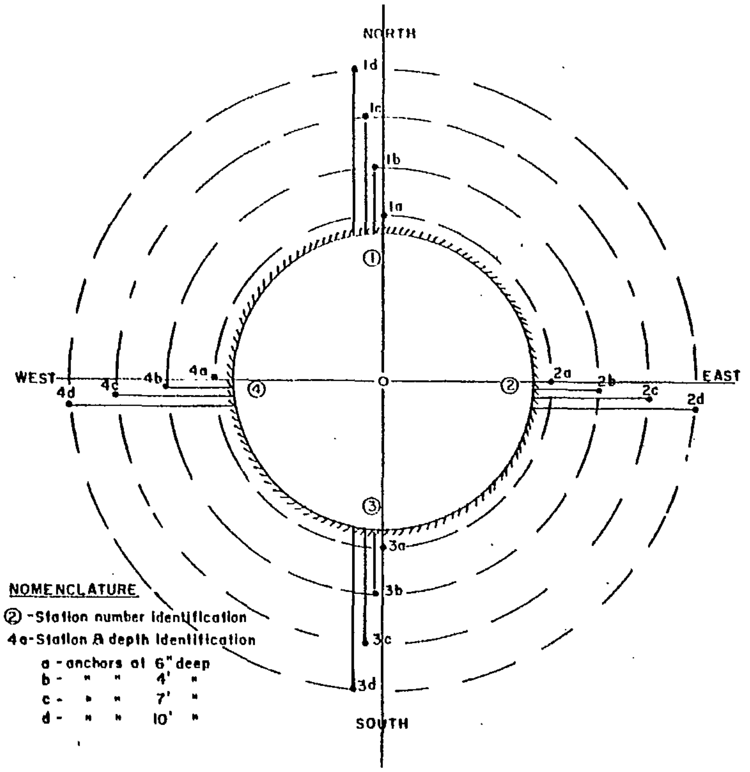

FIGURE 1 - LAYOUT OF THE MEASURING POINTS

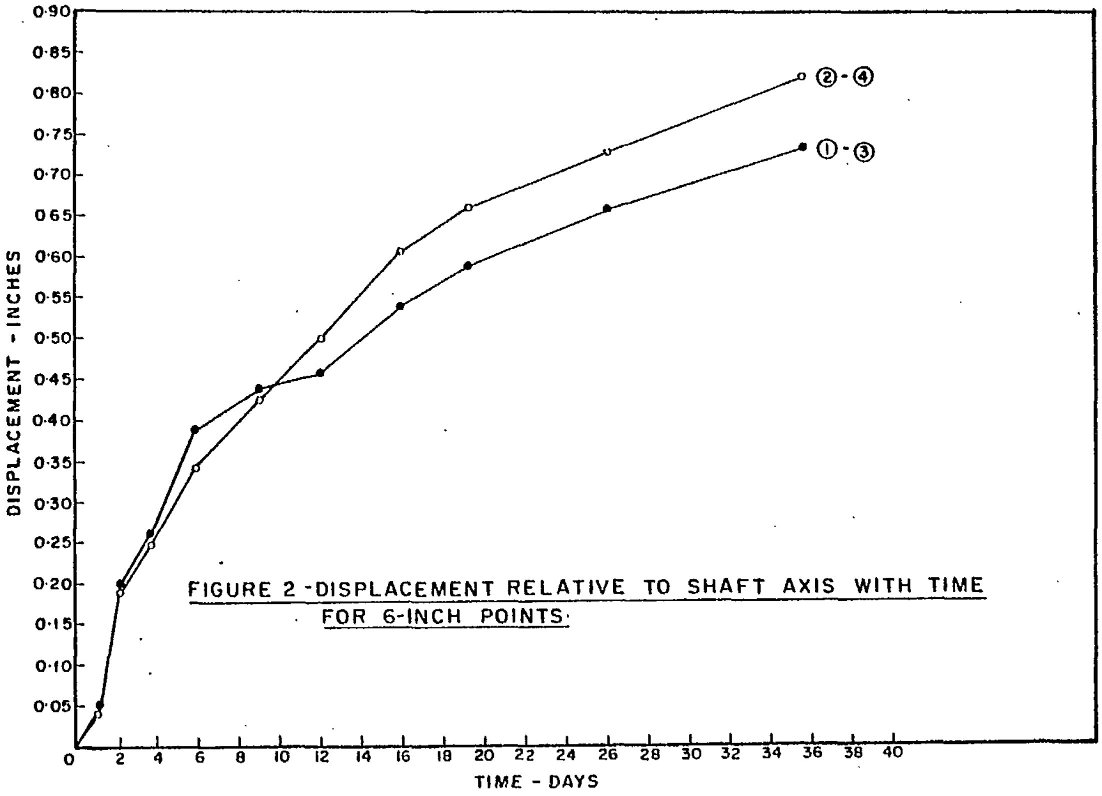

FIGURE 2 - DISPLACEMENT RELATIVE TO SHAFT AXIS WITH TIME FOR 6-INCH POINTS

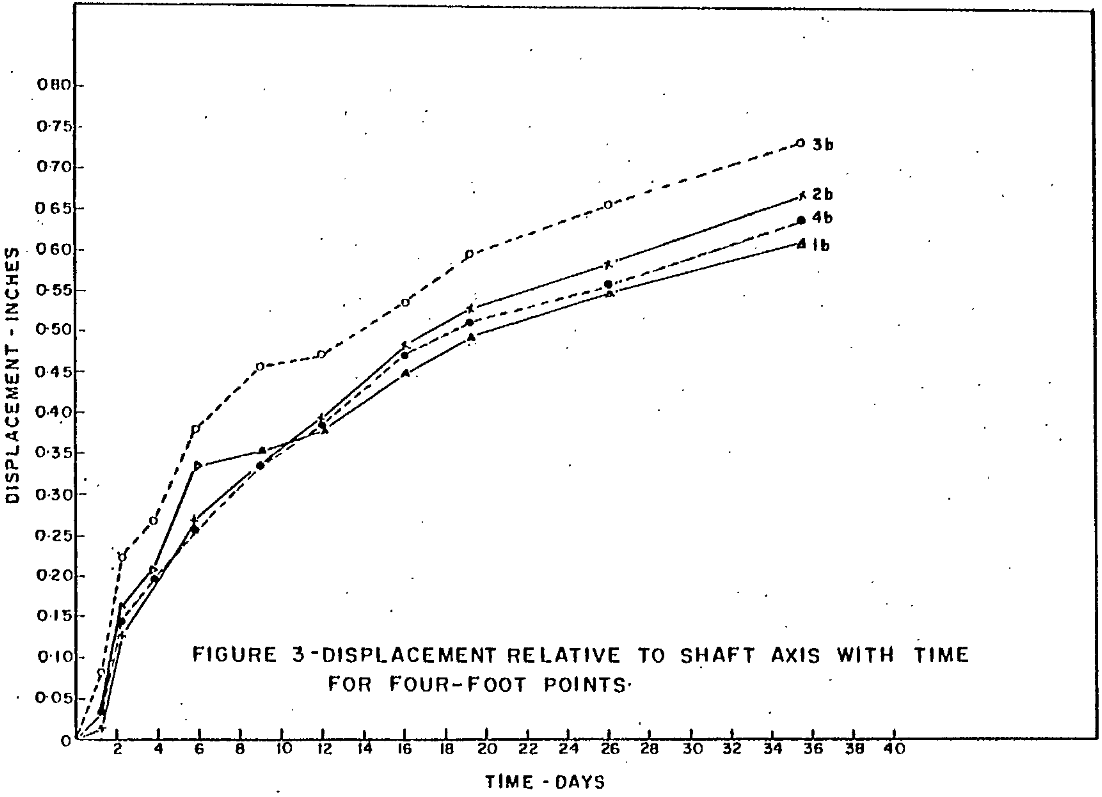

FIGURE 3-DISPLACEMENT RELATIVE TO SHAFT AXIS WITH TIME FOR FOUR-FOOT POINTS.

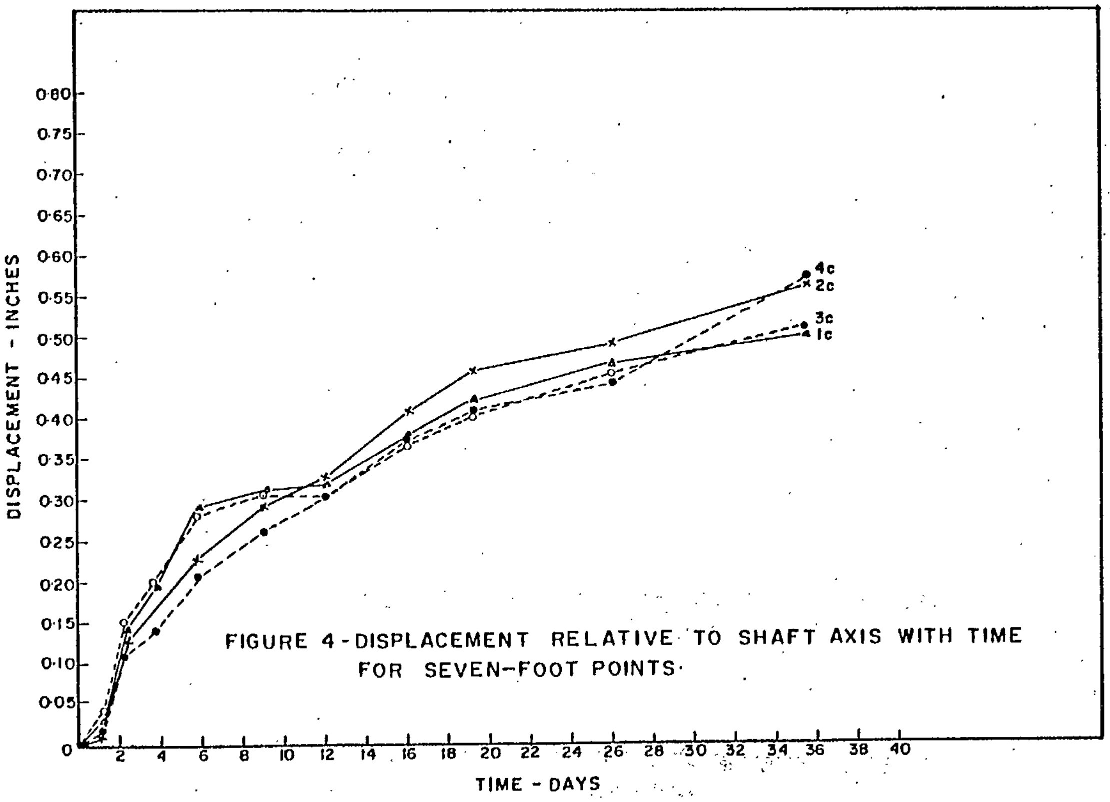

FIGURE 4-DISPLACEMENT RELATIVE TO SHAFT AXIS WITH TIME FOR SEVEN-FOOT POINTS.

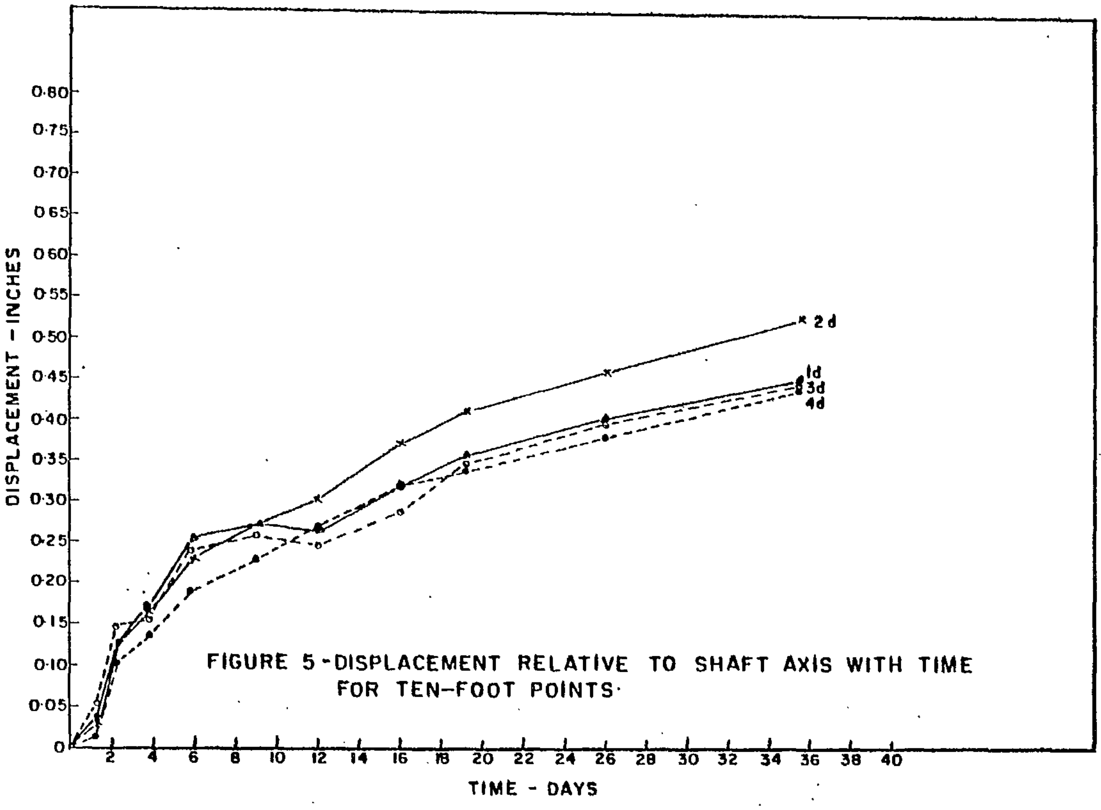

FIGURE 5 - DISPLACEMENT RELATIVE TO SHAFT AXIS WITH TIME FOR TEN-FOOT POINTS.

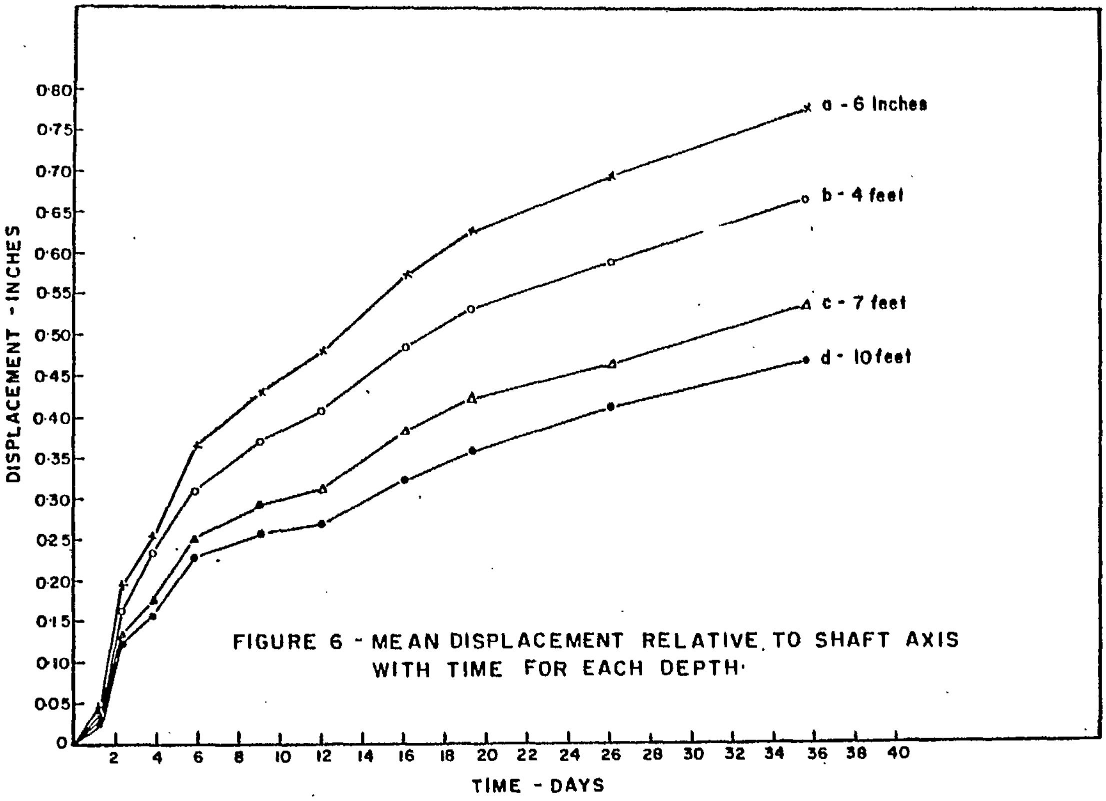

FIGURE 6 - MEAN DISPLACEMENT RELATIVE TO SHAFT AXIS WITH TIME FOR EACH DEPTH.

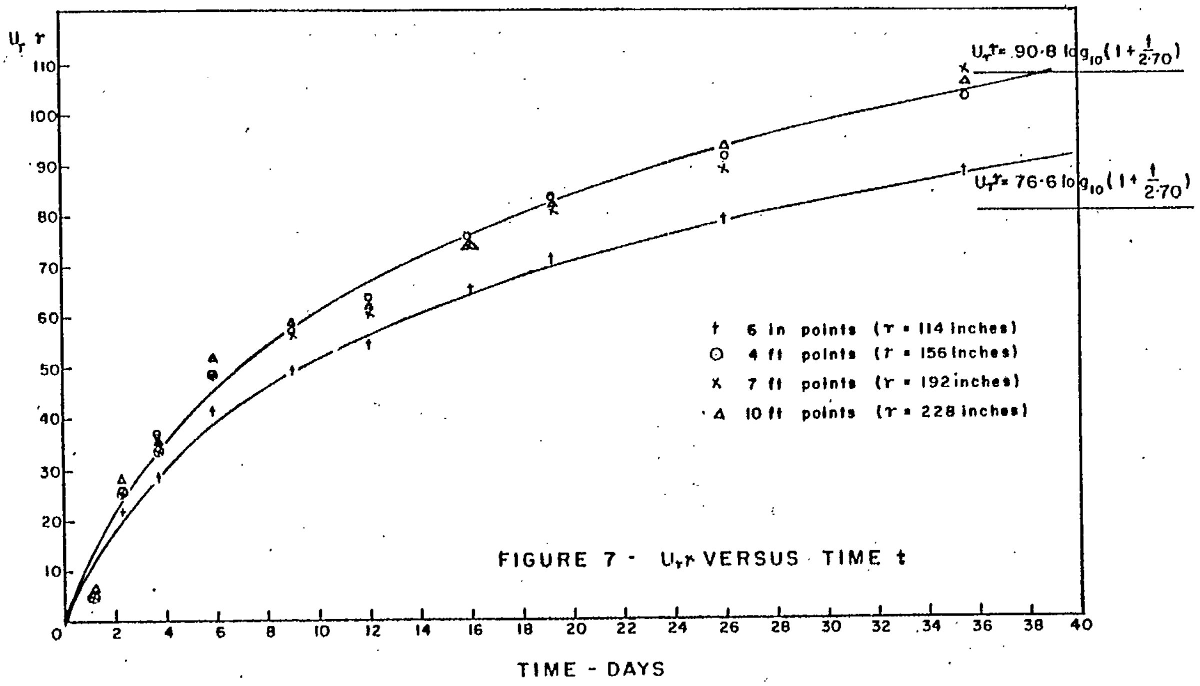

FIGURE 7 - $U_r r$ VERSUS TIME t

DISCUSSION

D.F. Coates, Head, Mining Research Laboratories, Fuels & Mining Practice Div., Mines Branch, Dept. Mines & Technical Surveys, Ottawa.

The data presented in this paper is very interesting for, among other aspects, it indicates that the salt is a linear material. This means that the rate of deformation varies directly with the level of stress.

On the other hand, we have heard in Dr. D. Deere's discussion that their testing on salt from another area indicated that, in this case, the salt was non-linear. In other words, the rate of deformation did not vary directly with the stress level but actually varied with the stress raised to the power of 2.8.

I would just like to point out, in view of these two sets of data, to those who are particularly concerned with problems of salt stability, that even though it is a comparatively uniform material few assumptions can yet be made about its behaviour. In other words, in any particular case it would be imprudent to assume, for example, that it was a linear material without first having obtained some test data to support such a postulate.

DISCUSSION

F.A. Reinarz, Consolidated Mining and Smelting Co. of Canada, Ltd., Kimberley, B.C.

1. Were any mineralogical studies carried out in the salt formation at the same time?
2. Were crystallographic orientations of the salt minerals involved in this particular section of the shaft determined?
3. Did associated phenomena like cleavage, flowage and preferred solubility play any role?

AUTHOR'S REPLY

1. No mineralogical studies were made in relation to this measurement program. However I can give you a general idea of the salt geology and minerology in the vicinity of the station. Six feet above the station is a

1.5-inch seam of grey and red mud, six feet below the station there is a 1-inch seam of red mud. The beds between these seams consist of halite with about 1.5 per cent sylvite and 1 to 10 per cent insolubles.

2. No determination was made of crystallographic orientation in the salt. However a study of crystal orientation in the potash orebed indicates that any preference obtained is in no case marked. Although no determinations were made in the salt at the station I would not expect a preferred orientation in a sedimentary salt deposit at this depth. Certainly the gross deformation measurements do not indicate any preferred direction of creep.

3. I do not know if the associated phenomena you mention played any part in the creep mechanism, quite probably they did. Our main interest was in the gross creep behaviour of salt en masse. We certainly measured flowage or creep but the mechanism within the material causing creep was not investigated. Quite probably cleavage planes between grain boundaries are a contributory factor to creep. Since the salt beds are very nearly pure salt I would not anticipate any role for preferred solubility within the creep mechanism.

I would like to thank Mr. Reinarz for his questions, he has clearly indicated the need for and the interest in an understanding of creep mechanisms.

ROCK MECHANICS AT INTERNATIONAL MINERALS & CHEMICAL CORPORATION (CANADA) LIMITED

George Zahary*

Abstract

Considerable emphasis has been placed on rock mechanics at this highly mechanized potash mine to insure that safe mining conditions prevail. Underground conditions are ideal for the study of ground movement. To insure maximum safety, tests to destruction in the mine are not permitted. Evaluations of ground stability are based on laboratory work and underground measurements. Ground movement is measured on bolts anchored in the roof, floor, and walls of the openings with specially designed instruments. The pattern of vertical and horizontal closure of an opening with time is shown, and strain patterns in the roof and walls are calculated.

Introduction

Mining and refining facilities of International Minerals and Chemical Corporation (Canada) Limited are located near Esterhazy at the eastern end of the Saskatchewan potash deposits.

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*International Minerals and Chemical Corporation (Canada) Limited, Esterhazy, Sask.

The first shaft was started in 1957 and completed five years later at a cost of $11 million. The difficulties encountered and the methods used in shaft sinking have been described by Scott (1). Production began in late 1962 at a rated capacity of one million tons of product per year and is presently being expanded to 1.6 million tons. A second shaft is now under construction and on completion of this work, combined potential hoisting capacity of the two shafts will be at the equivalent of about four million tons of product annually.

Early in the development of this property it was recognized that ground control would be an important factor in its success. There was, however, very little information available on the stability of openings in salt formation at this depth. As a result, research work was initiated to provide a basis on which mine openings could be dimensioned.

Laboratory testing of salt specimens was undertaken and theoretical values of movement in the periphery of an opening in salt were calculated. The first underground deformation measurements were made in the shaft during the final stages of sinking (2). Although the site was operational for only a short period, it provided an opportunity to field-test concepts of salt stability developed for laboratory work. Theoretical values of shaft deformation were closely approximated by the actual measurements and the validity of the laboratory work was accepted. Similarly, laboratory test results were used in the design of the initial mine openings.

As mining advanced on the level, sites were installed where closure measurements could be made over long periods. Measurements are now being obtained at 69 locations using the instruments and techniques developed for the original shaft station.

The research work being carried out at this mine is of particular interest because of the ideal underground conditions. The essentially flat lying ore zone is a mineralized portion of the larger Prairie Evaporite formation. This formation is uniform over large horizontal distances and free of structure normally associated with tectonic activity. As a first approximation the immediate salt surrounding the workings may be considered to be homogeneous, isotropic and continuous. The salt sustains extensive deformation without fracturing and ground pressure is sufficient to cause easily measured movement. Mining is carried out on one level, openings are unsupported and explosives are not used. Finally, every effort is being made to arrive at a rational mine design based on experimental evidence.

Rock mechanics work has now been carried out for slightly more than two years. Under present extraction ratios, ground conditions are ideal and research is concerned with the general problem of opening and pillar stability. As experience is gained and extraction is increased, greater emphasis will undoubtedly be placed on more specific problems. In the meantime, a description of the factors that must be evaluated in carrying out a mine design under local mining conditions is of interest. The general approach adopted in arriving at present room-and-pillar dimensions is indicated and some examples of salt deformation found in the mine are presented.

Geology

For the present purpose the geological section is generalized as shown in Table 1.

The workings are overlain by 100 ft of rock salt followed by a thin bed of competent dry shale. The strata in the next 1565 ft are generally competent and locally water bearing. Above this - 1,700 to 1,900 ft above the mining level - is the locally incompetent and water-bearing Blairmore formation. This was the most difficult ground to penetrate and has been sealed off in the shaft with a concrete-and-cast-iron lining. The remaining ground to the surface consists of shales and glacial till.

TABLE 1

Generalized Shaft Section

DEPTH	DESCRIPTION OF STRATA		
	300' Glacial till	Incompetent	Water in zones
1240'	940' Shale	Incompetent in zones	Dry
1440'	200' Sandstone and shale (Blairmore Formation)	Incompetent	Water to 475 # psi
	1045' Limestone, dolomite, anhydrite and shale	Competent to Very Weak	Water in zones
	350' Limestone and anhydrite	Competent	Water to 1100 # psi
	170' Limestone and dolomite	Competent	Water in zones
3035'	30' Shale	Competent	Dry
	345' Evaporites 105' Rock salt with potash zones and clay bands. *MINING HORIZON* 240' Rock salt with anhydrite bands.	Competent	Dry
3380	Shaft Bottom.		

Below the mining horizon, rock salt interbedded with anhydrite extends to the shaft bottom and beyond.

Of the three distinct potassium-bearing zones evident, mining is located at the base of the lowermost zone at an elevation of 3,140 ft. The seven-and-a-half-ft mining height includes three beds that are distinguished mainly by grade and clay content. The chief minerals are halite (NaCl) and sylvite (KCl) occurring as the mechanical mixture sylvinite together with carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$) in some areas. Disseminated clay up to about 2 per cent in content occurs in the bottom of the bed.

The ore is coarse-grained and massive with crystals averaging 1/2 in. to 3/4 in. across (3). Well defined or continuous bands of clay or anhydrite are not found in the vicinity of the mine openings.

Mining Methods

Access to the mine is gained through a single 18-ft-diam shaft which is protected by a shaft pillar 2400 ft in diam.

Mining is carried out on one level on a room-and-pillar pattern. Openings are oval shaped, seven and a half ft high by twenty-one ft wide (Figure 1), and pillars are rectangular. The major mining equipment includes boring type continuous miners, gathering arm loaders, shuttle cars, and rope belt conveyors (4).

Major development consists of a main entry from which block entries are cut at right angles. The entries are a system of usually four or five headings with large pillars on either side.

Panels are developed from the block entries by driving three headings up the centre of the panel and mining by retreat. Panel dimensions are set by the capacity of the equipment and are now 2400 ft long and 1400 ft wide.

The mining faces advance rapidly and active working areas are widely dispersed. After two years, production mining has been carried out one and a half miles on either side of the shaft (Figure 2) and approximately 100 miles of openings have been cut. About one-third of the ore is removed and the remainder is left in the pillars.

Approach to Basic Design

The approach adopted in arriving at the basic mining plan was somewhat unique in that a rational basis for designing the openings was formulated prior to the start of production mining. Although practical mining judgment played a significant part in the final decisions, the theoretical work was of prime importance.

Laboratory studies were carried out and general design criteria were formulated. These were applied to the assumed mining conditions and basic dimensions of rooms and pillars were established. As openings were cut, field measurements were undertaken to refine the design procedures.

Laboratory work and analyses were carried out by a consultant whose views on the stability of openings in slat have been published (5). Except for the comment that opening stability is related to deformation in the surrounding salt and that deformation is primarily a time dependent process, this work is not discussed here.

Research Objectives

The original design of the openings and pillars has proven to be a completely safe design in the past two years of operation. Current work is aimed at determining the maximum extraction ratio and the optimum relative dimensions of rooms and pillars consistent with safety and efficiency.

The basic requirement of the mining operation is a large tonnage from a thin orebody at low extraction. This is achieved by a highly mechanized, mobile face operation which results in rapidly advancing working faces. To maintain the pace the openings must be normally self-supporting and subject to a relatively slow rate of closure for the effective use of boring equipment.

Long haulage and access openings to the shaft compensate for the tabular shape of the orebody and the high cost of shaft sinking. The drive that will connect the two shafts will consist of five headings nine miles long. These openings will be required for ventilation and access for the life of the mine. Support of such a vast amount of ground is most economically done on pillars that will remain stable for a long period.

General stability and safety of the mine depend largely on the reaction of the overlying ground to mining. An object of our rock-mechanics studies is to predict and measure this reaction and thus insure the safety of the mine. Testing to destruction in the mine is not an acceptable means of obtaining information, therefore the emphasis has been placed on theoretical evaluations of structural stability backed by deformation measurements.

Underground Deformation Measurements

Deformation measurements are now being made at two types of sites, classified as 'main' and 'subsidiary'. 'Main' sites are extensive installations where the boundary closure and the dilation of the surrounding salt are measured in detail. 'Subsidiary' sites, where convergence of the roof and floor is measured, are simpler and more numerous.

A schematic sketch of a 'main' site is shown in Figure 3. It consists of a number of plates fastened to the perimeter of the opening by short rock bolts. Behind each plate, a series of pins varying in length up to 20 ft, are installed. The pins are coupled, 5/8-in. bolts anchored at the bottom of the hole by expansion shells.

Convergence of two opposite plates is measured with a tape-dial extensometer, Figure 4, while the relative movement between the plate and each pin is measured with a borehole extensometer, Figure 5. Assuming the two plates have contributed equally to the measured plate convergence, the movement of each of the pins may be calculated.

The measuring system was designed by the Mines Branch, federal Department of Mines and Technical Surveys, Ottawa, for the original deformation site in the shaft. The tape-dial extensometer combines a dial gauge with a spring loaded tensioning device and a steel tape with holes punched at intervals of 3/4 in. In use, the instrument is mounted between two points by reeling out tape until a hole in the tape and a bolt on the body coincide. The tape is bolted to the body and the tensioning device is adjusted to a standard value. The change in distance between the two points is calculated from the dial gauge readings and the distance between the holes in the tape. The borehole extensometer is essentially a dial gauge that is read on a dial face.

Readings are taken to 1/1000's of an inch and are considered to be accurate to 5/1000's of an inch. Frequency of the readings depends on the nature of the installation and varies between once or twice a day to once every three months at some of the older sites.

Calculations are now carried out on an IBM 140 computer and programs are being written to summarize the data for analysis. A permanent record of the measurements, the history of each site and the progress of mining in the area is maintained. Graphs showing the progress of movement are plotted as the readings are taken and periodic comparisons with theoretical predictions are made when sufficient data have accumulated.

At present, a complete description of the underground measurements and the analyses are not available for publication. The results selected give a good indication of the type of information available from the installations and the pattern of deformation occurring around an opening and in a pillar.

Site 000B

Site 000B is located across a dead-end opening in the shaft pillar about 50 ft off the main entry. Plots have been prepared to illustrate various characteristics of the measurements.

In Figure 6 total opening closure, as measured on rock bolts installed on the opening centre lines at a depth of 6 in. is shown in detail for the first month. The uniform pattern of the individual readings illustrates the capabilities of the instrumentation and the consistency of loading and deformation in the mine. Vertical closure is less than the horizontal although the exact magnitude is obscured by the fact that vertical measurements were started about two days later than the horizontal.

Figure 7 shows the total horizontal closure of the opening for the first 450 days after mining. The rate of closure decreases with distance into the wall and with increasing age of the opening.

Figure 8 has been plotted from Figure 7 and shows the pattern of horizontal movement in one wall. The curves indicate that room closure is due largely to expansion of the salt within 10 ft of the edge of the opening.

Strain in the wall has been calculated from the slope of the curves in Figure 8 and plotted in Figure 9. The horizontal strains decrease rapidly in the first 5 ft and at a progressively slower rate over the following 15 ft. At all points in the wall the increase in strain between 10 and 450 days is approximately proportional, by a factor of 3, to the strain measured in the first 10 days. However, the strain history at the different points varies with distance from the edge of the opening as shown in Figure 10. The salt within one ft of the edge of the opening deforms at a constant rate for the first 200 to 250 days after which the strain rate decreases to about one fifth of the original value; 15 ft from the edge of the opening, the strain rate is constant over the full 450-day period. The strain rate near the edge of the opening tends to approach the strain rate at a greater depth in the wall (Figure 11).

Total vertical closure has been plotted in Figure 12. Since a 20-ft pin was not installed in the floor at this site, the closure on the 20-ft pin is assumed to be twice the movement on the 20-ft roof pin. The similarity between readings in the floor and roof on the 5- and 10-ft pins at this site makes this a reasonable assumption.

The curves of vertical movement in the roof and floor (Figure 13) have been used to calculate vertical strain. The results, plotted in Figure 14, indicate a concentration of strain about 6 to 7 ft above and below the opening. The concentration becomes sharper as the opening grows older.

Site 121-A

Site 121-A is located across a room near the centre of a mining panel. The horizontal pins are installed in the narrow wall of the pillar.

Horizontal movement has been plotted against the distance from the edge of the pillar in Figure 15. Ten days after mining the movement on the 20-ft pin is slightly negative, that is, movement is toward the centre of the pillar. Since this anomalous behaviour is not due to reading error, it is assumed to be some fault in the measuring system being used. The curve showing horizontal movement for 100 days after mining has been extended to the centre line of the pillar on the assumption that the centre line of the pillar does not move.

Horizontal strain in the pillar has been calculated from the curves of horizontal movement. The results, plotted in Figure 16, indicate a minimum value of strain about 15 ft from the edge of the pillar.

Although the results presented are only a small part of the total available, they indicate the general pattern of movement in the immediate boundary of the mine openings. This information is used in estimating the stability of the individual rooms and in conjunction with the data from the 'subsidiary' sites is used in estimating the general stability of the panels.

Summation

The original research work provided criteria for the dimensioning of openings and pillars and a limiting extraction ratio beyond which conventional mining operations would not be feasible. Panels are being mined at different extractions and long-term measurements are being obtained to test the precision of the original design criteria. In addition, a completely independent evaluation of the deformation measurements is being carried out in conjunction with the Mines Branch staff in Ottawa.

Detailed studies are now being carried out to test the validity of some of the original assumptions. A program to measure accurately the thickness of salt cover by seismic testing is now in progress. Other projects, the influence of carnallite content, the effect of bedding, the influence of room width, etc. on room stability are being planned or are in progress.

This information will be of value in designing a safe mine.

Acknowledgments

The writer is grateful to R.D. Lindberg, General Manager, International Minerals and Chemical Corporation (Canada) Limited for permission to present this paper. The generous assistance of various staff members in preparing the paper is acknowledged and appreciated.

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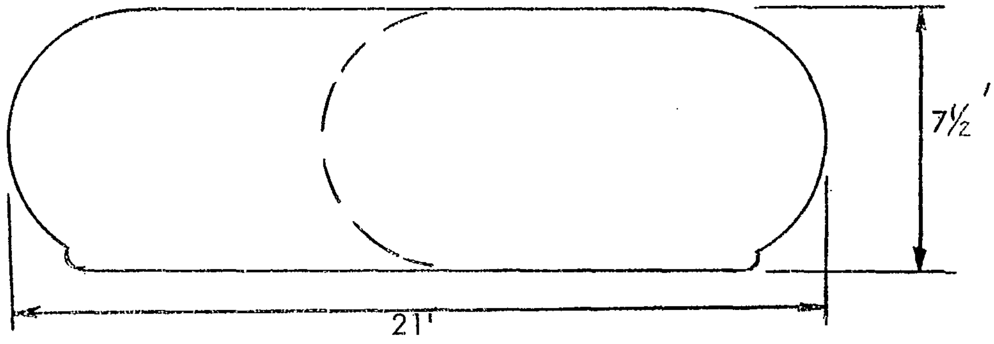

Figure 1. Standard opening dimensions.

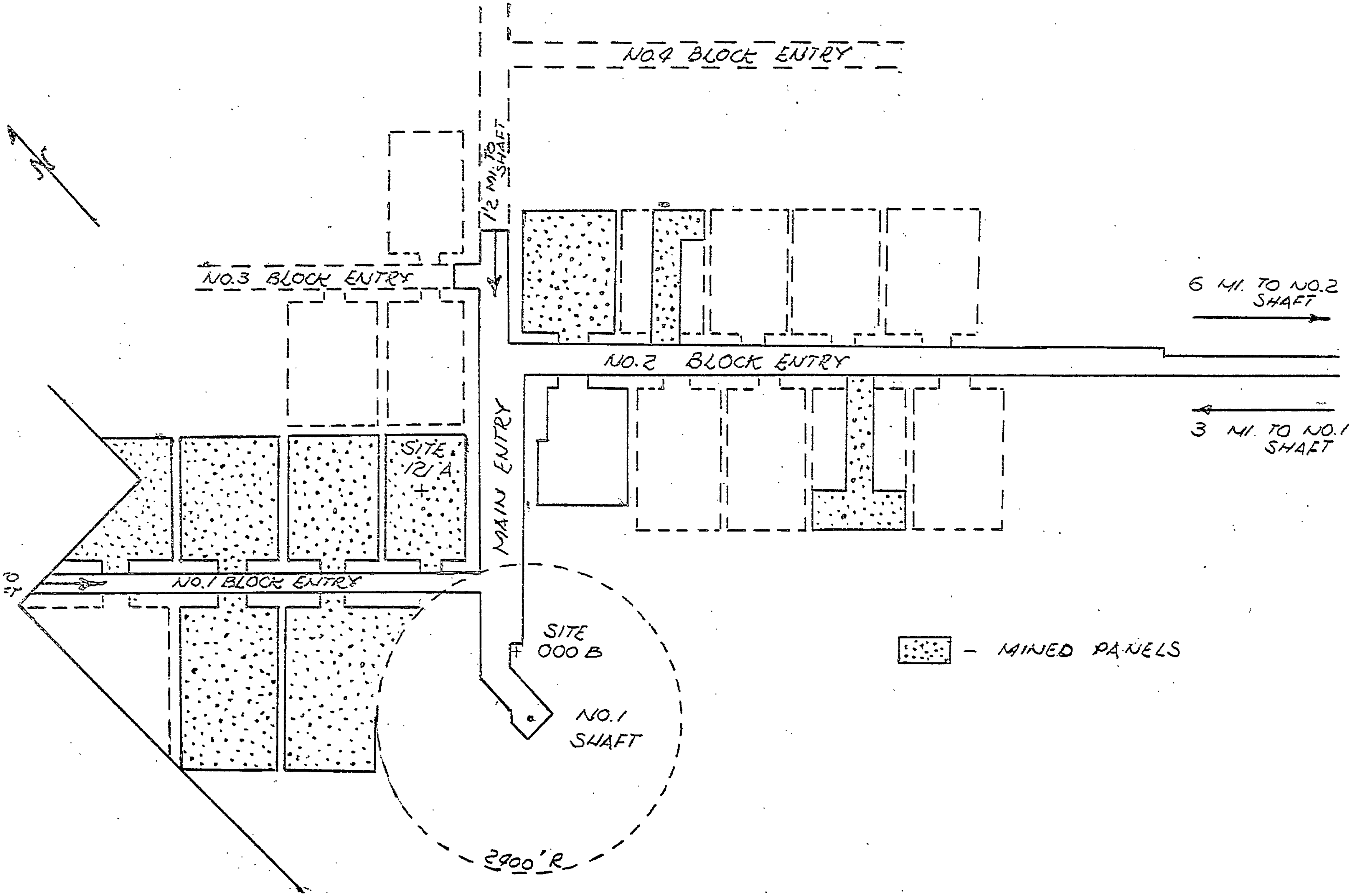

Figure 2. Sketch showing mine plan, IMC, Esterhazy, Sask.

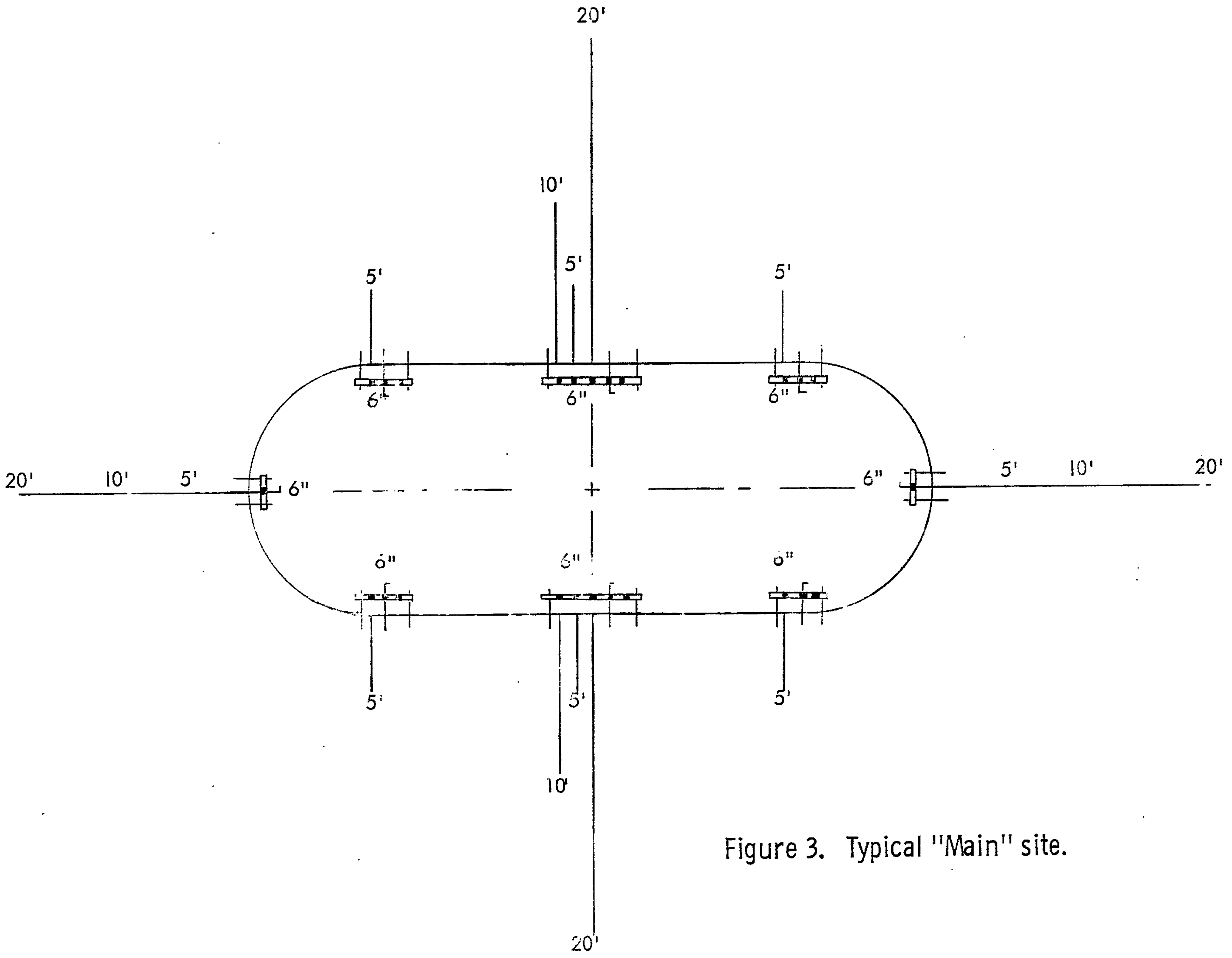

Figure 3. Typical "Main" site.

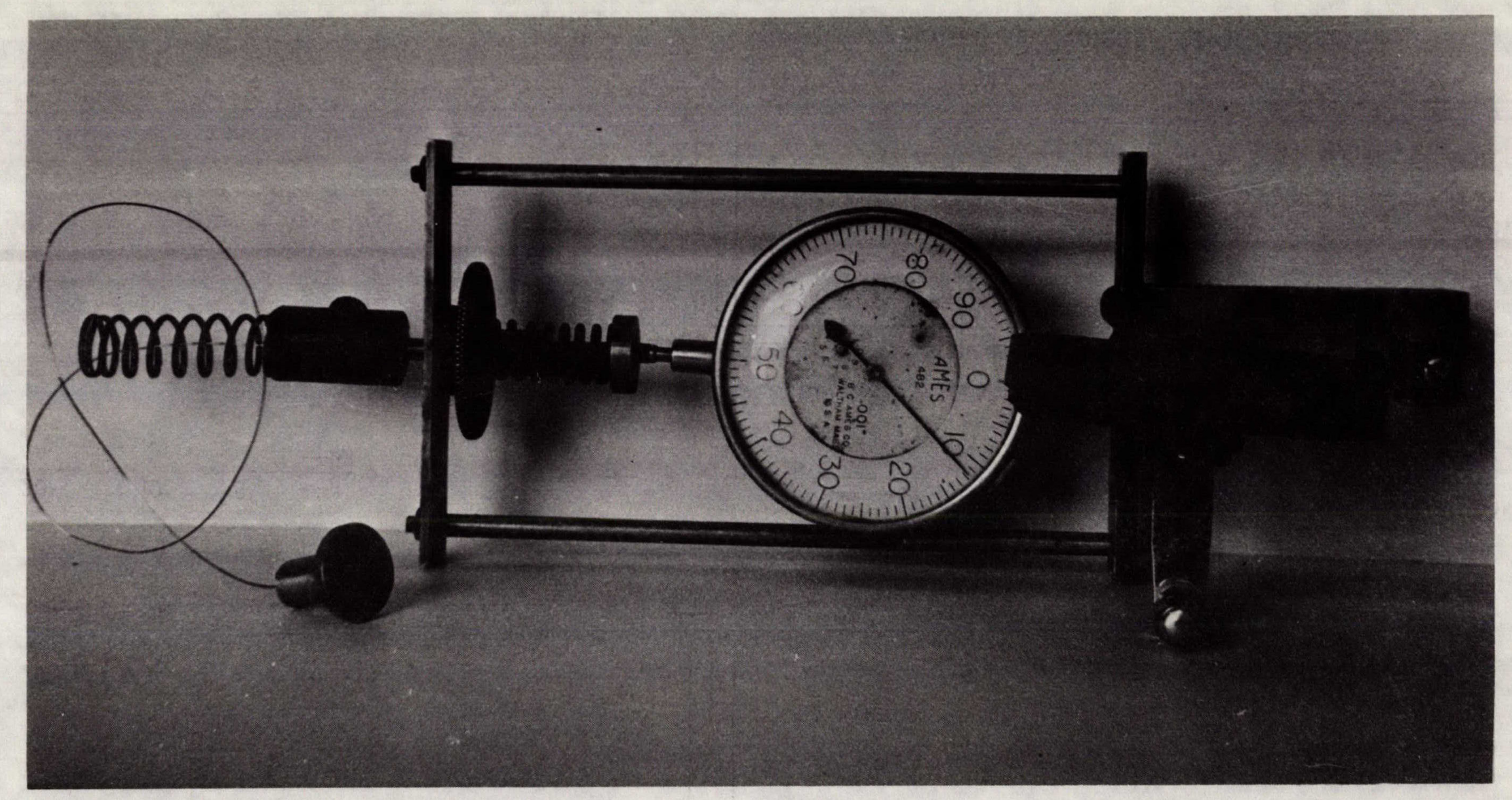

Figure 4. Tape dial extensometer.

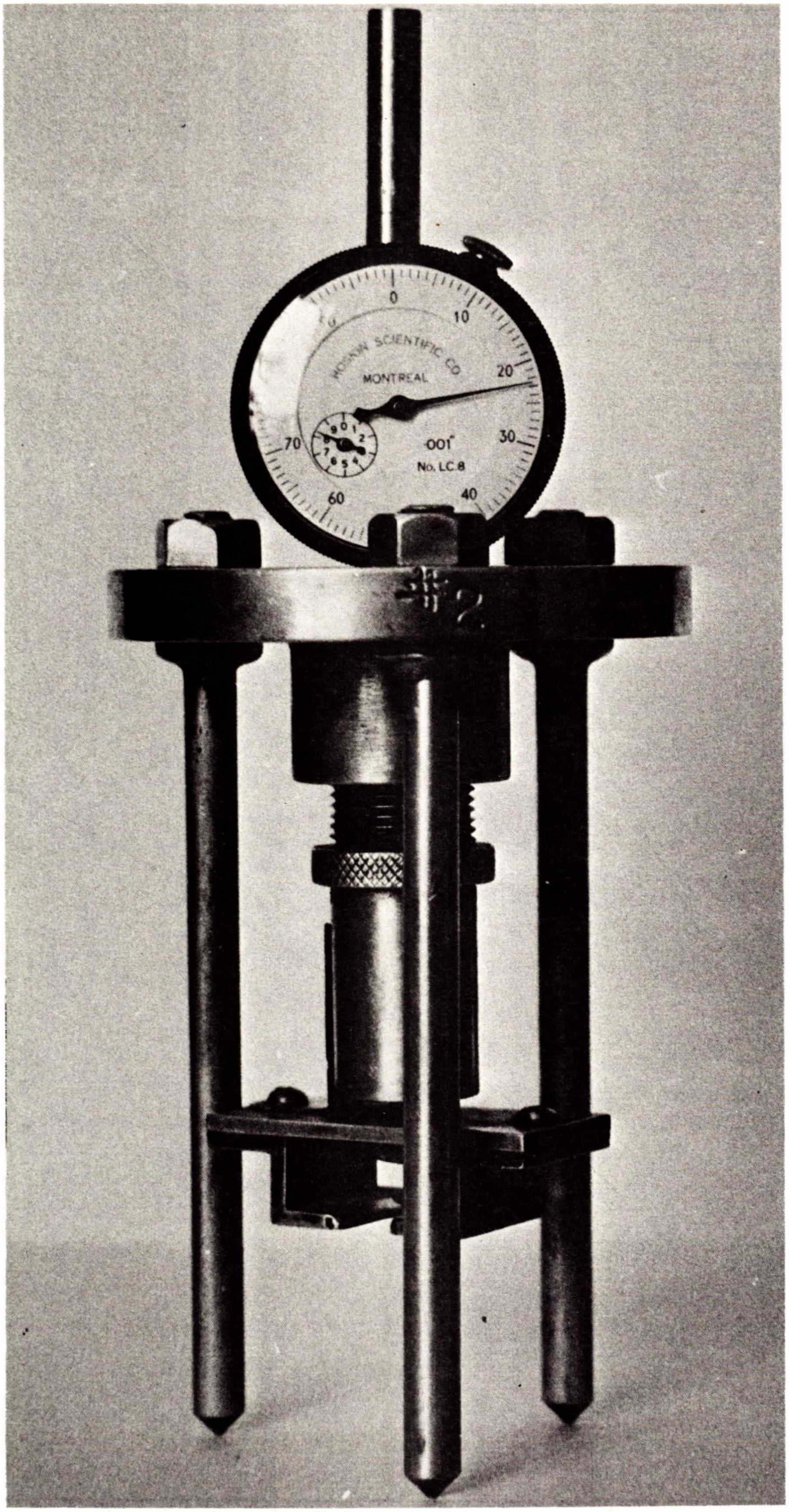

Figure 5. Borehole extensometer.

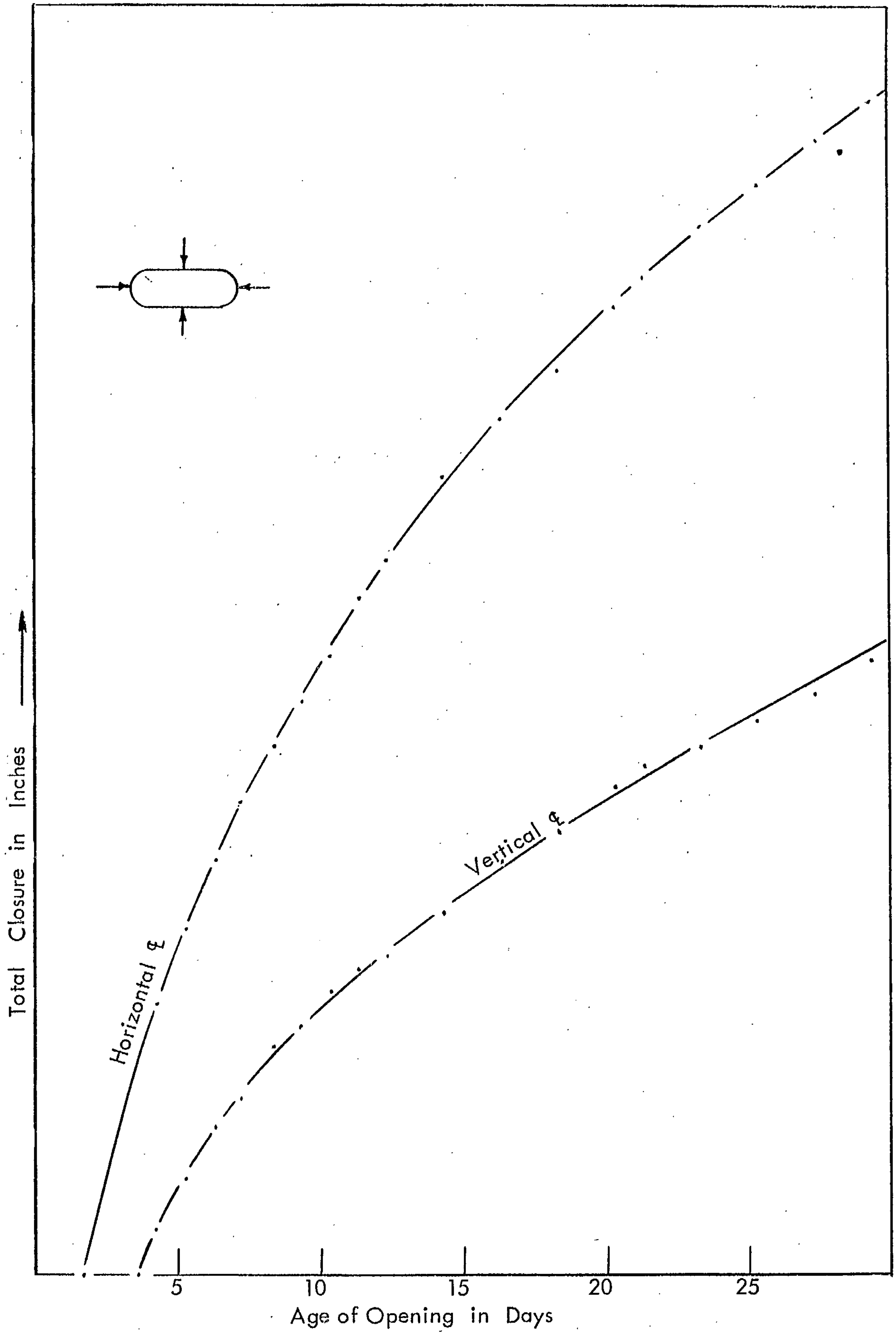

Figure 6. Total opening closure. Site 000B, 6-in. pins.

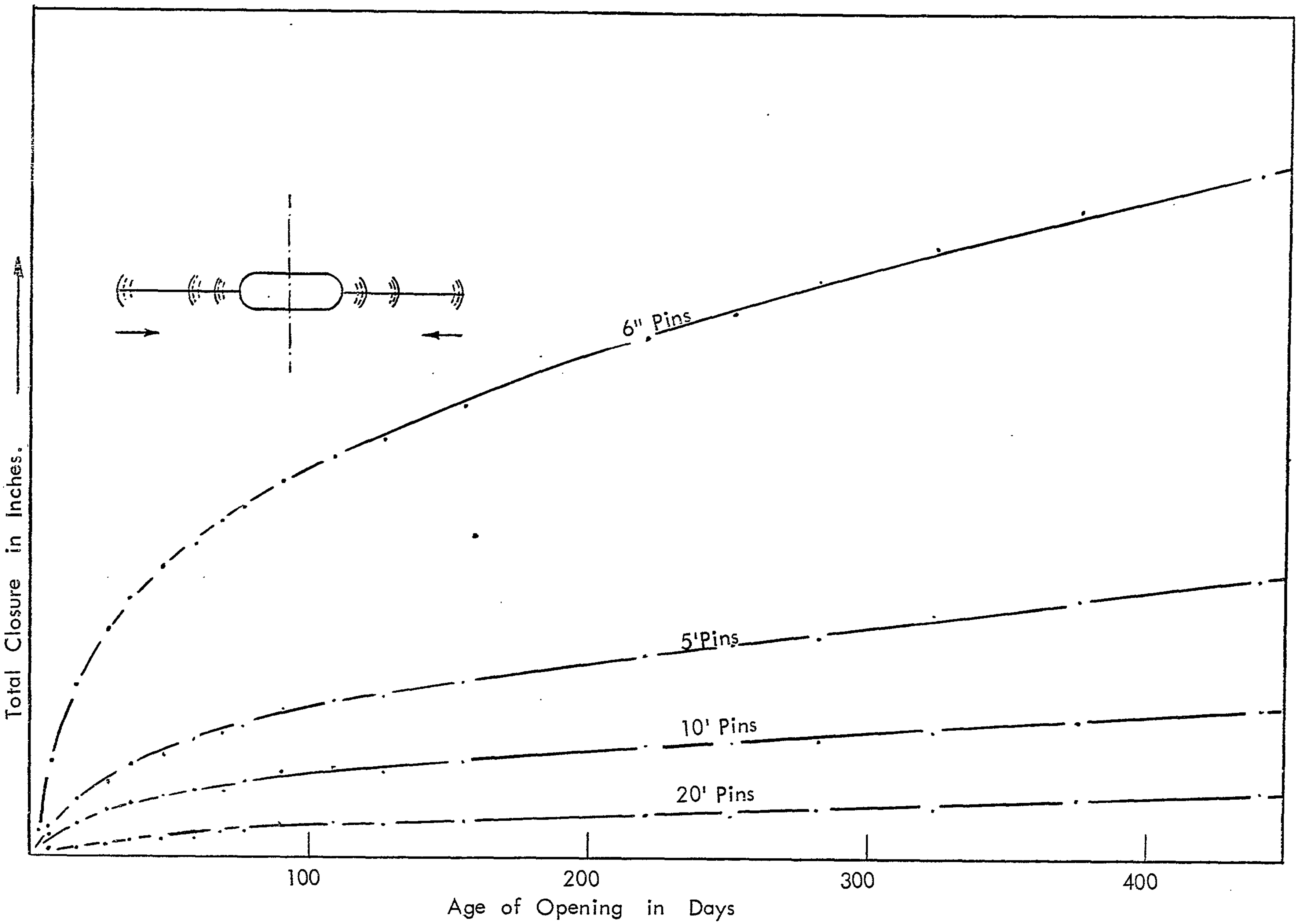

Figure 7. Total horizontal closure. Site 000B.

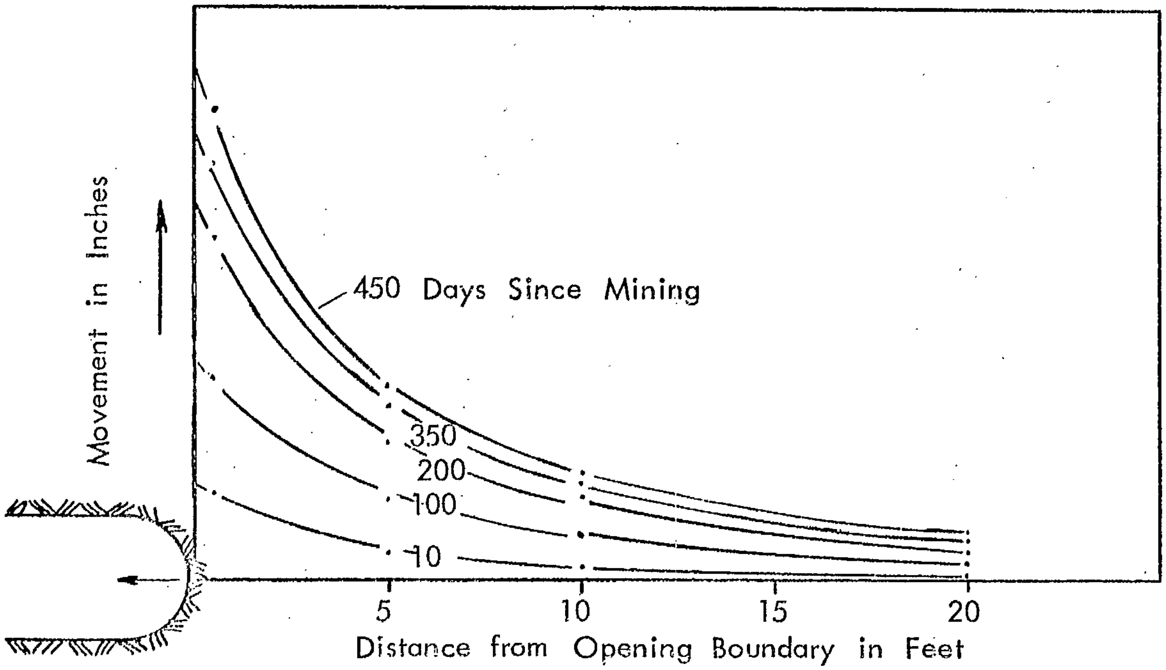

Figure 8. Profile of horizontal movement in wall. Site 000B.

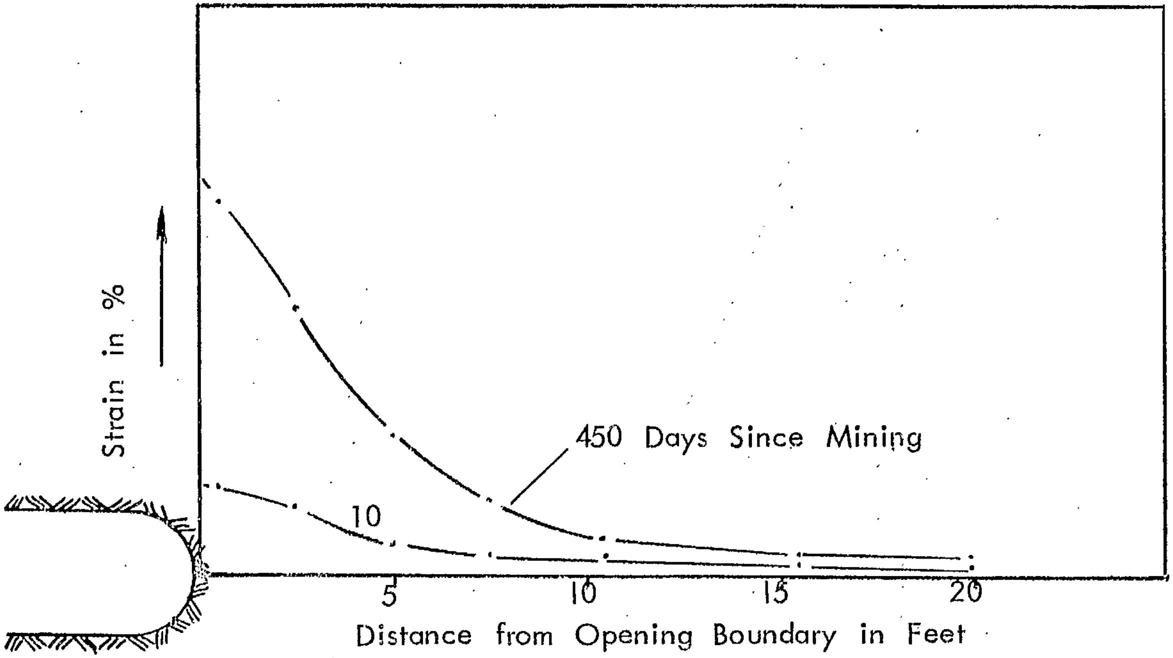

Figure 9. Profile of horizontal strain in wall. Site 000B.

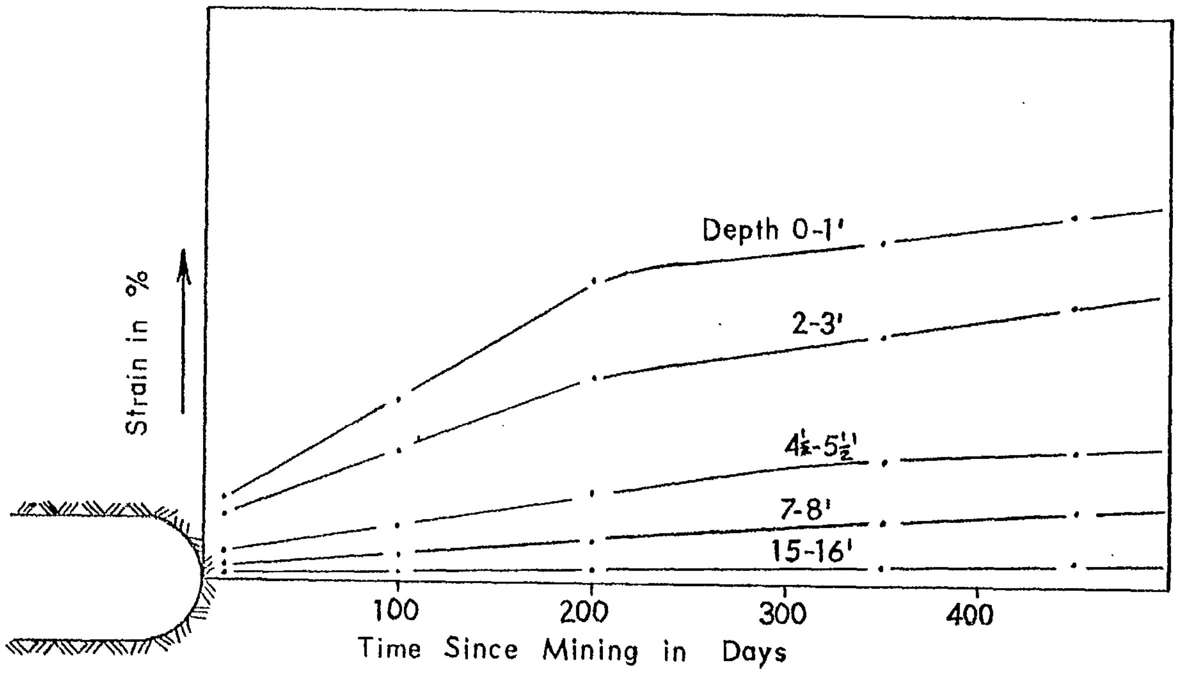

Figure 10. Horizontal strain history at various depths in wall. Site 000B.

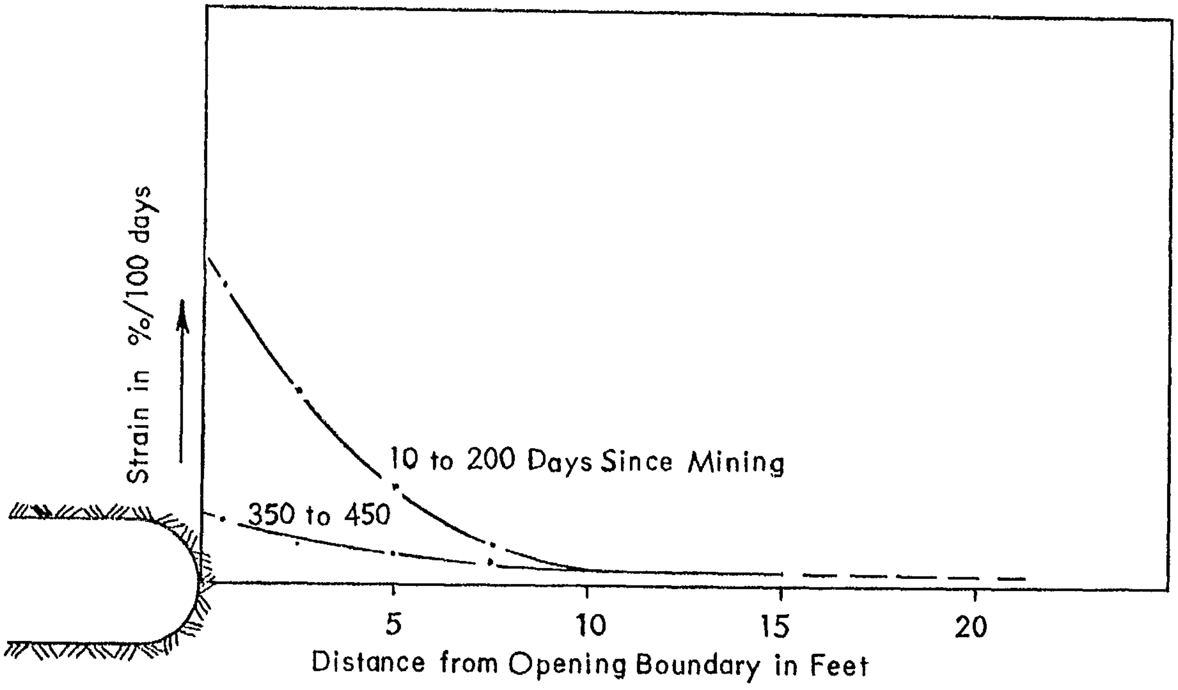

Figure 11. Profile of horizontal strain rate in wall. Site 000B.

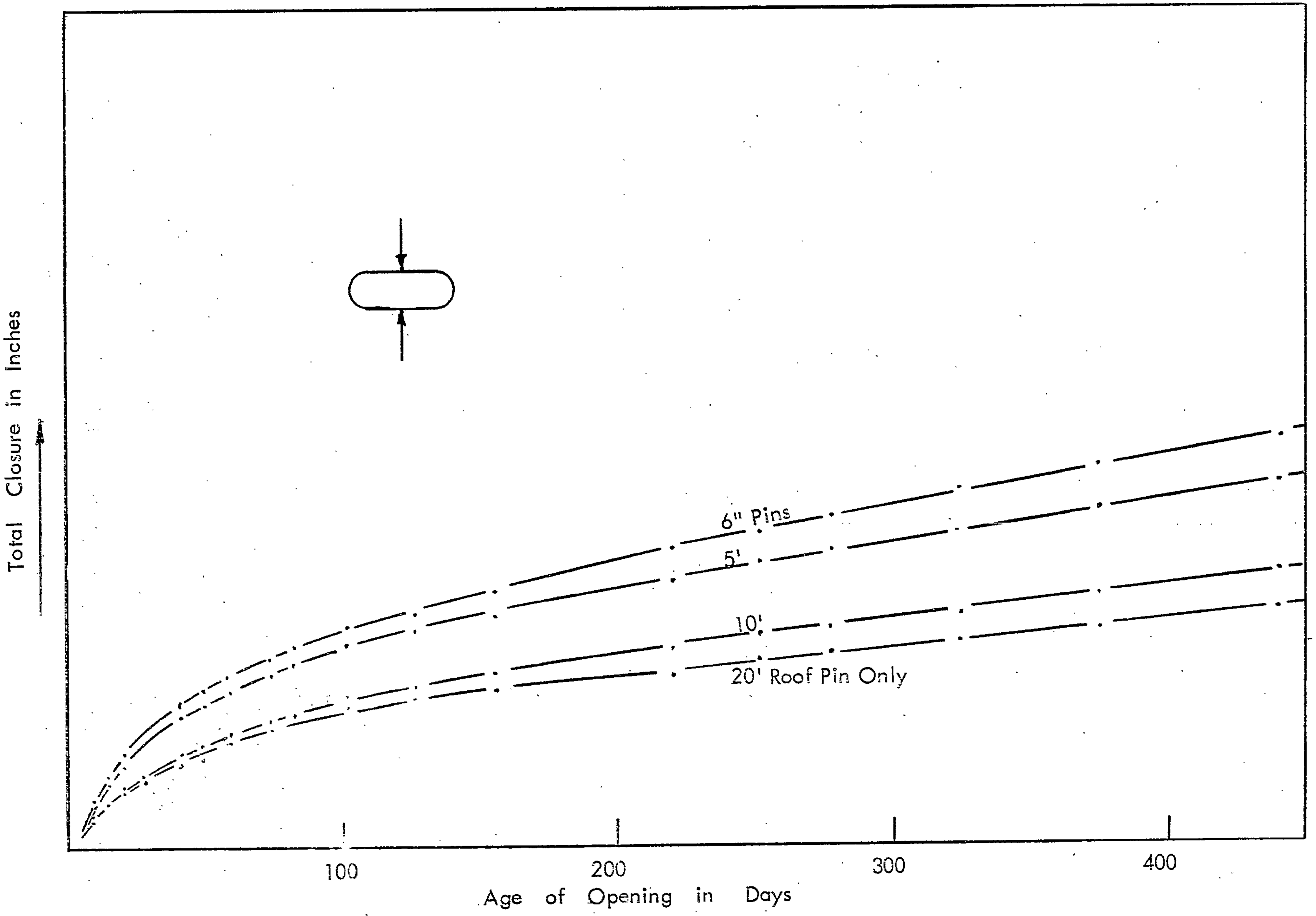

Figure 12. Total vertical closure. Site 000B.

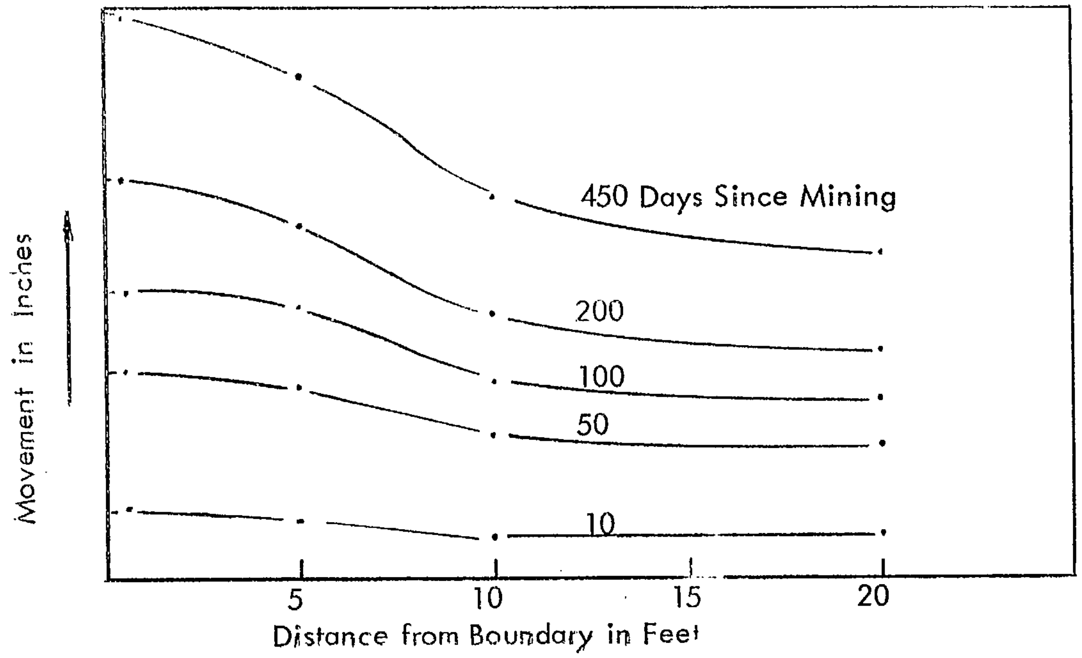

Figure 13. Profile of vertical movement in roof and floor along opening ℄ Site 000B.

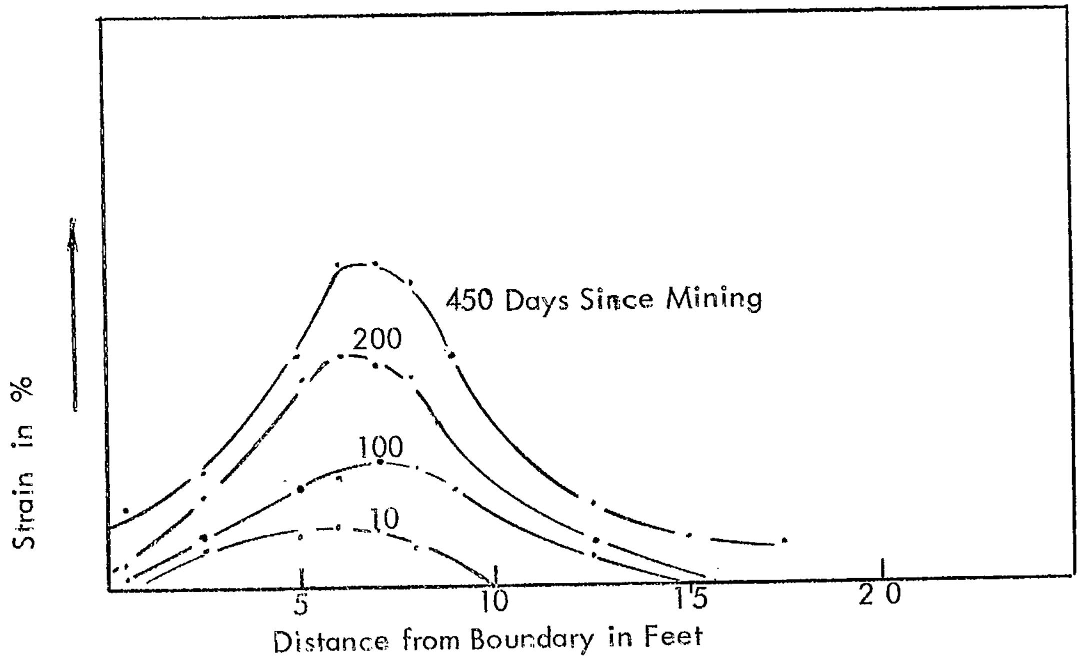

Figure 14. Profile of vertical strain roof and floor along opening ℄ Site 000B.

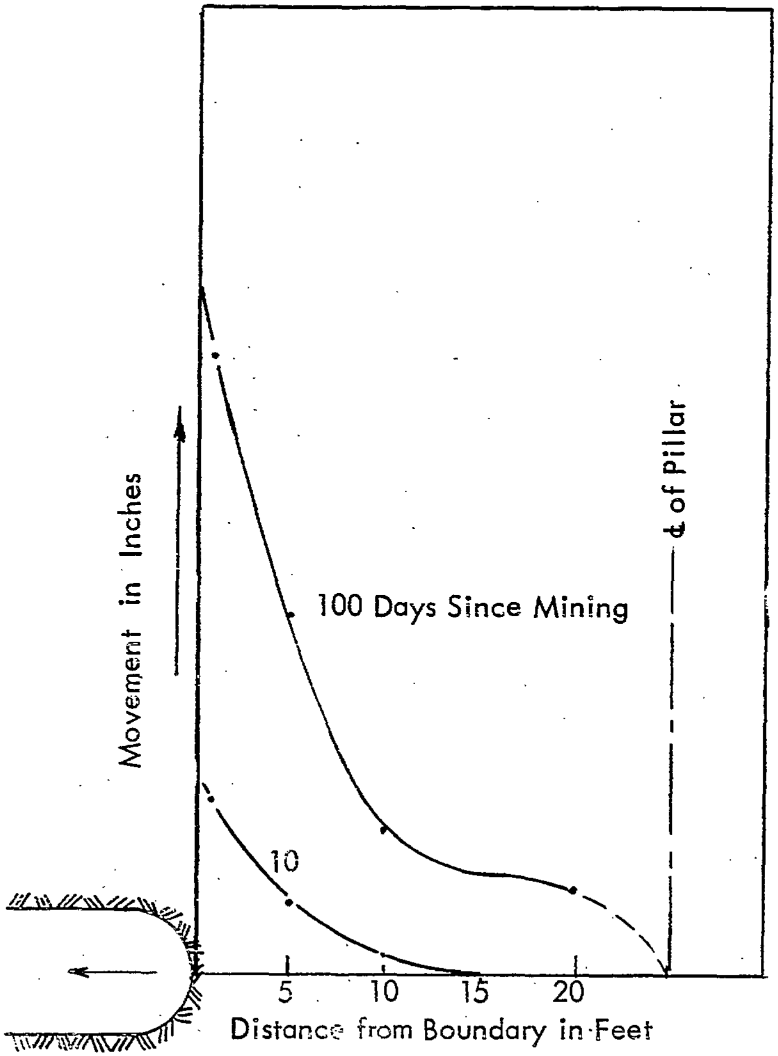

Figure 15. Horizontal movement in pillar wall. Site 121A.

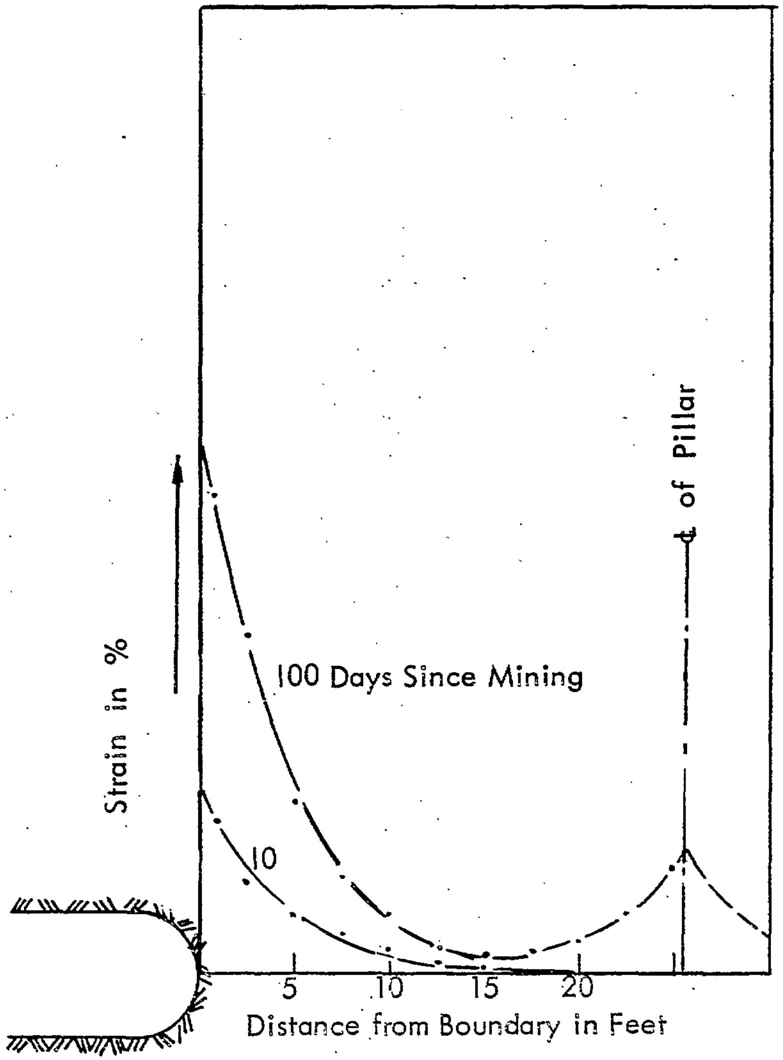

Figure 16. Profile of horizontal strain in pillar. Site 121A.

DISCUSSION

Professor B. Ladanyi, Dept. Civil Engineering, Laval University, Quebec.

Has any systematic study of stress-strain-time behaviour of this particular potash been made that would permit an analytical study of the problem of closure to be performed?

AUTHOR'S REPLY

Yes, the present dimensions of the mine openings are based largely on the results of such a study.