Some Aspects of Strata Movement relating to Mining under Water Bodies in New South Wales, Australia

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ABSTRACT

Successful mining layouts for mining coal under large water bodies should ensure that a substantial thickness of overburden strata remains undisturbed to prevent the flooding of mine workings. One of the criteria followed in many countries for controlling sub-surface strata disturbance is to specify a limit on the rockhead tensile strain. However, the generally specified rockhead strains are well in excess of the strain required to cause surface fracturing. It therefore leads to the conclusion that the composition of strata between the cracked zone on the surface and the caved zone above the extracted seam plays an important role in preventing water inflows into mine workings. Ductile beds like shales, mudstones and clay bands appear more effective than sandstone beds of the same thickness.

INTRODUCTION

One of the important considerations in the design of mine layouts for mining coal beneath water bodies is the prevention of mine inundation. The ingress of water into a mine can be controlled by pumping except when the rate of flow is so great that it is described as an "inrush". When the water body is large, consequences of inundation would be catastrophic. Sealing off the affected working or the connection between the surface water body and the working which causes the inrush may not be possible in some cases. The safety of mine workers and the mine could then be under threat. To prevent these incidents occurring, guidelines have been developed in various countries for limiting mining and the surface and sub-surface strata disturbance.

The criterion for designing mine layouts under large water bodies in many countries is almost solely based on limiting the rockhead tensile strain to 7.5mm/m. It does not distinguish between the different types of overburden strata in terms of their ability to provide a barrier to vertical movement of water. In other words, the nature of rocks and the thickness of individual beds, which act as aquicludes, are not taken into account. However, strata under varying conditions of constraint may crack differently ranging from brittleness to plasticity. Therefore, there is no reason to believe that surface cracking caused by mining penetrates any deeper than the particular stratum at or just below the surface. For this reason, it can be argued why a particular relationship can be postulated between tensile strain at a free surface and the penetration of water into mine workings. The adoption of a limit on the surface strain is probably only a means of controlling the general strata disturbance.

Many successful cases of mining under large water bodies designed on the basis of the limiting rockhead tensile strain of 7.5mm/m lead to the conclusion that fractures caused by the rockhead strain are either healed or they do not extend deep down the strata to reach the caving zone. In the latter case, there is a zone between the cracked zone on the surface and the caving zone above the extracted seam, which is free from fracturing. In either case, the criterion of limiting the rockhead strain does not in itself provide a complete explanation for mine safety.

CRITERION IN NEW SOUTH WALES FOR PREVENTING WATER INRUSH

Mining under inexhaustible bodies of water like tidal lakes and the Pacific Ocean in New South Wales (N.S.W.) is controlled in accordance with the regulations framed and administered by the Chief Inspector of Coal Mines[1]. The present regulations in relation to minimising surface and sub-surface strata disturbance are based on the following guidelines.

1. The minimum solid strata depth (D) for any extraction to occur is 46m.
2. The maximum horizontal tensile strain (Emax) at rockhead is limited to 7.5mm/m.
3. For total extraction to occur, the minimum solid strata depth is sixty times the extracted seam thickness (T).

Guideline 3 was obtained from Guideline 2 using the following relationship connecting strain, subsidence and depth.

Emax = K x Smax/ D where,
Smax = maximum subsidence (m)
K = tensile strain coefficient (non-dimensional)

Guidelines in N.S.W. are based on a report prepared by Wardell[2], who assumed the following values in arriving at the minimum solid strata cover D for mining a seam of thickness T.

Emax = 0.0075; K = 0.75
Smax = 0.6 x T, where T is the extracted seam thickness
D = K x Smax / Emax = 0.75 x 0.6 x T / 0.0075 = 60 x T

Relating 60T to the rockhead tensile strain of 7.5mm/m is valid only for the assumed values of Smax and K. If the values for Smax and K are changed, the minimum depth would be different for the same rockhead tensile strain of 7.5mm/m. In other words, the rockhead tensile strain is the independent and essential criterion, and 60 times the extracted seam thickness is the dependent and nonessential criterion.

The limiting rockhead strain refers to the sum total of strains resulting from the extraction of all seams. In the case of panel and pillar layouts, panels and pillars are to be superimposed irrespective of the parting distance between seams.

THEORETICAL ASPECTS OF STRATA MOVEMENT AND PERMEABILITY

Limitation of the strain criterion

Even strong and homogeneous rock specimens have found to fail in laboratory tests under relatively low tensile strains of the order of 1mm/m. Surface strains greatly in excess of 1 mm/m are common in longwall mining. Experience in N.S.W. and elsewhere indicates that surface cracking occurs at strain levels much less than the permitted rockhead tensile strain of 7.5mm/m. The limit on tensile strain is therefore not an attempt to restrict strain to a value which will not cause fracturing of the seabed rocks.

The reason for the ability to work under sea without undue amounts of water entering the mine workings appears to be due to factors other than the limiting rockhead strain, including the following.

1. an undisturbed strata of adequate thickness, below the cracked zone at the sea bed and above the caved zone. The degree of impermeability of rocks within the middle zone probably determines the adequacy of its thickness. The more impermeable the strata, the lesser the required thickness.
2. impermeable sediments in the sea floor which will fill the surface cracks.
3. flexibility of shales and mudstones compared with sandstones and conglomerates in deforming without or with minimum fracturing.
4. swelling shales and mudstones in the strata which can fill the cracks.

Although some or all of the above mechanisms and possibly others must operate to explain the successful application of undersea mining, their relative importance and even their existence has yet to be proven. In any case, local geology must have a significant effect on the relative importance of the mechanisms, particularly the concept of impermeability and flexibility of some strata.

Hypotheses of strata movement

According to the simplest hypothesis in which the undermined strata is treated as a uniform rock beam in bending, the tensile and compressive stresses are induced in the extremities of the beam. Zones of horizontal tension occur immediately above and below the extraction void and on the surface above the abutments. The strata between these two zones is the undisturbed central zone in a state of horizontal compression in which the permeability is not increased. This would be the case even when the rock mass is not uniform, but consists of a number of beds, if the various beds do not slide relative to one another due to overburden pressure and friction along bedding planes. In the vertical direction, strata dilate above the extraction void as the measured subsidence is generally less than the extracted seam thickness. Above the abutments, the strata is compressed vertically.

However, if the undermined strata is considered as a mass with horizontal bedding planes along which beds are capable of slipping, then on bending, beds would move parallel to their stratification. Each bed would then bend with tension on its convex lower surface and compression on the concave upper surface creating subsidiary horizontal tensile zones throughout the full depth of strata. This case is analogous to the bending of a laminated beam in which each layer bends independently with bedding pane slip between layers.

In either case, whether the rock mass behaves as one massive unit or as several units each slipping relative to the other, extensive zones of horizontal compression and tension form during bending without any neutral axis parallel to the stratification becoming discernible.

Bed separation occurs if there are stronger and weaker layers or thicker and thinner layers in the sequence. As the number of layers increases, the thickness of zones of compression between the tensile zones is considerably reduced.

Change in permeability

Bedding plane separation, bedding plane slip and horizontal tensile strains, individually or in combination, will lead to changes in strata permeability.

Bulk permeability of strata can be divided into two components, horizontal and vertical. Horizontal permeability will clearly increase due to bedding plane separation. If bedding planes, which are not perfectly flat initially, do not fit together perfectly after the slip, voids can be formed resulting in an increase in the horizontal permeability. In zones of horizontal tensile strains, if the tensile strains exceed the tensile strength of rocks, vertical cracking will occur resulting in an increase in vertical permeability. In many cases, it is not necessary to invoke tensile failure of rocks, since sedimentary rocks normally have prominent jointing at right angles to bedding. Before mining, joints may be held tightly closed by the in-situ horizontal stresses. When tensile stresses are induced by mining, these joints may open and cause an overall increase in vertical permeability. Joint opening may be further increased by water pressure in the cracks, once seepage commences.

In the context of mining under water bodies, the vertical permeability is important, as mine flooding is possible only if there is a continuous hydraulic connection between the water body and the mine workings caused by increased vertical permeability. Horizontal permeability may increase throughout the overburden, but it need not necessarily lead to a continuous hydraulic connection without an increase in vertical permeability.

Influence of Geology

In a tightly constrained condition, many rocks including coal are impermeable and remain so until they are fractured and expanded. In constrained condition, shales, mudstones, siltstones and coal are impermeable, whilst sandstones and conglomerates are considered more permeable. In spite of this, most rock materials with a few exceptions have relatively low permeability when compared with the high permeability caused by the joints and fissures in the rock mass. It can be said that the water flow occurs almost entirely through the voids and fissures in the rock mass and not through the rock material. Therefore, the permeability of the rock mass will depend on the degree of jointing and fracturing and the opening and interconnection of these fractures.

Mudstones, shales and claystones absorb a large amount of strain energy before fracture. Thus, these beds in the overburden can subside significantly without fracturing and therefore are preferred to sandstones and conglomerates in providing a barrier against downward movement of surface water. In the U.K., an analysis of shaft sections and borehole logs from most of the coalfields with undersea workings indicated an average of 35% sandstone, 47% shale and 13% fireclay[(3)]. In N.S.W., the proportion of ductile strata in the overburden is relatively less. It has been further suggested that for a successful undersea mining, half of Coal Measures strata should be impervious and it is important to avoid fracturing the middle of the "sandwich".

A most important aspect of geology relevant to undersea mining in the presence of faults or dykes which may form continuous feeders of water to the mine and so cause flooding even at considerable depths.

INVESTIGATION INTO SUB-SURFACE STRATA MOVEMENT

Surface Fractured Zone

The effect of tension fractures on the surface in creating hydraulic continuity in the vertical direction was studied in N.S.W. by Morton(4). Mining consisted of total extraction of two seams, one at 277m and the other at 301m depth below the surface. The extraction thickness was 1.8m and 3m respectively in the upper and the lower seams. The total subsidence was of the order of 2.1m. On the basis of the average depth of mining of 289m and total extracted thickness (T) of 4.8m, the overburden thickness was 60T. Where the surface fractures were extensive and were up to only 9m apart, inclined boreholes were drilled and pressure tested. Morton observed that the surface fractures did not extend to depths greater than 12m (2.5T), in terms of their ability to create vertical hydraulic continuity.

In another study of permeability of strata undermined by longwall mining at 116m depth, significant changes in bulk permeability was noticed in the strata extending to a depth of 20m (8T) below the surface(5). The extracted seam thickness was 2.7m and the overburden was equivalent to 43T. The extraction was, however, sub-critical, the width of extraction being 145m.

The above two studies indicate that the effect of surface fractures in creating vertical hydraulic continuity is confined to a depth probably not exceeding 10T.

Caving Zone

In order to understand the behaviour of undermined strata, sub-surface strata movements were monitored over longwall panels by a multi-wire anchoring system installed in a vertical borehole extending from surface to the extracted seam(5,6,7). Table 1 summarises the details of mining geometry and caving heights in two boreholes, one over a longwall panel at the Ellalong Colliery in the Lower Hunter valley of N.S.W. and the other over a longwall panel in the Invincible Colliery in the Western Coalfield.

The immediate roof of the Greta seam at the Ellalong Borehole, up to 50m height, consisted primarily of massive sandstones (80%), siltstones (10%) and mudstones and coal bands making up the remainder. The overburden above the 50m horizon to the surface generally consisted of massive sandstones. The caving height was approximately 12% of the cover depth and 14% of the extraction width.

Table 1
Details of mining geometry and caving height

name of colliery	mining depth (H)	extraction width (W)	extraction thickness (T)	caving height (X)	X/T
Ellalong	370m	340m	3.5m	46m	13
Invincible	116m	145m	2.7m	23m	9

In the case of the Invincible Borehole, the strata were more bedded and consisted of an interbedded succession of sandstones, siltstones and mudstones each making up approximately 25% of the overburden thickness. The remainder of the overburden was made of coal bands either existing independently or interbedded with mudstones and claystones. The immediate roof of the Lithgow seam consisted of carbonaceous mudstones interbedded with siltstone and coal bands. The caving height was approximately 20% of the cover depth and 16% of the width of extraction.

Distribution of Subsidence and Strains in the Middle Zone

The movement of sub-surface subsidence in the two boreholes is shown in Figure 1. In the case of the Ellalong Borehole, large vertical dilations were confined only to the caving zone. In the shallower Invincible Borehole, the dilation (which is a measure of bed separation) was relatively large throughout the overburden due to smaller overburden pressure and more bedded nature of the overburden.

The distribution of vertical dilation is shown in Figures 2 and 3. The average dilation of strata extending to 320m (90T) below the surface was only 1.28mm/m in the case of the Ellalong Borehole. In the overburden extending to the depth of 75m below the surface, the dilation was less than 1mm/m. Understandably, large vertical dilations, ranging between 1 and 10mm/m, were monitored throughout the shallow overburden (40T) of the Invincible Borehole.

The strain contours were layered, which indicates a possible correlation between strata dilation and geology. Vertical dilation tended to be much more closely related to stratigraphy than to proximity to the extracted seam roof. This tends to be more pronounced at the Invincible Borehole, where larger dilations were associated with layers of sandstone, siltstone and conglomerate. Layers of mudstone, claystone and coal beds subsided with relatively smaller dilations. This observation suggests that beds of shale, mudstone and coal bands can be effective in preventing the development of continuous channel for surface water to flow into mine workings.

A similar multi-wire borehole study of sub-surface strata movement was carried out over a longwall panel at 420m depth in the Tahmoor Colliery in the Southern Coalfield of N.S.W.[8] The study extended to a depth of only 165m below the surface (Figure 4). The Hawkesbury Sandstone Formation to the depth of 150m below the surface consisted of fairly massive or thickly bedded sandstone. The Bald Hill Claystone Formation between 150m and 170m consisted of chocolate shale. The average vertical dilation in the overburden extending from the surface to 165m depth was 0.77mm/m and in the region extending to the depth of 110m below the surface, dilations were less than 0.5mm/m.

In all cases, the regions of larger dilations were separated by regions of smaller dilationss. It means that even if the strata undergoing relatively larger dilations fractured, these fractured beds would be sandwiched between beds undergoing smaller dilations and probably not fractured. In this situation, vertical continuous hydraulic connections extending from the surface cracked zone to the caved zone is unlikely to develop in the overburden.

From the above, it can be concluded that the rockhead strain cannot be the sole criterion for mining under large water bodies, but the composition and distribution of strata within the overburden also play an important part in preventing miné flooding.

Strata Fracturing and increased Bulk Permeability due to Mining

Strata fracturing expressed as RQD factor, fracture frequency and bulk permeability was compared in two boreholes, one drilled before and the other drilled after the completion of mining at Invincible and Tahmoor Collieries[5,8]. In both cases, RQD factors were lower and the number of fractures per metre length was more in the post-mining borehole for the mining depth range from 116m to 420m (Figure 5 and 6).

Post-mining bulk permeability generally increased after mining in both cases with some important exceptions. The increase in permeability in shales, mudstones and coal bands was less than that in sandstones and conglomerates. The change in bulk permeability tended to be much more closely related to stratigraphy than to proximity to the extracted seam. Even though an increase in bulk permeability does not necessarily mean a corresponding increase in vertical permeability, no increase in bulk permeability obviously means no increase in vertical permeability. In other words, if the overburden strata consist of beds of shales, mudstones and coal bands, continuous vertical hydraulic connections to mine workings are unlikely to occur.

CASES OF LONGWALL MINING UNDER WATER BODIES

Mining under Lake Macquarie

In N.S.W., limited retreat longwall mining has been carried out underneath the Pacific Ocean and tidal water bodies like Lake Macquarie in the Newcastle Coalfield. Table 2 gives the details of the mining geometry adopted for mining in the Dudley seam. The panels were separated from each other by stable chain pillars. There was alluvium of around 25m thickness in the lakebed above the solid strata. The calculated rockhead tensile strains were under 2mm/m.

Beds of sandstone, siltstone and conglomerate made up 50% and the more ductile beds of shale, coal and mudstones made up the remaining 50% of the overburden. The strata composition based on the information from two boreholes in the area is as below.

sandstone and siltstone	36 - 43%
conglomerate	16 - 7%
tuffs	13 - 14%
shale, coal, mudstone	35 - 36%

The average overburden thickness was 110T. Allowing for the caving zone and the surface cracking zone, the middle zone was well over 60T thick of which nearly 50% consisted of ductile strata. There was no reported water entry into mine workings.

TABLE 2
Details of longwall mining layout under Lake Macquarie

longwall no.	solid cover depth (D)	thickness of seam (T)	panel width (W)	(panel width / solid cover)
1	260m	2.1m	155m	0.60
2	250m	2.2m	115m	0.46
3a	245m	2.1m	140m	0.57
3b	245m	2.3m	140m	0.57
4	245m	2.1m	145m	0.59
5	245m	2.1m	125m	0.51

Mining under the Pacific Ocean

Five longwall panels were extracted from underneath the Pacific Ocean during the 1980s, four in the Borehole seam (LW1, LW4, LW5 and LW7) and one in the overlying Victoria Tunnel seam (LW3). Mining operations were carried out commencing approximately 1 km from the shore line and retreating to pass under the sand dunes of the coastal plain. Panel LW4 in the Borehole seam was directly below panel LW3 in the Victoria seam. Table 3 gives the details of the mining geometry.

There was considerable alluvium on the lakebed, the thickness varying between 40m and 50m. The strata between the two seams and up to 140m height above the Victoria Tunnel seam consisted predominantly of sandstone, shale mudstone and tuff. There was a massive 85m thick bed of conglomerate above the 140m horizon and extending to the bottom of the alluvium bed.

The overlying LW3 panel was mined before mining in LW4 panel commenced. The calculated strain due to mining in LW3 panel was 3.5mm/m. The cumulative strain after the extraction of LW4 panel was nearly 6mm/m after taking into account the superimposition effect of adjacent panels.

The solid cover above LW3 panel was equivalent to 60T with conglomerates contributing 30T and the interbedded sandstone, mudstone, shale and coal bands contributing the remaining 50%. Allowing for the surface cracked zone (10T) and the caved zone (15T), there would be effectively 20T of conglomerate cover and 15T of shale-sandstone cover for providing a barrier to the lake water getting into mine workings. During mining in LW3 panel, six major inflows of water occurred in which the inflow for a few days was more than 2.5 times the normal make of water. Analysis of water indicated that, although saline in nature, it was not sea water, but originated from locations in the strata above the Victoria Tunnel seam. Saturated sandstone lenses within shales existed along with perched water tables which were considered the likely sources of water inflow.

TABLE 3
Details of longwall mining layout under the Pacific Ocean

longwall no.	solid cover depth (D)	thickness of seam (T)	panel width (W)	(panel width / solid cover)
LW1	225m	2.3m	78m	0.35
LW4	230m	2.3m	130m	0.57
LW5	205m	2.2m	113m	0.55
LW7	250m	2.2m	142m	0.57
LW3	165m	2.7m	138m	0.84

CONCLUSIONS

The limiting tensile strain at the rockhead specified for mining under large water bodies in many countries is far in excess of the tensile strain required for fracturing the rockhead strata. It is therefore difficult to understand why one could postulate a relationship between the tensile strain on a free surface and the penetration of water into mine workings. In spite of this, many countries including Australia have regulated mining by specifying an upper limit on the rockhead tensile strain.

The successful extraction of coal under large water bodies must be largely a combination of empirical experience and trial (but not a trial and error). Error must be avoided, if it means the flooding of a mine. Perhaps the most important safeguard is the existence of a substantial thickness of more or less impermeable strata, but it also seems reasonable to at least analyse and compare the deformations of the overburden with that of a successful past mining layout.

The limiting tensile strain of 7.5mm/m was suggested by Wardell for N.S.W. on the basis of mining experience in the U.K., where the proportion of shales and fireclay within the undermined overburden was higher than that in N.S.W. In N.S.W., mining under the Pacific Ocean and Lake Macquarie has occurred so far with rockhead tensile strains well under 7.5mm/m. In all cases, there was a substantial thickness of strata consisting of shales and mudstones.

It cannot be stated that limiting rockhead horizontal strain will provide total safety against any inflow of surface water while working below it. In developing guidelines, past experience, surface and sub-surface subsidence considerations and experience and knowledge of fractures and caving in a given geological environment and a contingency to allow for incomplete knowledge of all factors should be taken into account. At the end of the day, all rules and regulations will have to be based on experience and any limitation for underwater workings must incorporate a large safety factor.

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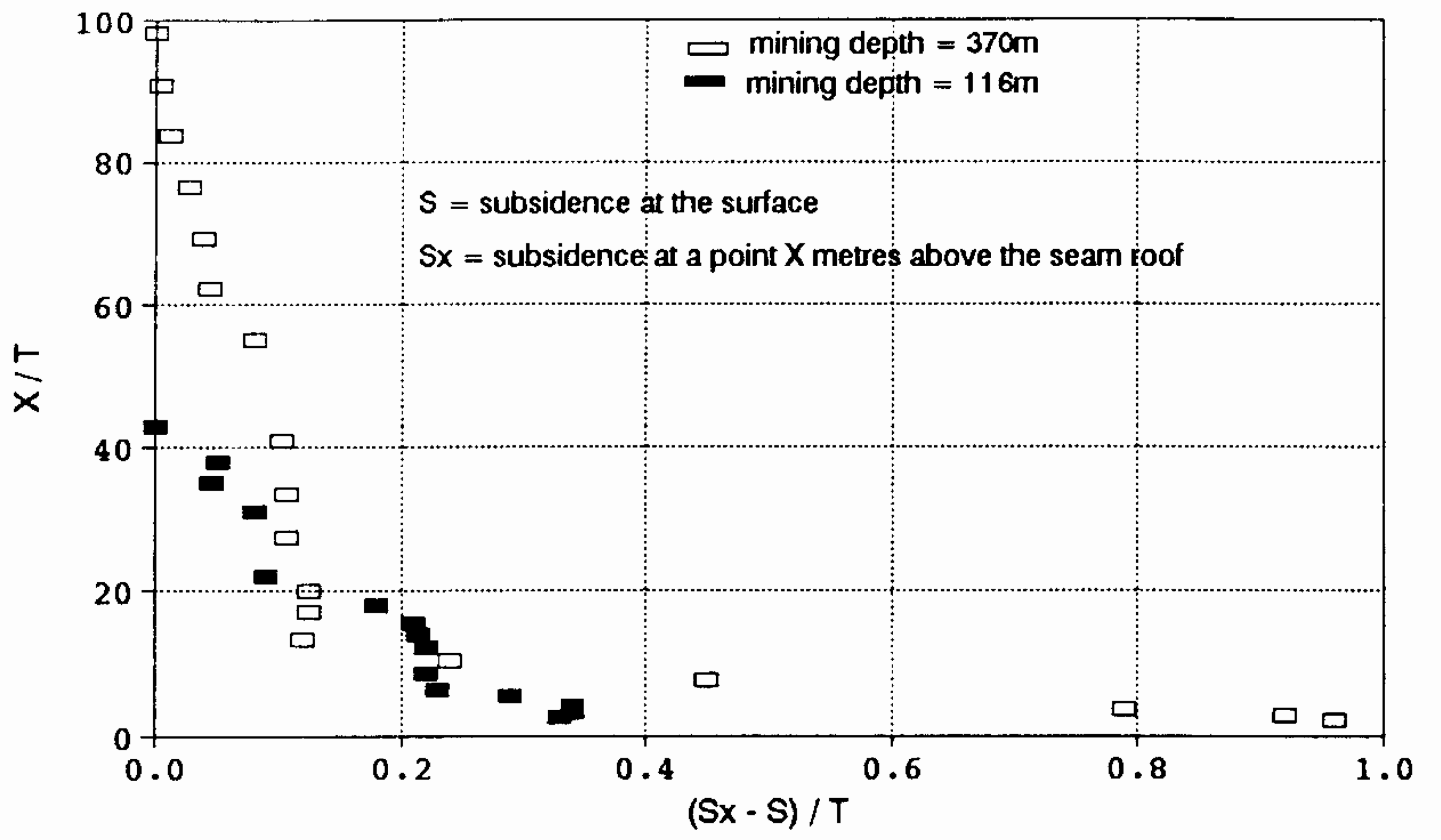

FIGURE 1 - Strata movement within the overburden

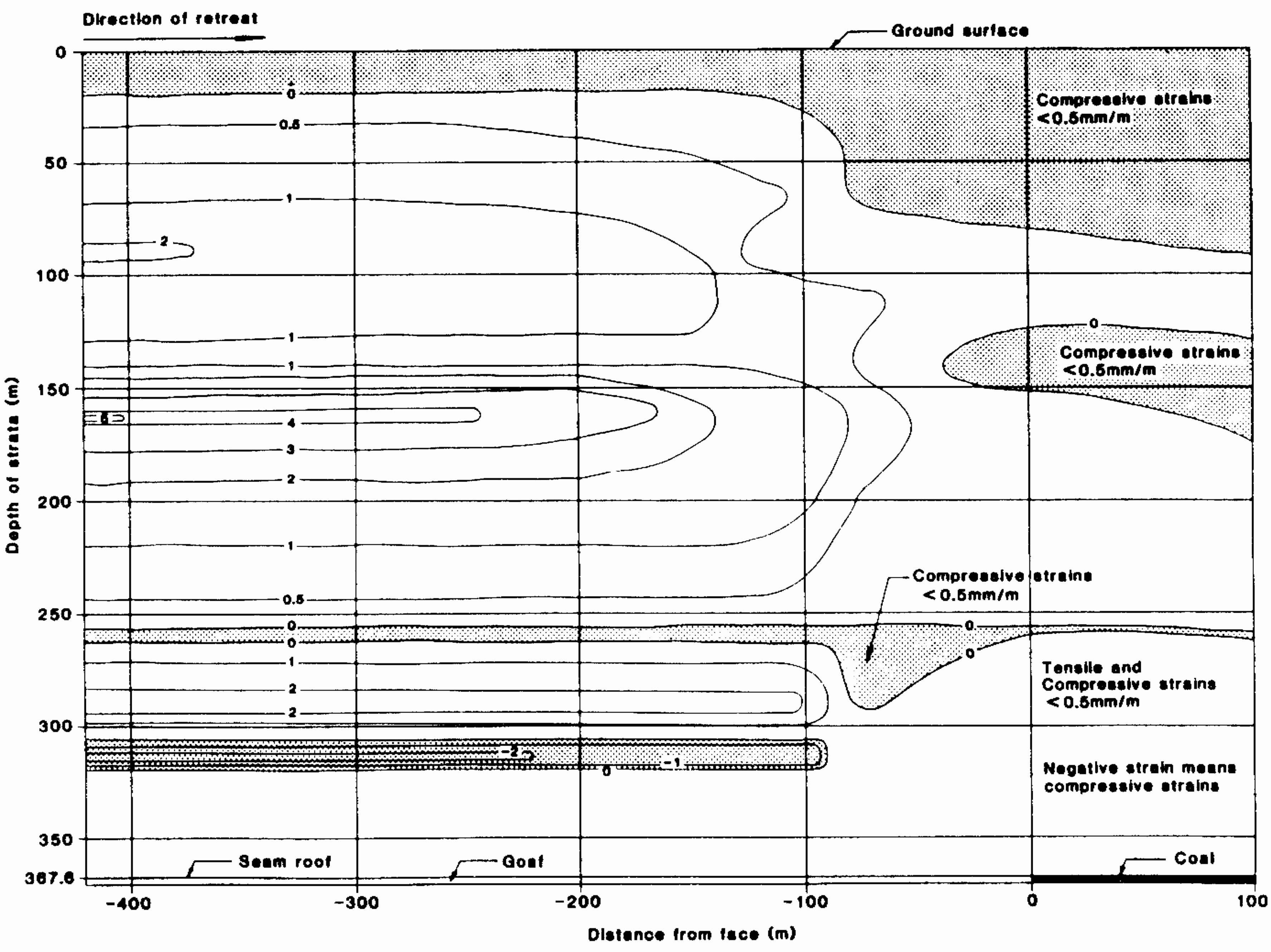

FIGURE 2 - Contours of vertical dilation (mm/m) in the overburden - Ellalong Borehole

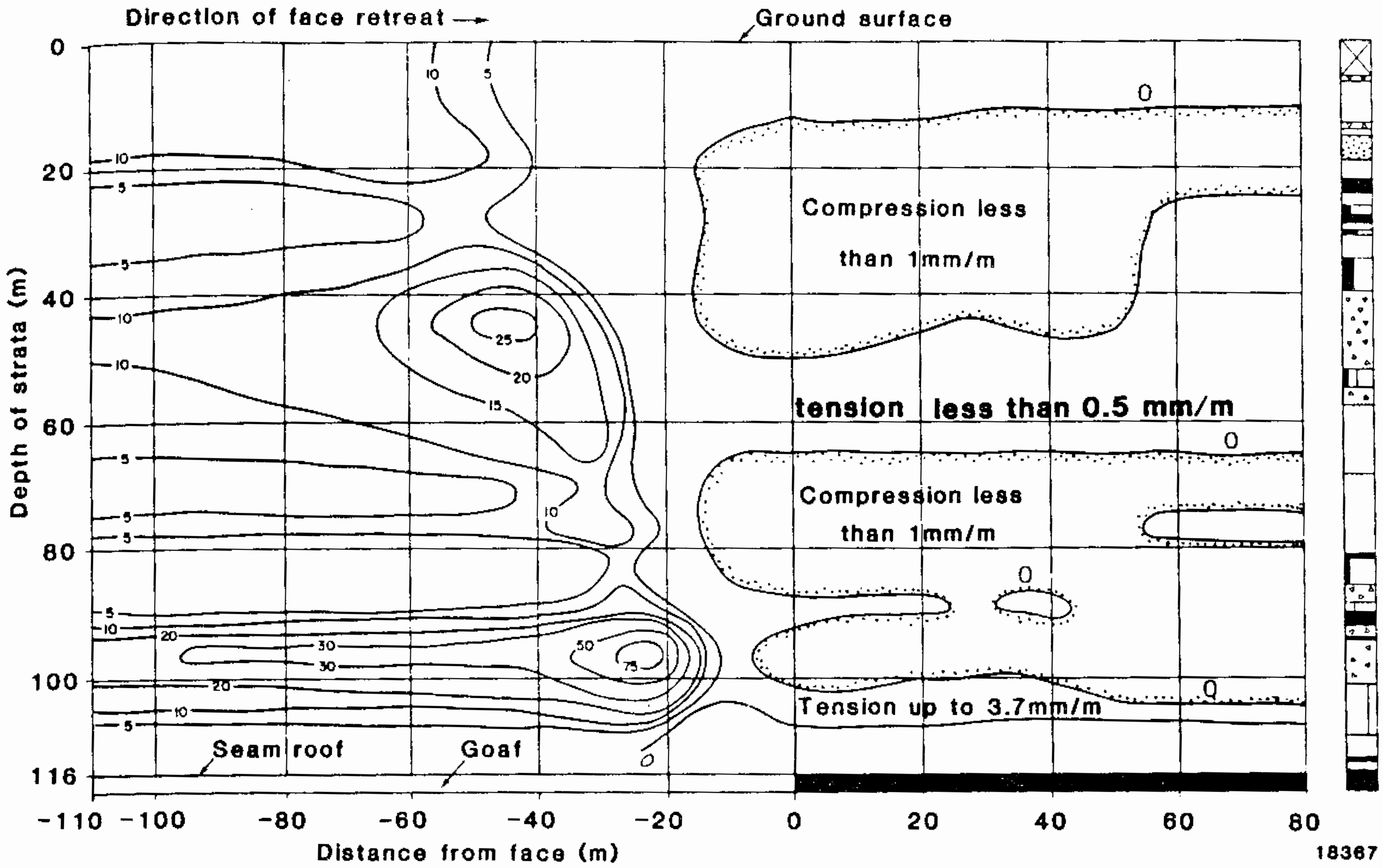

FIGURE 3 - Contours of vertical dilation (mm/m) in the overburden - Invincible Borehole (depth legend as in Figure 5)

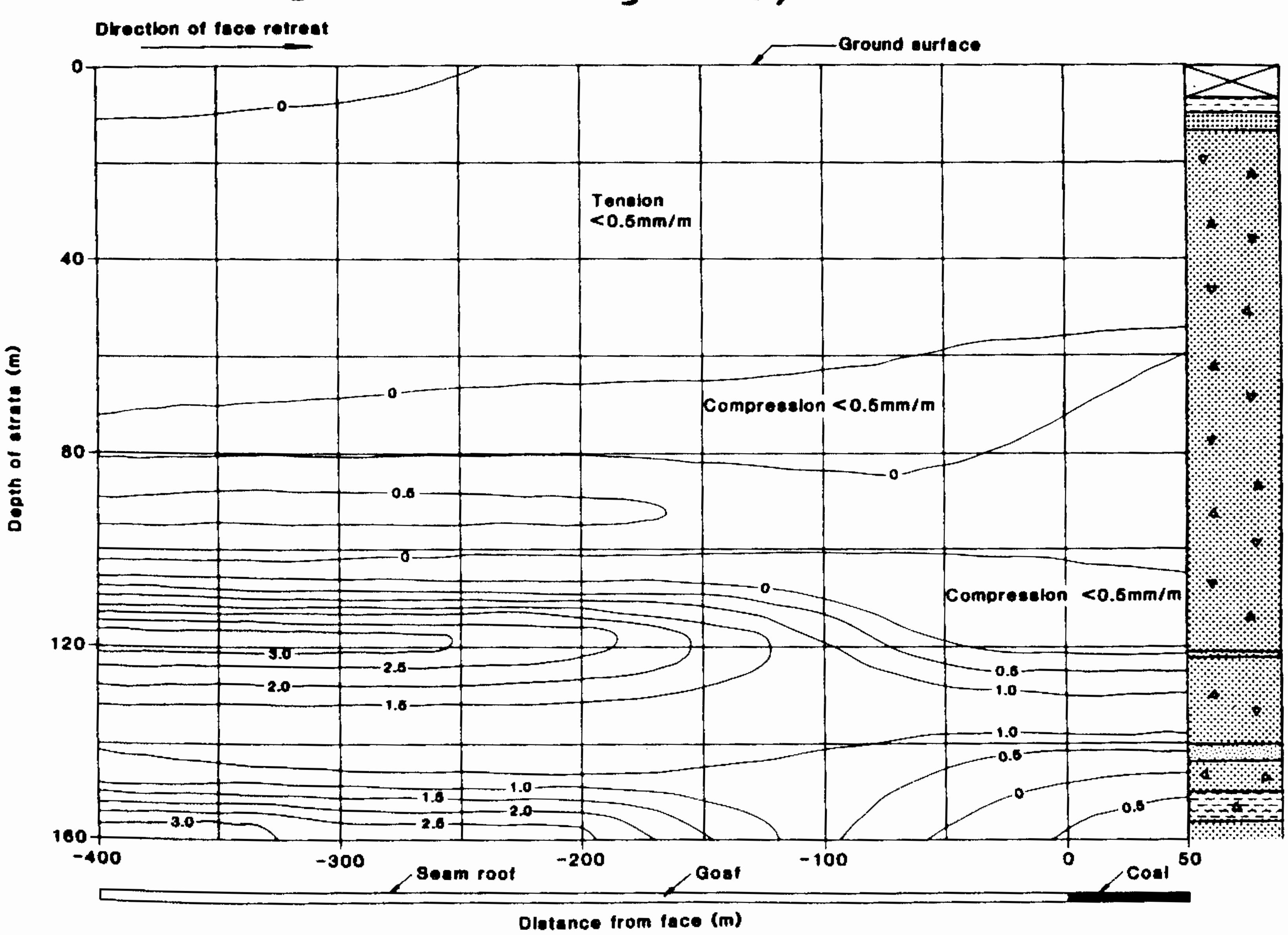

FIGURE 4 - Contours of vertical dilation (mm/m) in the overburden - Tahmoor Borehole (depth legend as in Figure 6)

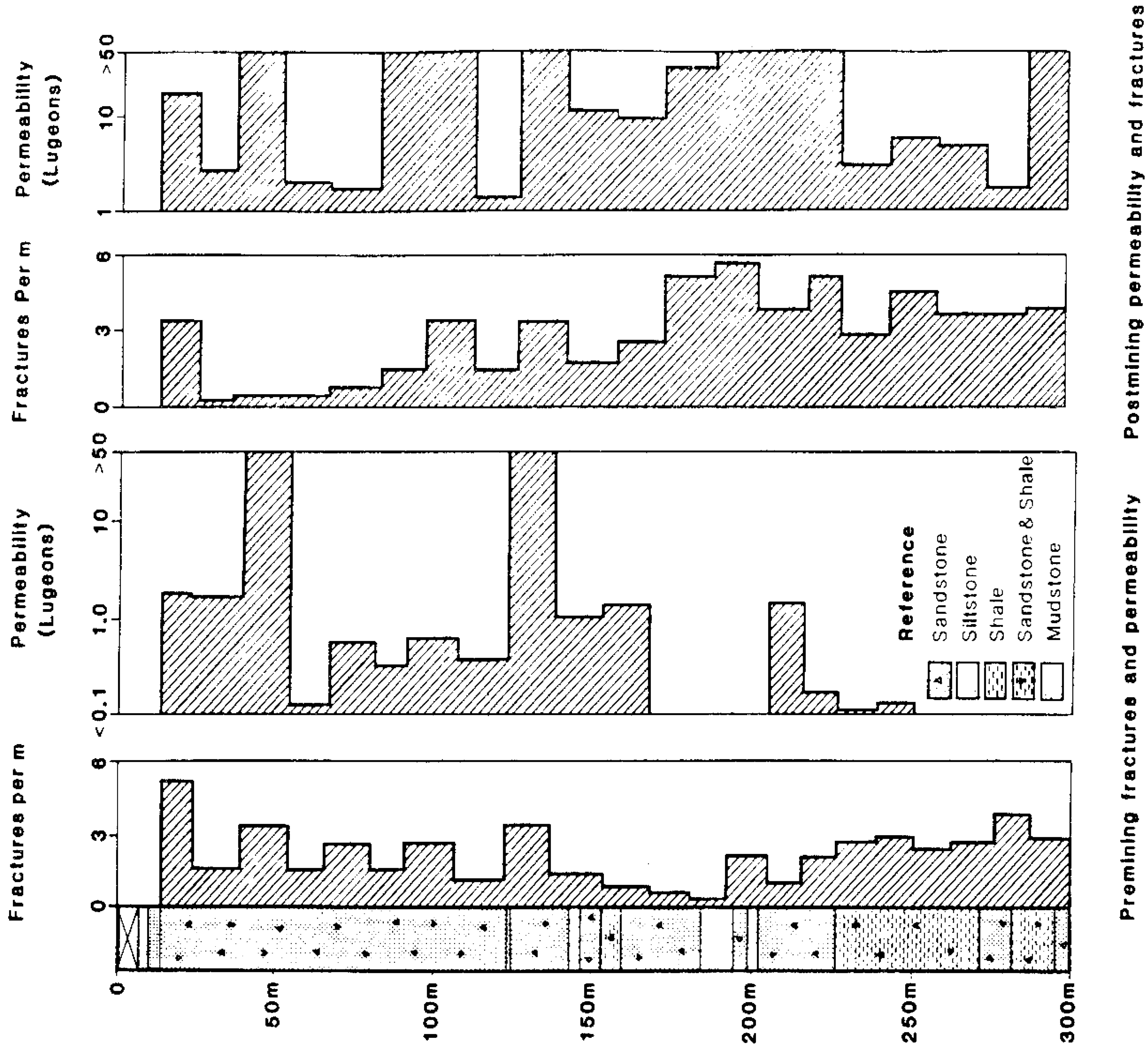

FIGURE 6 - Changes in bulk permeability and fractures - Tahmoor Borehole

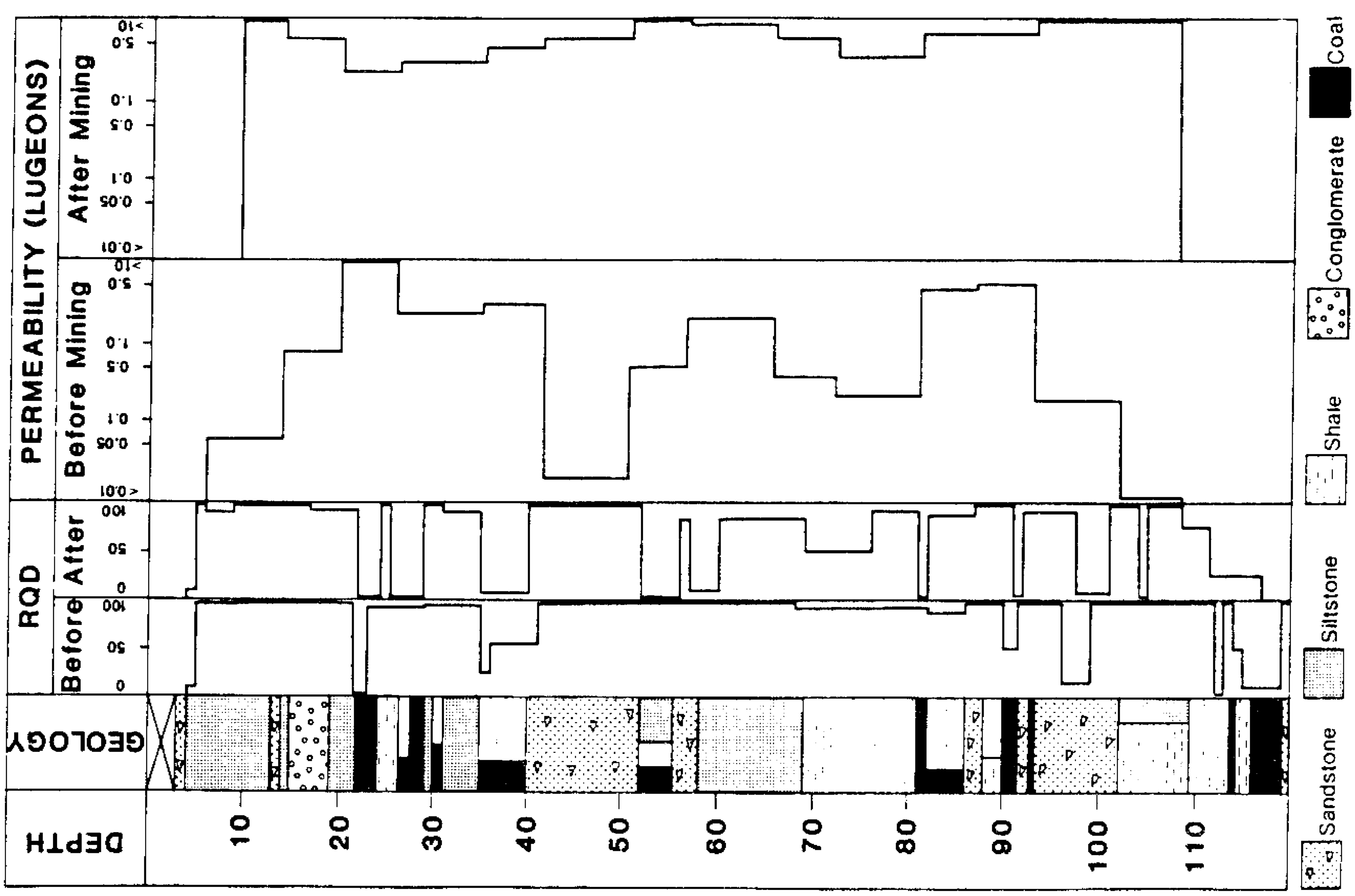

FIGURE 5 - Changes in bulk permeability and RQD - Invincible Borehole