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SOME OBSERVED DEFORMATIONS UNDERGROUND IN VARIOUS CANADIAN MINES

D. F. COATES AND W. G. MUIR

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Mines Branch Research Report R 226

SOME OBSERVED DEFORMATIONS UNDERGROUND IN VARIOUS CANADIAN MINES

by

D. F. Coates * and W. G. Muir **

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SUMMARY

Over the years research work has been conducted in Canada on deformations underground resulting from mining. Most of the work has been done in coal mines, some in salt and potash mines, and increasingly in metal mines. The measurements are associated primarily with room- or stope-and-pillar mining, only a modest amount of work having been done in connection with longwalls. Most of the work has been done to obtain information for developing more effective support methods.

It has been found that the understanding of deformations underground resulting from mining excavations is assisted by using the concept of "excavation stress". The physical act of removing the rock is equivalent to the act in mechanics of applying an increment of stress on the resultant boundary, which produces "excavation deformations".

Considering the entire mining zone as an opening in an infinite mass with some resistance to closure being provided by the pillars, it was thought that the deflections should vary according to the theoretical relationship $(1 - (x/L)^2)^{\frac{1}{2}}$ where x is measured from the centreline of the mining span, L. In an extensive series of model tests it was found empirically that the simpler relationship of $(1 - 0.2\ x/L)$ provided a better correlation with the measurements.

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(Summary, concluded) -

Closure and bed separation measurements in coal mines have shown the effect of applying the downward excavation stress at the roof line. The variation of the deflections and bed separations across the span of a room indicates clearly that the span affected is greater than the breadth of the opening. Tests showed that for a room 5. 5 m in breadth, the actual unsupported span was greater than 8. 5 m. The measurements also showed that a critical deflection occurring within the first 24 hours after exposure could be established which, if exceeded, would lead to much greater deflections and instability.

Measurements in salt and potash mines have shown that the reaction to excavation stresses is to produce time-dependent deformations. There is some indication that roof deflections occur fairly quickly but closure continues over a long period of time because, primarily, of creep in the pillars as the result of the relatively high compressive stresses.

The horizontal inward excavation stresses acting on the sides of the pillars cause not only the pillars to expand horizontally but also the roof strata to be compressed to the point of either buckling or shearing.

Closure measurements throughout the mining zones in salt have shown that closure rates, comparable to absolute closure in elastic ground, vary across the mining panel according to the relationship $(1 - 0.2\ x/L)^c$ where c seems to be about 3. 7.

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Direction des mines
Rapport de recherches R 226

QUELQUES DÉFORMATIONS OBSERVÉES SOUS TERRE DANS DIVERSES MINES CANADIENNES

par

D.F. Coates* et W.G. Muir**

RÉSUMÉ

Durant plusieurs années des travaux de recherche ont été effectués au Canada sur les déformations résultant de l'extraction souterraine. La plus grande partie de ces travaux ont été effectués dans des mines de charbon, certains dans des mines de sel et de potasse, et de plus en plus fréquemment dans des mines de métaux. Les mesures ont été faites en majorité dans les exploitations par la méthode des massifs longs ou des gradins; quelques travaux seulement ont été faits dans les exploitations par longue taille. La plus grande partie de ces travaux a été effectuée en vue d'obtenir des données pour mettre au point des méthodes d'étayage plus efficaces.

On s'est aperçu qu'il était plus facile de comprendre les déformations souterraines résultant du creusement des mines si l'on recourrait à la notion de "contrainte d'excavation". L'action physique d'enlever la roche est équivalente à l'application, en mécanique, d'une contrainte supplémentaire à la limite résultante, ce qui produit des "déformations d'excavation".

Considérant toute la zone d'extraction comme un vide dans une masse infinie, où l'affaissement est entravé par les piliers de soutènement, on a estimé que les affaissements devraient varier selon la relation théorique $(1 - (x/L)^2)^{\frac{1}{2}}$ où x est mesuré à partir du centre de la travée de mine, L. A la suite d'une longue série d'essais de modèles on s'est aperçu que la relation (1 - 0.2 x/L), plus simple, donnait une relation plus exacte par rapport aux mesures.

Des mesures de l'affaissement et de la séparation des couches dans des mines de charbon ont montré les effets que la contrainte d'excavation en profondeur exerce sur la ligne de toit. La variation des affaissements et des séparations des couches en travers d'une chambre indique clairement que l'étendue touchée est plus grande que la largeur de cette chambre. Des essais ont montré que pour une chambre de 5.5 m. de largeur, l'étendue non soutenue dépassait 8.5 m. Les mesures ont également montré qu'un affaissement important se produisait dans les 24 heures suivant le creusement, et qu'après ce laps de temps on obtenait des affaissements et une instabilité bien supérieurs.

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Les mesures effectuées dans des mines de sel et de potasse ont montré que la réaction aux contraintes d'excavation est l'apparition de déformations qui sont fonction du temps. Il semble que l'affaissement du toit se produit assez rapidement mais l'affaissement complet ne se produit qu'après une longue période, progressivement, essentiellement en raison du renflement des piliers, sous l'influence des contraintes de compression assez importantes.

Les contraintes d'excavation horizontale qui s'exercent sur les côtés des piliers provoquent non seulement l'expansion horizontale des piliers mais également la compression des couches du toit, jusqu'au point de flexion ou de cisaillement.

Les mesures des rythmes d'affaissement effectuées dans toute la zone d'extraction des mines de sel ont indiqué que ces rythmes, comparables à ceux de l'affaissement absolu en terrain élastique, varient à travers la zone d'extraction, selon la relation $(1 - 0.2\ x/L)^c$ où c semble être de l'ordre de 3.7.

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INTRODUCTION

Over the years, research work has been conducted in Canada on deformations underground resulting from mining (1-36)*. The majority of the work has been done in coal mines, some in salt and potash mines, and increasingly in metal mines. The measurements are associated primarily with room- or stope-and-pillar mining, only a modest amount of work having been done in connection with longwalls. Much of the work has been done to obtain information for developing more effective support methods; a report has been published recently summarizing the findings with respect to roof bolting (36).

It has been found that the understanding of deformations underground resulting from mining excavations is assisted by using the concept of "excavation stress". The physical act of removing the rock is equivalent to the act in mechanics of applying an increment of stress on the resultant boundary, which together with the original stress produces the necessary zero resultant boundary stress. It is the increment of stress and the associated stress changes within the rock mass that are called "excavation stresses", with the associated deformations being called "excavation deformations".

Figure 1 shows various elements of excavation stresses caused by the mining of a series of rooms. In Figure 1(a) the excavation stress applied to the roof of the rooms is shown. There is reason for believing that the deflection of the pillars varies from the centre of the mining span, L, according to the relation $(1 - (x/L)^2)^{\frac{1}{2}}$ where x is measured from the centre-line of the span (24). In addition to the deformation reaction to the excavation stress, it follows that excessive movement can lead to either tensile failures in the immediate roof or shear failures towards the abutment zones. The excavation stress along the roof line of the rooms would also pull down the roof rock so that the ground surface would show a subsidence crater.

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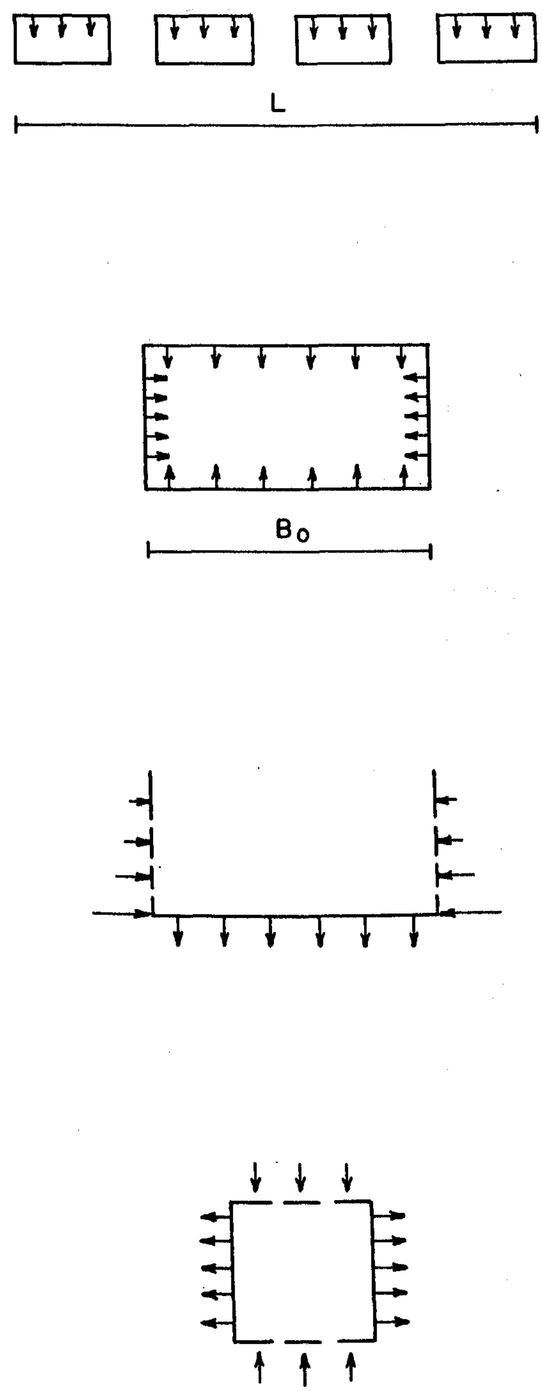
* These numbers refer to the sources of information listed in the Bibliography at the end of this paper.



(a)

(b)

(c)

(d)

Figure 1. Excavation stresses in room-and-pillar mining: (a) acting on the roof of rooms; (b) acting on the roof, floor and sides of pillars in an individual room; (c) acting on the roof strata of an individual room; and (d) acting on a pillar.

In Figure 1(b) the excavation stresses acting on the roof, floor and sides of the pillars of an individual room are shown. The resultant deflection of the roof line could be expected to vary according to the relationship $(1 - (x/B_o)^2)^{\frac{1}{2}}$, where B_o is the breadth of the room and the origin is at the centreline of the room. Again, excessive movement could lead to tensile failure in the immediate roof near the centreline and to diagonal tensile failure, together with shear failure, near the abutments. In addition, the sides of the pillars will be pulled out, possibly into a curve according to the relationship $(1 - (y/H)^2)^{\frac{1}{2}}$, where H is the height of the pillar and the origin is at the mid-height. Associated with this action would be the shortening of the pillar, due to Poisson's effect. The common slabbing of the sides of pillars is undoubtedly caused by the action of the excavation stress here (actually, the release of stress).

In Figure 1(c) a section of roof rock over one room is shown with the excavation stress acting downwards at the roof line and induced compressive stresses acting on the ends of the strata. These stresses could be expected to cause a shortening of the strata, possibly leading to buckling of the immediate roof layers.

In Figure 1(d) the excavation stresses acting outwards on the sides of the pillars and downwards on the top of the pillar both contribute to the total shortening of the pillar. Under excessive stresses the pillar may fail either in shear along an oblique plane or by splitting longitudinally.

MODEL STUDIES

In an extensive series of models, pillar stresses were related to deflections that could be predicted analytically across a mining zone as indicated in Figure 2. Whereas it was thought that the deflections would vary according to the relationship $(1 - (x/L)^2)^{\frac{1}{2}}$ where x is measured from the centreline of the mining span, L, it was found empirically that the simpler relationship of $(1 - 0.2\, x/L)$ provided a better correlation with the measurements (24, 25).

MEASUREMENTS IN COAL MINES

Of the various sets of data taken in a number of different mines, some of those obtained at Michel illustrate representative patterns. The mines in this area are located in Cretaceous formations that are strongly affected by structural features. Thick sandstone layers are interbedded with shale and bituminous coal. The dominant orogeny has been a regional east-west thrust producing folding, faulting, and intensive jointing. Bedding slippage is widespread. Whereas it is still

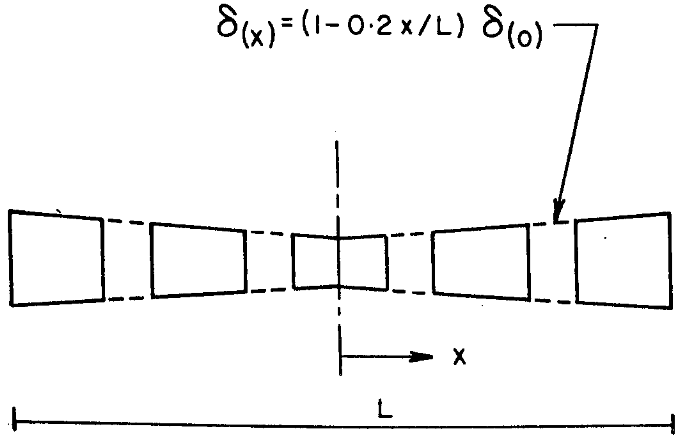


Figure 2. Variation of deflections across a mining panel.

a moderately active earthquake zone, studies showed that bumps in other mines of the region were not related to seismic disturbances (2).

As a result of the shearing action associated with the thrust, the original structure of the coal has been destroyed. Local contraction faults, which can normally be traced from the floor into the roof, are quite common. Extension faults, presumably associated with a period of release of thrust, are more numerous although they can rarely be traced across the seams. The thickness of the seams varies from 15 cm to 36 m as a result of the tectonic action (15).

Location with respect to fold axes has been found to be important with regard to mining. The dip of the seams varies from 0 to 25 deg. In one mine the greater frequency of contraction faults, together with relative roof stability, was thought to be the result of the greater tectonic compressive stresses related to the location on the flank of an anticline. In a second mine near the axis of a syncline, a much higher frequency of extension faults and unstable roof conditions was observed (15,16).

Joints are usually perpendicular to the bedding, sometimes in a single set and sometimes in two sets perpendicular to each other. The spacing of joints in one set commonly varies from a few centimetres to about a metre.

The thickness of the overburden, owing both to the mountainous surface topography and to the rolling seams, varies from 100 m to 500 m. However, support difficulties do not seem to be related to depth. The roof rock in these mines is predominantly carbonaceous shale and is classified as Strong, Yielding, Layered, Blocky to Broken, with the average uniaxial compressive strength, Q_u, of the rock substance being 1500 ksc(kg/cm^2), the modulus of deformation being 3.5×10^5 ksc, and creep at a stress level of 0.5 Q_u after 200 minutes being 11 μ/hr (27).

Mining is by the room-and-pillar method, with the rooms being normally 5 to 6 m in breadth and the pillars 6 to 13 m in breadth and 20 to 65 m in length (28).

Two test entries had been selected to determine the effectiveness of bolting compared to timber support. Besides other observations, measurements were made of closure, bed separation in the roof, and the amount of relaxed ground in the coal ribs. The entries were driven on strike, and the roof beds were found to be from 2 to 15 cm thick, often being detached through interlayer slip. Both extension and contraction faults were present, with stratigraphic separations of up to 17 cm.

In one roof bolt hole towards the rib, relative movements between strata of 1.6 cm were observed at a distance of 37 cm into the roof and another of about 0.6 cm at a distance of 130 cm. The movements seem to corroborate the existence of excavation stresses acting on the ends of the roof strata, as shown in Figure 1(c).

Figure 3 shows bed separations at a station where movement was sufficient to cause instability. Examination of all the bed-separation curves showed that the major part of the movement generally occurred between 0 and 1.2 m. In some cases a separation between 0 and 0.6 m was proportionally greater, but in an equal number of cases the reverse was true. In the latter cases, presumably the excessive movements destroyed the elastic gradient pattern, between these measurements, that would be caused by the excavation stresses of Figure 1(b). In contrast to Figure 3, at many stations the expansion between 0 and 2.1 m was as little as 6 mm.

It was found that where the ultimate separation was relatively small, more than 50% of the movement occurred within about 24 hr, whereas where the ultimate movement was relatively large (more than 2.5 cm) the majority of the movement took up to 5 days to occur. However, in these latter cases it was also observed that a critical value of 0.6 cm between 0 and 2.1 m would be exceeded within the first 24 hr, thus providing a warning of impending deterioriation. A rock bolt anchored at 2.1 m and floating freely in an aluminum sleeve collar wrapped with a 0.6-cm width of reflective tape, provided a simple method of monitoring when this critical figure would be exceeded.

Concerning the urgency of bolting immediately at the face, at many stations a period of about 6 hr seemed to exist before any bed separation occurred, providing a reasonable amount of time for installing support. However, at some stations, particularly where bad roof conditions developed, the curves showed that the installation of bolts even 1 hr after the face had passed would have been too late to prevent serious movement. Furthermore, by carefully recording the miners' observations on the quality of the roof during the shift in which it was exposed, together with geological observations on the structural details, it was found that the correlation with subsequent roof conditions was not good. Many drummy roofs remained quite stable whereas initially good roofs subsequently often produced falls; hence the superiority of quantitative measurements for anticipating critical conditions was established.

In Figure 4, curves show for relatively stable ground

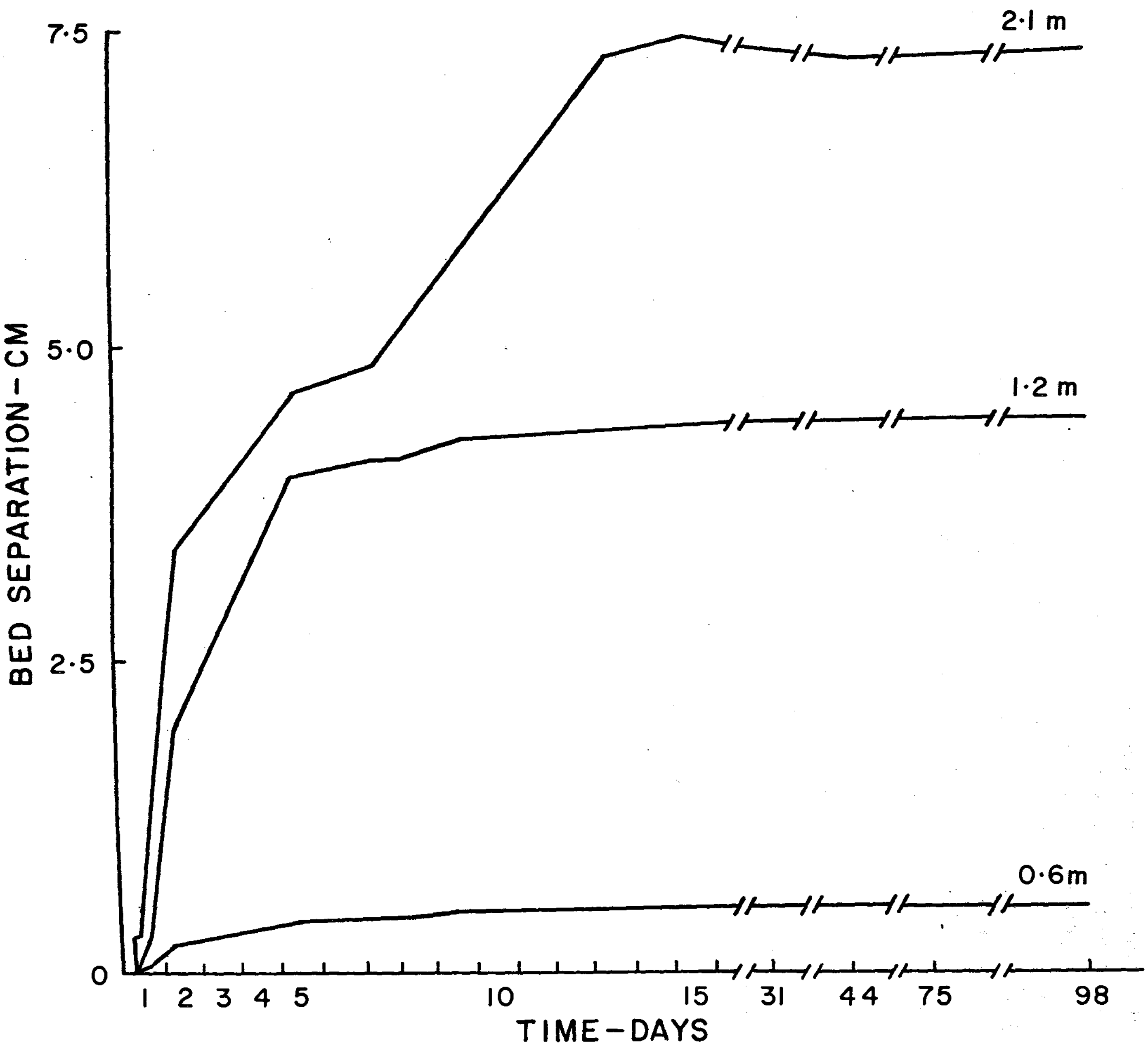


Figure 3. A typical case of damaging bed separations and their variation with time between the immediate roof line and 0.6, 1.2 and 2.1 m into the roof.

typical closure and bed separation in the roof between 0 and 2.5 m. The difference between these two curves substantially represents the compression of the pillar, which incidentally explains why the deflection function mentioned above, $1 - 0.2\,x/L$, is not equal to zero when $x = L/2$. Because the bed separations, measured at the rib line, were commonly of a significant magnitude and only somewhat less than those measured at the centreline, it was concluded that the effective span of the roof was greater than the nominal breadth of the opening indicated in Figure 1(b). Rib probing with hand augers substantiated this conclusion, showing that the boundary of the high-stress zone was more than 1.5 m from the surface of the pillar.

The general experience that intersections are critical zones was documented by the large increases in bed separation that were measured when intersections were driven into the test entries. Figure 5 shows first the effect of a slope being driven into one side of an entry to form a Y-junction, and then the effect of the creation of an X-junction by continuing the slope on the other side of the entry. The influence of such junctions on bed separation was noted at distances up to 40 m.

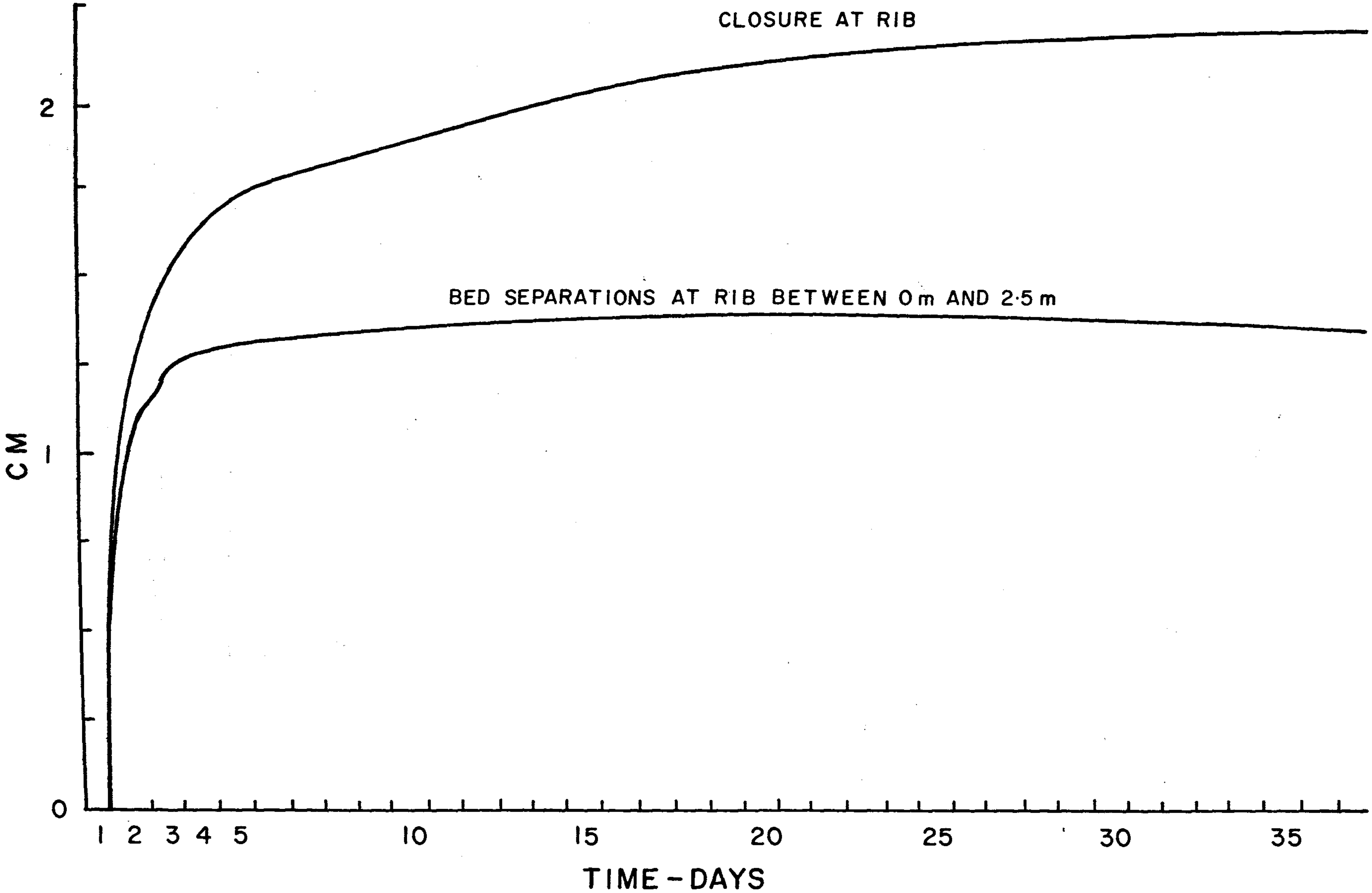


Figure 4. Comparison between closure and bed separation at the rib; the difference representing pillar compression.

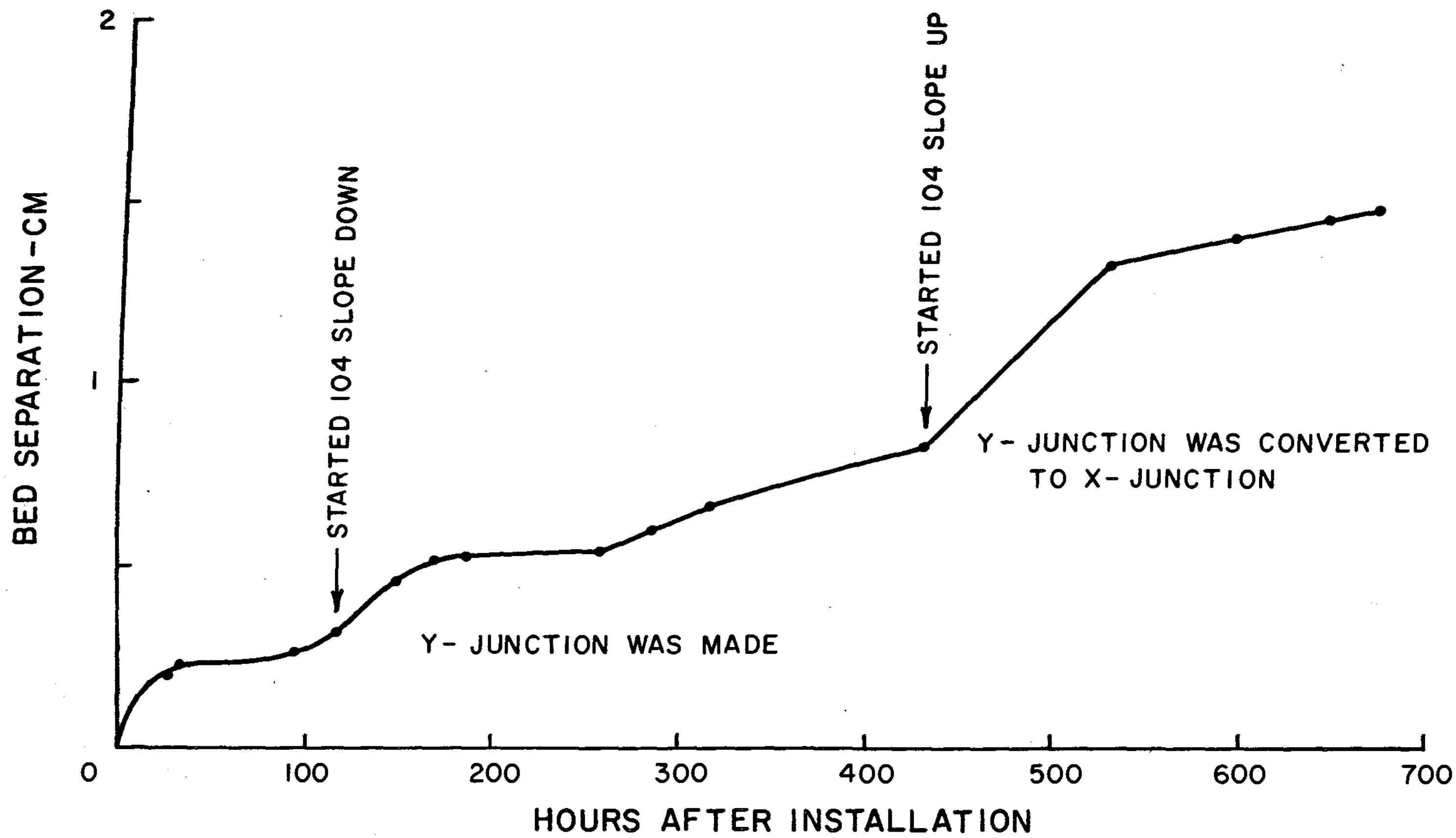


Figure 5. Effects on bed separation of driving a slope into one side of an entry and continuing on the other side.

MEASUREMENTS IN SALT MINES

Measurements have been made in various salt mines to obtain information for the design of rooms and pillars and, in addition, for the design of support systems such as roof bolting. A selection of some of these data shows typical reactions to mining, i. e. , the reactions to the application of excavation stresses.

Extensive measurements have been taken at Goderich, Ontario, where the mine is in the Salina formation of Silurian age. The salt beds occur from 240 m to 820 m below the surface, and are remarkably continuous without structural interruptions. Mining is being conducted at a depth of 540 m in a bed, 24 m thick, composed of 98.5% to 99.3% NaCl. Only the bottom 13 m of the bed are being mined (26).

The roof rock is classified as Weak, Yielding, and Layered. The rock substance has an average uniaxial compressive strength, Q_u, of 156 ksc, with a modulus of deformation obtained from the last unloading curve of 1.8×10^5 ksc, and a creep rate of 93 μ/hr at 200 minutes after applying a load of 0.5 Q_u (27).

Mining is by the room-and-pillar method, with rooms typically 18 m in breadth and pillars 64 m square, which gives an extraction rate of approximately 40%.

Convergent measurements were made at one station installed at the boundary of the mine 1041 days after excavation of the site (26). The breadth of the opening is 19 m and the height is 5.5 m. Three sets of telescopic rods with dial gauges were used to obtain measurements at the centreline and at the two ribs. Over a subsequent period of 1127 days, convergence was found to be equal at all three stations to 4.8 cm. It is probable that the uniform increment in convergence was due to the increased deformation in the adjacent pillars resulting from creep.

Another station was installed in a room of normal mining dimensions 153 days after excavation. Besides three sets of rods spaced across the room, a horizontal rod was suspended at a height of 5.5 m above the floor to measure the closure between the sides of the pillars. As shown in Figure 6 the increment of closure at the centreline of the room was greater than towards the ribs, as would normally be expected from the application of the excavation stresses as shown in Figure 1(b). The horizontal closure is also consistent with these excavation stresses, which can lead to the buckling stresses shown in the roof of Figure 1(c). The continuing increase in convergence at a decreasing rate is probably due to the creep of the pillars under their increased loading. These figures represent a ratio of vertical strain to horizontal strain in the pillar of approximately 3/1.

There has been some spalling and caving of roofs here. Observations suggest that the horizontal stresses in the roof strata of Figure 1(c) cause the shearing failure that commonly occurs near the ribs without tensile cracking at the centres. In other cases, cracking has occurred at the centre, which is probably due to buckling action. Figure 7 is a photograph of one such roof failure.

Most failures in this mine have occurred a short time after exposure, usually when forming a fourth side of a pillar or developing more than one heading from an intersection. The falls do not occur at the face but in adjacent headings. Since the introduction of bolting, the number of falls have been diminished or delayed.

Another set of convergence measurements has been made along 400 m of an entry representing approximately half the span of the mining zone. The time between mining and installation of these stations was from 46 months for No. 1 to 22 months for No. 5. Stations 1, 3 and 5 produced constant convergence rates with the relative magnitudes substantially as expected. Station 2 produced an accelerating convergence rate for about the first 70 days and then a substantially constant rate, which was greater than that at Station 1 owing to bed separation. Station 4 showed a continuing accelerating convergence rate leading up to collapse of the adjacent roof at 220 days.

It has been shown empirically that in ground where increased strain is proportional to increased stress, the increase in stress caused by mining in the resultant pillar varies across the span of the mining zone according to the relationship $(1 - 0.2\, x/L)$, as opposed to the theoretical variation of $(1 - (x/L)^2)^{\frac{1}{2}}$ (25). For mining geometries where the height, H, and breadth, B, of the pillars are small with respect to the span of the mining zone, L, i.e. where H/L and B/L are small, the equation used for predicting pillar stresses can be used to provide the following relation:

$$\frac{\Delta \sigma_p(x)}{\Delta \sigma_p(o)} = 1 - 0.2\, x/L,$$

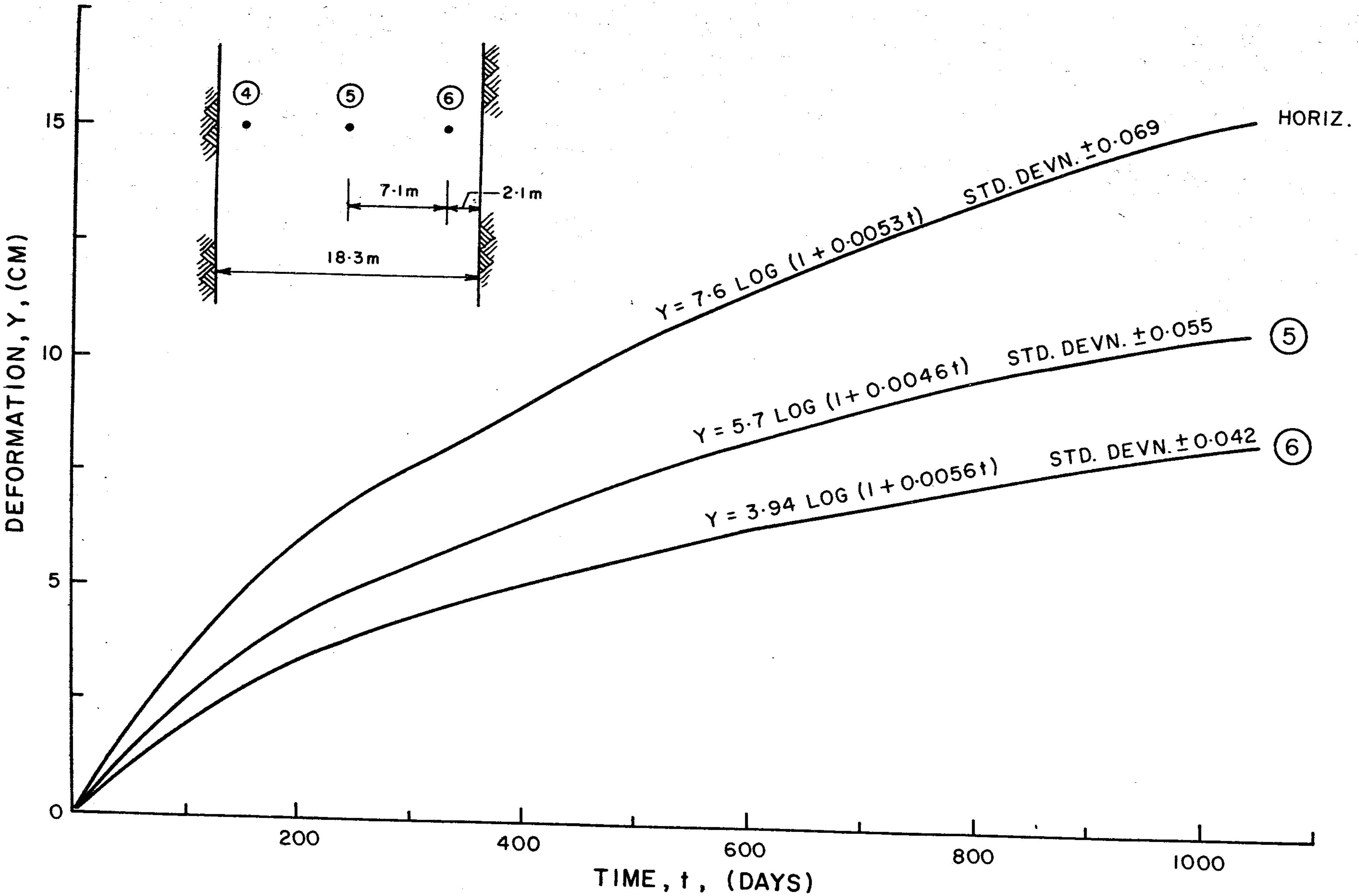


Figure 6. Vertical and horizontal creep deformations in a room, 18 m in breadth and 13 m high, in a salt mine with pillars typically 64 m square.

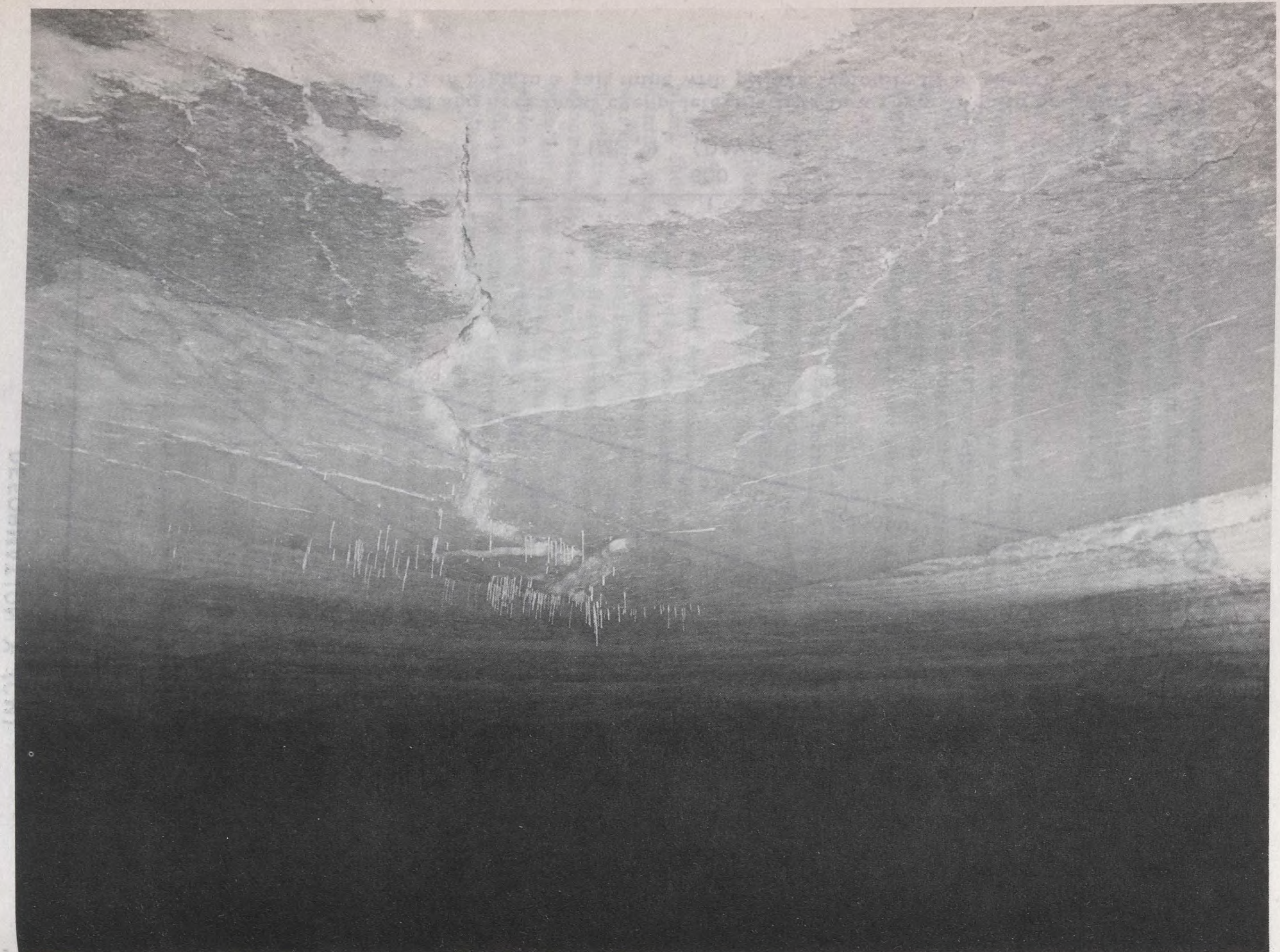


Figure 7. Buckling in the roof of a salt mine preceding a second fall from this area.

where $\Delta\sigma_p(x)$ is the increase in pillar stress at the distance represented by x from the centre of the mining span, and $\Delta\sigma_p(o)$ is the increase in pillar stress at the centreline.

If it is assumed, for practical purposes, that the stress-strain-time relations in salt can be represented by the following equation:

$$\dot{\varepsilon} = K\sigma^c t^a ,$$

where $\dot{\varepsilon}$ is the strain rate, K, c and a are constants, σ is the stress or change in stress causing $\dot{\varepsilon}$, and t is the duration of σ, the rates of pillar deflection, or closure, at different locations within the mining zone can then be compared for equal periods of time, using the following relationship:

$$\frac{\dot{\delta}_p(x)}{\dot{\delta}_p(o)} = \left[\frac{\Delta\sigma_p(x)}{\Delta\sigma_p(o)}\right]^c = (1-0.2\ x/L)^c$$

where $\dot{\delta}_p$ is the time rate of change of pillar deflection or shortening.

Figure 8(a) shows the convergence rates that existed 200 days after installation of Stations 1 to 5. The curve $y = (1-0.2\ x/L)^{3.7}$ fits the points for Stations 1, 3 and 5 very well, suggesting that c = 3.7. This convergence rate curve is thus comparable to the deflection curve obtained in harder rocks consistent with the excavation stresses acting on the roof as shown in Figure 1(a).

Measurements have also been taken in some of the Saskatchewan potash mines. The potash occurs in a thick evaporite formation of middle Devonian age and is commonly about 100 m thick. The overlying rocks consist of shales, dolomites, limestones and sandstones, to a thickness of about 1000 m. The principal potassium mineral is sylvite (KCl), with varying amounts of carnallite, which is contained in substantially pure halite. Minor amounts of clay impurities occur, both disseminated and as thin layers or partings. The mining horizon commonly has 10 m to 30 m of salt-back classified as Weak, Yielding, and Massive with the rock substance having a uniaxial compressive strength, Q_u, of 127 ksc, a modulus of deformation obtained from the last unloading curve of 0.7×10^5 ksc, and a creep rate of 44 μ/hr at 200 minutes after applying a load of 0.5 Q_u (27). The ore is underlain by perhaps 100 m of salt and anhydrite (22).

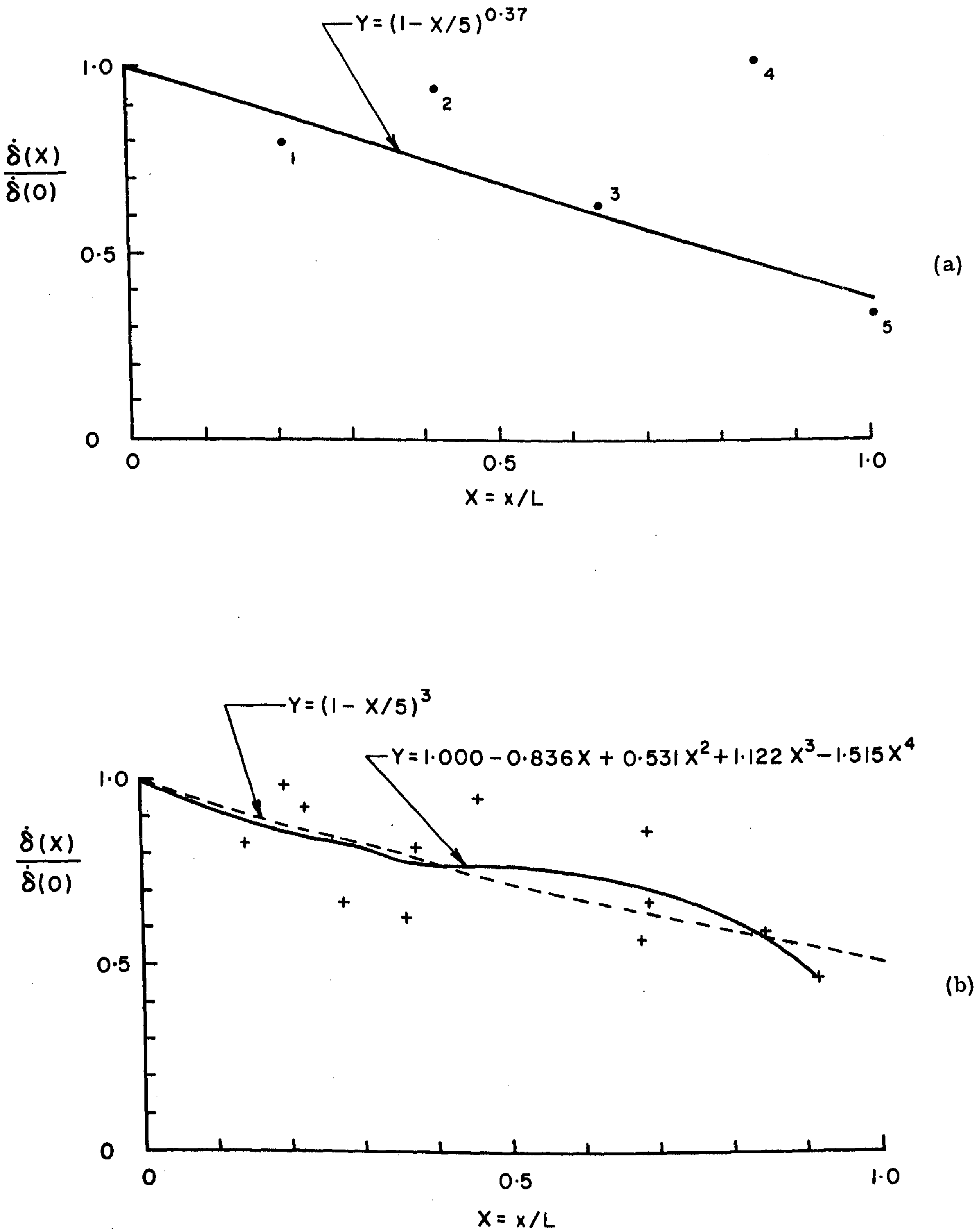


Figure 8. Variation of convergence rates across mining panels: (a) in a halite mine with a span of 744 m, and (b) in a potash mine with a span of 572 m.

Closure stations were established in one mine in the various panels. Two adjacent panels were mined during an overlapping period; consequently, the analysis of the results was made assuming that they constituted one mining zone 570 m by 850 m. The height of the pillars was 2.3 m and the breadth of the rooms was 6.4 m. The closure stations were 210 to 300 m from the ends of this mining zone, hence the effect of end support was not considered to be significant.

Figure 8(b) shows the results of analysing closure rates for the time 100 days after excavation at each station. There is considerable scatter in the data as some of the measurements, which were made in the centre of the rooms, include elements of closure related to deflections and bed separations of the immediate room. A polynomial regression curve through the data is shown; however, the variation of closure rates is probably more validly correlated according to the factor $(1-0.2\,x/L)^3$ (in fact, using $c = 3.7$ would provide a curve that might be even more valid as it would give less weight to the higher values of closure rates, which might include the local deflections and bed separations).

The correlation of these closure rates with respect to the position in the mining panel suggests that the simple equation of strain rate being proportional to stress and time raised to some constant powers, as shown above, may be adequate for mine design purposes.

To provide more information on the type of deformation that can be expected in these salts, some results of laboratory tests can be given. Figure 9 shows the data obtained from a classification test (27). This is a uniaxial compression test with loading and unloading cycles up to 25%, 50% and 75% of the uniaxial compressive strength, Q_u, the load being kept constant for 30 minutes each time before unloading. The samples were approximately 4.8 cm in diameter with a length-to-diameter ratio of approximately 2.5. The average crystal size was 8 mm, with a maximum size of 15 mm. It was found, from this series of tests, that the cycling procedure does not affect the ultimate strength. The results show that most of the strain is plastic, or irrecoverable. The ratio of elastic to total strain in these tests varied from 7% to 36%, with 10% being a representative value.

The variation of creep rates with stress, shown in Figure 9, suggests the existence of a yield point (in the sense of the stress beyond which abnormal creep rates occur) at approximately 140 ksc. The uniaxial compressive strength was about 175 ksc at a strain of approximately 1.5%. Beyond this strain, the reaction of the specimen decreased

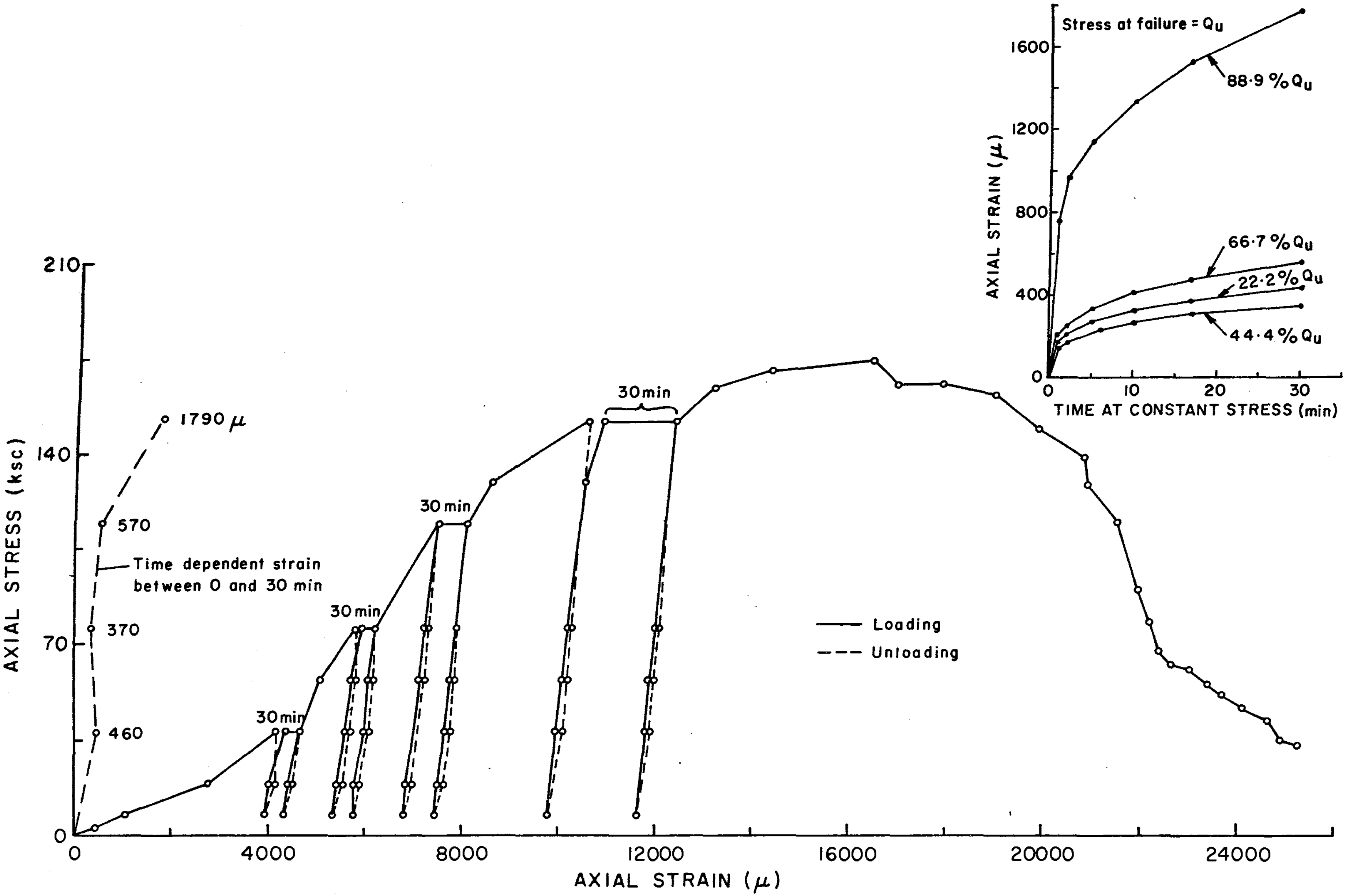


Figure 9. Classification uniaxial compressive test on potash, showing (a) strain-stress relations before and after the maximum stress had been reached together with plastic and viscous strains; and (b) creep curves for various levels of stress.

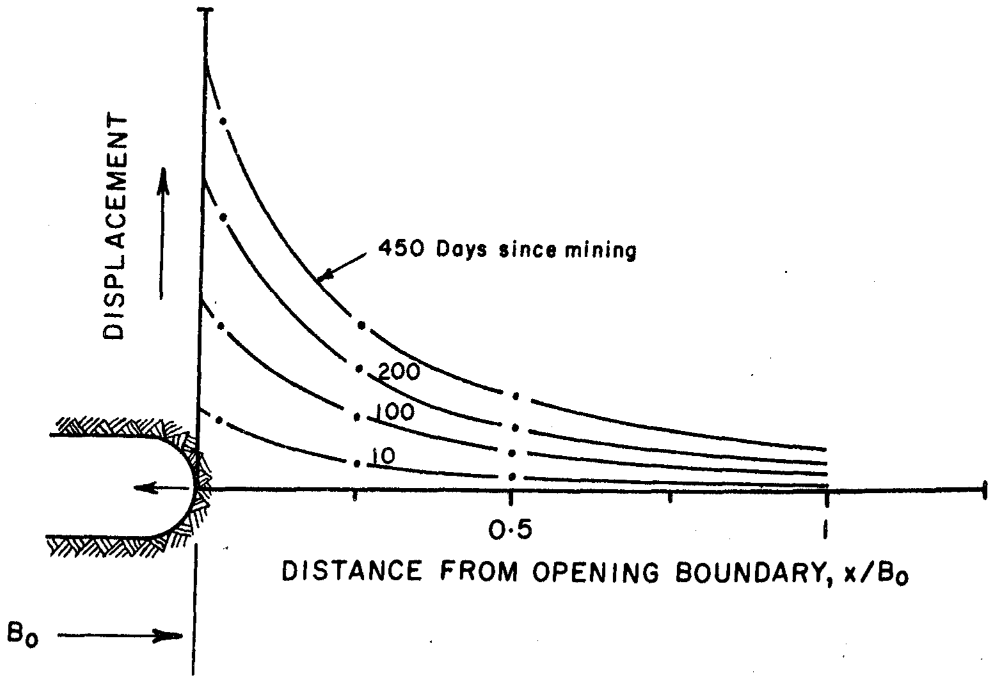


Figure 10. Horizontal displacements in the wall of a pillar in potash with an opening breadth, B_o, of 6.4 m.

considerably but the material remained intact. When the strain was somewhat more than 3%, about 20% of the outer surface of the specimens usually had flaked off.

The results shown in Figure 9 actually include an additional unloading-reloading cycle before each 30-minute period of sustained load. The purpose of the modification was to determine whether viscous, or time-dependent, strain affected the resultant plastic, or irrecoverable, strain that was measured. It can be seen from the results that the slopes of the unloading curves are the same and hence the plastic strain was independent of any viscous strain. The moduli of deformation obtained from the unloading curves varied between 1.4 and 2.0 x 10^5 ksc.

Figure 9 also shows typical creep curves that were obtained from the sustained loads at the various stress levels. It is possible that below some critical, or yield, stress the creep rate is constant, with the variation in the curves at stresses of 22.2%, 44.4% and 66.7% of the uniaxial compressive strength being merely dispersion about a mean value. From tests done on specimens oriented horizontally and vertically with respect to the bedding, it was found that creep rates were less in the vertical direction than in the horizontal direction. Other tests examining the effects of carnallite indicated that for contents between 12% and 40% no detectable changes seemed to occur in either strength or creep rates.

Finally, Figure 10 shows typical results of displacement measurements made with borehole extensometers in the walls of pillars (22). (Similar patterns have been obtained in hard rock but without creep (34).) This pattern is substantially as would be expected from the application of the excavation stress shown in Figure 1(b) on the sides of the pillars.

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