Laboratory testing of samples collected from underground produced a similar effective modulus (130 to 185 MPa). Since instruments were ultimately located in the lower third of the pillars they would not have detected the maximum changes in pillar displacement and ashfill pressure which could have occurred nearer the mid-height of the pillars.

With the exception of a major intersection fall, attributed to an excessive local bord width of 8.5 m, no support problems were encountered during mining. Slabbing and spalling of the exposed upper 3 m of pillars since the completion of mining has also been minimal. In addition to providing lateral confinement to the coal pillars, the ashfill acted as a good working platform. No load-bearing or dust problems were encountered and the smooth, level surface resulted in easily and well-maintained travelling ways.

It may be assumed that the lack of ashfill confining the upper 3 m of the 12 m high pillars had no significant effect on pillar stability since ashfill extended to at least two-thirds of the pillar height. Had the entire mining height been ashfilled and had ashfill increased pillar strength by 50 per cent the ultimate effective safety factor of the workings would have been 0.9. The lack of strata displacement which occurred indicates that the final effective safety factor was probably much greater. This may be due to the increased effectiveness of the ashfill associated with the considerable pillar width (16 m) and the large initial pillar width:height ratio (4.27). It may also be partly due to the limited panel dimensions in relation to the depth below surface and to the associated reduction in panel pillar load which occurs when panel pillar stiffness is reduced as mining height is increased. These aspects are to be investigated further in another experimental panel of larger dimensions in which new ashfilling technology is also to be evaluated.
8.6 Conclusions

Thick seam bord and pillar mining methods incorporating stowing are only economically feasible under South African conditions if power station ash, specifically P.F.A., is utilized as the source material. This material has a number of advantages over other commonly employed stowing materials, the most significant of which are that it possesses self-cementing properties in the presence of water and that the costs of stowing the material underground are comparable to the costs associated with disposing of it on surface. Experience with disposal orientated underground ashfill placement systems has highlighted that the in-situ quality of P.F.A. derived ashfills can vary considerably if the in-situ water:P.F.A. ratio is not carefully controlled. With improved ashfilling technology it is practically and economically feasible to achieve a consistent, good quality in-situ ashfill.

Model pillar tests indicate that good quality ashfill increases pillar strength by about 50 per cent. Theoretical considerations and practical in-situ experiences indicate that this strength increase may be greater at depth because of the favourable influence of a large pillar width on ashfill effectiveness. The results of research currently in progress are required before the effects of ashfill on pillar behaviour can be quantified accurately.

In the interim it is not unreasonable to accept a fixed increase of 50 per cent in pillar strength due to the presence of ashfill. On this basis, bord and pillar mining with top- or bottom-coaling followed by ashfilling will result in the extraction of an additional 3 to 6 per cent of reserves at shallow depth (±50 m) from seams less than 11 m thick. At a depth of 200 m an additional 9 per cent of reserves can be recovered from a 6 m thick seam reducing to 5 per cent in an 11 m thick seam. Alternatively, bord and pillar mining with repeated cycles of ashfilling and
top-coaling may result in the extraction of an additional 8 per cent of reserves from a 6 m thick seam and up to 30 per cent of reserves from an 11 m thick seam at a depth of 50 m. At a depth of 200 m an additional +12 per cent of reserves can be extracted from seams 6 to 11 m thick.

Assuming that ashfill increases pillar strength by 50 per cent, the incorporation of ashfilling into bord and pillar mining in the South Rand Coalfield will result in a 60 to 80 per cent improvement in percentage extraction. Unit costs associated with achieving this additional extraction are likely to be comparable to, or even less than, those associated with current mining operations (section 7.7). This aspect alone justifies further research into the incorporation of ashfill into thick seam bord and pillar mining methods. An accurate assessment of the percentage increase in extraction to be gained from bord and pillar mining incorporating ashfill in the other three potential thick seam mining coalfields can only be made in the light of site specific conditions, but indications are this is of the order of 15 to 30 per cent.

Ashfilling may also find application in other areas of thick seam mining. In particular, an assessment of the geography of potential thick seam mining coalfields (Appendix VI) has revealed that structures usually occupy or influence 15 to 20 per cent of the surface. Salamon and Oravecz (1975) note that the area of influence of these structures on underground workings extends to a distance of D/2.7 away from the structures, where D is the depth to the workings. Thus, up to 35 per cent of thick seam reserves are affected by surface restrictions. The incorporation of ashfill into bord and pillar mining in these areas may relax some of the severe constraints currently imposed on mining in these areas and enable a considerable increase in the overall percentage extraction achieved from a lease. Other areas where ashfill and the findings of research into ashfill may find application in thick seam mining include:
1) the construction of packs;

ii) the limiting of surface subsidence;

iii) the prevention of spontaneous combustion in goaf material;

iv) the consolidating of goaf material.
9.1 Introduction

The Karoo dolerites represent a widespread hypabyssal phase contemporaneous with the Stormberg Series (Table 16). The majority of these dolerites take the form of sills, that is bodies intruded parallel to the bedding, or dykes, that is bodies intruded vertically or near vertically. Area A of the South Rand Coalfield and large portions of the Vereeniging-Sasolburg Coalfield which currently offer the greatest potential for implementing thick seam mining methods are overlain by dolerite sills exceeding 30 m in thickness. Since the strength and the elastic modulus of these sills are an order of magnitude greater than those associated with the adjacent stratum, the sills influence significantly the manner in which stresses are distributed around mine workings. Thus, an appreciation of the behaviour of massive dolerite sills is required when designing mine layouts and extraction procedures.

Unfortunately, the geometry and characteristics associated with massive dolerite sills in South African coalfields constitute a specific, almost unique problem. Recent mining experiences have highlighted that previous research conducted into the behaviour of these sills is inadequate. In particular, experience has shown that the theory of dolerite behaviour developed on the basis of this research is unreliable when applied to different conditions to those on which it was derived. Consequently, if thick seam mining methods, especially those which result in caving of the roof strata, are to be implemented successfully in the South Rand
and Vereeniging-Sasolburg Coalfields, further research must be conducted into the theory of the behaviour of massive dolerite sills.

### 9.2 The Significance of Dolerite Sills

#### 9.2.1 General significance

Investigations into the influence of massive dolerite sills on nine workings were initiated following the disastrous collapse of bord and pillar workings overlain by a 36 m thick dolerite sill at Coalbrook Collieries in 1960. The investigations were extended in 1964 to include the monitoring of massive dolerite sills overlying 'total' extraction panels and have continued in stages to date. Three important points relevant to the present discussion which have emerged from these investigations are:

1. The strength and elastic modulus of dolerite are an order of magnitude greater than that of normal coal measure rocks. Table 29 records the typical range in the value of these two parameters for shale, sandstone, coal and dolerite stratum.

#### Table 29

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Typical</td>
</tr>
<tr>
<td>Sandstone</td>
<td>60 - 80</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>40 - 100</td>
<td>70</td>
</tr>
<tr>
<td>Coal</td>
<td>15 - 40</td>
<td>30</td>
</tr>
<tr>
<td>Dolerite</td>
<td>250 - 390</td>
<td>300</td>
</tr>
</tbody>
</table>
2. Dolerite sills less than 15 m in thickness have only a minor influence on mining operations.

3. Dolerite sills more than 30 m in thickness have a significant influence on mining operations. In particular such sills are capable of bridging over spans exceeding 250 m and thus, over whole panels if the minimum panel dimensions are too small to induce failure of the sill.

On the basis of point 3, all future references to dolerite sills as 'massive' implies that such sills are in excess of 30 m thick.

9.2.2 Bord and pillar workings

It is a well-known fact that the load acting on individual pillars in bord and pillar workings depends on the deformation characteristics, or stiffness, of both the surrounding strata and the pillars themselves. A simple qualitative proof of this fact has been provided by Salamon and Oravecz (1975). Briefly, it may be stated that pillar stiffness decreases with decreasing pillar width, decreasing material modulus and increasing pillar height. The stiffness of the surrounding strata increases with increasing panel width, decreasing material modulus and decreasing strata thickness. As the ratio of surrounding strata stiffness:pillar stiffness increases the load acting on a panel pillar decreases. This feature is illustrated for a constant pillar height and constant strata thickness by the graphs in Fig. 1, which were derived by Oravecz (1973) using an electrical resistance analogue. The graphs show the maximum average load, \( q_{\text{max}} \), relative to the modified cover load*, \( q_{\text{mod}} \), which acts on the centre

* Modified cover load = \( q_{\text{mod}} = \frac{q_g D}{1-e} \), where \( q_g \) is the specific weight, \( D \) is the depth and \( e \) is the percentage areal extraction.
2. Dolerite sills less than 15 m in thickness have only a minor influence on mining operations.

3. Dolerite sills more than 30 m in thickness have a significant influence on mining operations. In particular such sills are capable of bridging over spans exceeding 250 m and thus, over whole panels if the minimum panel dimensions are too small to induce failure of the sill.

On the basis of point 3, all future references to dolerite sills as 'massive' implies that such sills are in excess of 30 m thick.

9.2.2 Bord and pillar workings

It is a well-known fact that the load acting on individual pillars in bord and pillar workings depends on the deformation characteristics, or stiffness, of both the surrounding strata and the pillars themselves. A simple qualitative proof of this fact has been provided by Salamon and Oravecz (1975). Briefly, it may be stated that pillar stiffness decreases with decreasing pillar width, decreasing material modulus and increasing pillar height. The stiffness of the surrounding strata decreases with increasing panel width, decreasing material modulus and decreasing strata thickness. As the ratio of surrounding strata stiffness:pillar stiffness increases the load acting on a panel pillar increases. This feature is illustrated for a constant pillar height and constant strata thickness by the graphs in Fig. 1, which were derived by Oravecz (1973) using an electrical resistance analogue. The graphs show the maximum average load, $q_{\text{max}}$, relative to the "modified cover load", $q_{\text{mod}}$, which acts on the centre

\[
q_{\text{mod}} = \frac{SGD}{1-e}, \quad \text{where } SG \text{ is the specific weight, } D \text{ is the depth and } e \text{ is the percentage areal extraction.}
\]
Figure 37. The influence of the ratio of surrounding strata stiffness:coal strata stiffness on pillar load. (Oravecz, 1973).
pillar in a panel of pillars, for various pillar widths, expressed in terms of percentage extraction, panel widths, expressed in terms of the number of panel pillars, and ratios of surrounding strata modulus:coal strata modulus, expressed in terms of the factor 'c'.

In order to satisfy equilibrium conditions a reduction in the load acting on panel pillars must result in an increase in the load acting on the panel abutments. Almost invariably interpanel pillars, or barrier pillars, constitute two or more of the panel abutments. Thus, the load acting on the interpanel pillars will be greater than that calculated by the modified cover load, or tributary area, theory. However since interpanel pillars are usually designed to a width:height ratio exceeding 8, and often 10, which is considered sufficient to make the pillars indestructable, the increased load acting on these pillars will have a negligible effect on their stability. It should also be noted that when panel widths exceed about twice the seam depth, pillars in the centre of a panel are usually subjected to the full modified cover load regardless of the nature of the surrounding strata.

The ratio of surrounding strata stiffness:coal strata stiffness also has a significant influence on the manner in which a collapse of bord and pillar workings occurs. This phenomenon has been described in detail by Salamon (1966), and Salamon and Oravecz (1975). It suffices to note that, should pillar load exceed pillar strength, the possibility of an unstable, or sudden uncontrollable, pillar collapse reduces as the magnitude of the surrounding strata stiffness:coal strata stiffness increases.

From the discussion, it may be stated that for all other parameters constant, as the modulus of elasticity of the
strata surrounding a panel of limited width (less than twice the depth) increases:

i) the load acting on the panel pillars decreases whilst the load acting on interpanel pillars increases, and

ii) the possibility of a sudden pillar collapse occurring reduces.

Therefore, it can be concluded that the presence of a massive dolerite sill in the roof strata of limited width bord and pillar panels separated by substantial interpanel pillars results in an effective increase in the stability of the workings. This conclusion has been verified quantitatively using the boundary element program 'DINCL' developed by Stephansen (1981). The program, an extension of the popular displacement discontinuity program, 'MINAP', developed by Crouch (1976) enables two dimensional stress analysis in inhomogeneously layered rock. Further research by the author has enabled an accurate three dimensional solution to be obtained from the program when modelling bord and pillar workings. This is achieved by manipulating the size of the rib pillars modelled in the two dimensional program so that the stiffness of these pillars is the same as that of the actual three-dimensional square or rectangular pillars. It suffices to note that the solution so obtained agrees to within 0.4 per cent with solutions obtained from three dimensional finite element programs.

The numerical solution 'DINCL' was used to obtain the stress distribution associated with four mining geometries, namely:

1. for a 4 pillar wide panel and for a 10 pillar wide panel with no dolerite sill present in the superincumbent strata, and for
ii) a 4 pillar wide panel and for a 10 pillar wide panel with a 35 m thick dolerite sill present 20 m above the seam horizon.

The input values of parameters employed in these solutions, along with the actual stress distribution profiles so obtained, are recorded in Fig. 38. In previous research the input value for the elastic modulus of each stratum differed slightly to that 'typical' value recorded in Table 29. In order to utilize these existing (and costly) solutions, the same input values have been specified in solutions presented in this section of the thesis. The solutions verify that when a massive dolerite sill is present in the superincumbent strata, the load acting on pillars in a panel of limited width is reduced significantly whilst the load acting on panel abutments is increased. In addition, as panel width increases, the load acting on pillars in the centre of the panel approaches that based on the modified cover load theory, irrespective of the presence of a massive dolerite sill in the superincumbent strata.

Finally, it is worth noting that the presence of a massive dolerite sill above bord and pillar workings can serve to mask the effects of undersized pillars. At moderate panel widths such pillars may not appear to be overloaded because they do not carry the full weight of the overburden. But, if the panel width continues to be increased, deflection of the dolerite sill will also increase, thereby increasing the load acting on the pillars. Eventually, the pillars in the centre of the panel may fail, resulting in a load transfer on to the adjacent pillars. This behaviour, in conjunction with the fact that when the area of mining is large the surrounding strata will behave as a 'soft testing machine', will result in a sudden, uncontrollable collapse of the bord and pillar workings. The Coalbrook
FIGURE 38 Influence of a massive dolerite sill on pillar load.
disaster of 1960 bears testament to this behaviour. Within a 20 minute period, more than 4 000 pillars underlying a 36 m dolerite sill failed. This disaster also emphasises the need to limit panel dimensions by leaving interpanel pillars.

9.2.3 'Total' extraction workings

In this chapter, 'total' extraction workings refers to either pillar extraction operations or longwall mining operations, both of which are practised extensively beneath massive dolerite sills in South African coalfields. If pillar extraction operations are conducted such that negligible coal is left unrecovered in the form of snooks, fenders and the like, then the behaviour and influence of massive dolerite sills in the superincumbent strata is very similar to that in longwall mining. Therefore, no distinction has been made between the two operations for the purpose of the present discussion.

The minimum panel dimension is the most important factor in inducing failure of an undermined massive dolerite sill. Experience has shown that, typically, this dimension must be at least 180 m if failure of a massive sill is to be achieved. When the minimum panel dimension is less than 150 m a massive sill will usually bridge over an entire panel, or even a number of adjacent panels if the interpanel pillars are sufficiently wide.

Prior to the failure of a massive sill, caving of the nether roof extends only up to the base of the sill. This phenomenon is referred to as 'discontinuous subsidence'. Salamon et al. (1972) have proven analytically and have shown in practice that this results in the development of a cavity between the base of a massive sill and the top of the caved material.
Thus, the weight of the undermined sill and the strata above the sill must be carried by the abutments of the excavation. This may result in high stresses being induced ahead of the mining face and in the panel abutments.

The magnitude of these stresses depends to a large extent on the location of the dolerite sill within the superincumbent strata, and the magnitude of the minimum panel dimension, Fig. 39. In Fig. 39(a), the minimum panel dimension is small and the dolerite sill is located near to surface, a considerable distance above the seam. Thus, the sill only supports a small thickness of overlying strata over a limited area and so the additional weight, $W$, which acts on the panel abutments is small. In Fig. 39(b) the minimum panel dimension is large whilst the dolerite sill is located near to the seam. Under these circumstances, the sill is supporting a considerable thickness of strata over a large area. A much greater weight acts on the abutments and so very high stresses are induced in the abutments. An indication of the actual magnitude of these abutment stresses is given in Fig. 40. Again, stresses have been calculated using the boundary element programs 'MINAP' and 'DINCL'. It can be seen that the higher abutment stresses also extend for a much greater distance into the abutment.

Experience has shown that once a massive dolerite sill has failed, caving of the roof strata extends to surface and then continues to keep pace with face advance. Consequently, abutment stresses are reduced considerably. When a sill does not fail Galvin et al. (1981) have shown that the maximum stress acting in the base of the sill changes insignificantly once the face advance exceeds twice the panel width. Similarly, the abutment stresses ahead of the working face also reach a maximum at a face advance of about twice the panel width.
Figure 39 Influence of dolerite location and panel dimensions on abutment stresses.

(a) Dolerite near to surface and span small.

(b) Dolerite near to seam and span large.
FIGURE 40 Influence of a massive dolerite sill on abutment stresses around a 'total' extraction panel.
Experience has also shown that the failure of a massive sill does not pose a threat to the safety of mining operations if a sufficient protective cushion is provided to the failing sill. This cushion should consist of a thickness of parting between the dolerite sill and the seam of at least 8 to 10 times the mining height.

The preceding discussion forms a basis for highlighting and summarising the more significant influences which massive dolerite sills have on 'total' extraction operations. These include:

1. Panel dimensions. The minimum panel dimension must be either:

   i) sufficiently large to induce failure of a massive dolerite sill as soon as possible after the commencement of mining operations, or

   ii) sufficiently small to ensure that a bridging sill does not induce excessive abutment stresses, especially at the working face.

The use of a sub-critical minimum panel dimension, whereby dolerite failure is imminent but never actually occurs, can have serious consequences since very high abutment stresses exist throughout the life of the mining operation. Roadways may deteriorate and support and maintenance costs may become prohibitive. Excessive spalling and slabbing of the working face may also occur unless additional support procedures are adopted. The productivity and safety of the mining operation is also usually reduced considerably.
2. Roadway location and support. If panel dimensions are chosen such that a massive sill bridges over a panel, roadways should be located outside the region of high abutment stresses and/or well supported. If dimensions are chosen so as to induce failure of a massive sill, sections of roadways subjected to very high abutment stresses prior to the failure of the sill must be well supported.

3. Face support. Wagner et al. (1977) have discussed the effects of a massive dolerite sill on longwall face requirements. Briefly, a massive sill results in severe fracturing and slabbing of the coal face, especially just prior to failure of the sill. In addition, the phenomenon of discontinuous subsidence has the effect of reducing the lateral stresses acting on the fractured immediate roof strata. The combination of these two factors leads to the potentially dangerous situation whereby massive wedges can slide out of the roof close to, or at, the face. This failure mechanism is particularly dangerous since it can lead to a complete loss of control of the roof strata, resulting in a major collapse. Obviously, therefore, the presence of a massive dolerite sill has a significant influence on the selection of face support systems.

4. Interpanel pillar design. If panel dimensions are such that failure of a massive sill does not occur, then interpanel pillars must be sufficiently wide so that not only do the pillars remain stable but also, that under local economic conditions roadways can be located in low stress regions to minimise support requirements. Wagner (1980) has developed a simple method of determining interpanel width under such conditions. The failure of an interpanel pillar could have serious consequences when a
sill spans over a number of adjacent panels. Such a failure could be sudden, in view of the soft nature of the loading system, and not only lead to the failure of neighbouring pillars but also result in large air blasts and high concentrations of methane in the mine ventilation system. When it is proposed to fail overlying massive sills, the width of interpanel pillars is based on the need to locate roadways for adjacent panels in low stress regions.

5. Surface subsidence. Schümann (1979, 1981) has analysed surface strains and tilts associated with failure of massive dolerite sills and has concluded that they are sufficiently large to cause severe damage to any surface structure in the vicinity.

Previous Investigations and Theories

9.3.1 Elastic thin plate model

Investigations into the behaviour of massive dolerite sills overlying 'total' extraction panels were initiated in 1965 at DNC (Durban Navigation Collieries) in the Klip River Coalfield and extended to Sigma Collieries in the Vereeniging-Sasolburg Coalfield in 1967. The formulation of a mathematical model of dolerite behaviour by Salamon et al. (1972) culminated the investigations. Various aspects of these investigations have been reported by Salamon (1966a), Oravecz (1966), Hardman (1968a), Hardman (1968b), Oravecz (1968) and Hardman (1971), and have been summarised concisely by Salamon et al. (1972). The more important and relevant findings and conclusions were:
1. Prior to failure of a massive dolerite sill caving of the roof strata only extends up to (or near) the base of the sill. As a result of this discontinuous subsidence a gap forms between the top of the caved material and the base of the uncaved strata.

2. The possibility of a sudden and violent failure of a dolerite sill can be excluded.

3. After the initial failure of a dolerite sill, the progress of subsidence keeps pace with the progress of mining.

4. A close agreement exists between measured displacements and those derived from elastic theory. This supports the concept that a massive dolerite sill behaves as an elastic plate, at least up to a span which corresponds to its failure. Accordingly, this model offers a simple means for comparing different mining situations. The maximum stress in a uniformly loaded, infinitely long rectangular plate is proportional to the intensity of the load, to the square of the span, S, and inversely proportional to the square of the thickness of the plate, t. As the load intensity is approximately proportional to the depth, D₀, of the base of the dolerite below surface, the maximum stress in the sill is proportional to the factor $D₀S²/t₀²$, where $t₀$ is the thickness of the dolerite sill. If it is required to compare two mining situations then the dimensionless factor, $\phi$, can be formed such that,

$$\phi = \frac{\left(\frac{S_1D_2}{S_2D_1}\right)}{D_2}\frac{D_0}{D_1}$$
Theoretically, if $\theta = 1$, two geometries are identical from the point of view of magnitude of stress. Therefore, assuming that all sills fail at the same magnitude of stress and having determined $S_1$ from experience, Eqn. (12) can be used to calculate the minimum panel dimension, $S_2$, required to induce failure of a sill.

Between 1966 and 1976 seven longwall panels at DNC and three longwall panels at Sigma Collieries were dimensioned on the basis of the model. The predicted result, that is failure or non-failure of a sill, was achieved in each instance at Sigma Collieries but at DNC the expected failure of the sill over one panel never occurred, whilst over two panels failure only occurred some months after the completion of mining. Nevertheless, no further consideration was given to the model until 1977 when it was applied, unsuccessfully, to conditions at Coalbrook Collieries.

9.3.2 Refined elastic thin plate model

The longwall panels at Coalbrook Collieries are overlain by the same massive dolerite sill which overlies the longwall panels at the nearby Sigma Collieries. The face width of the first longwall panel at Coalbrook Collieries was 210 m, and failure of the dolerite sill was expected to occur at a face advance of about 170 m. However, failure only occurred at a face advance of 231 m. As a consequence, mining operations were adversely affected by the high abutment stresses induced by the unfailed sill, especially after the face advance had exceeded 150 m. The sudden relief of these stresses when the sill did fail adversely affected mining operations even further. Although the high abutment stresses had resulted in intense fracturing of the immediate roof and coal strata ahead of the face, these
stresses had also effectively confined this strata. When the stresses were relieved, the deadweight loading on the face support system, especially near to the face, was increased and, as well, excessive slabbing and spalling of the coal face occurred. The face support system could not provide adequate tip load close enough to the face to control strata movement and a very large roof fall which extended for up to 30 m into the roof strata and 3 m ahead of the face line occurred along the middle third of the face. This roof fall delayed mining operations for six weeks, corresponding to approximately 800 hours of lost production. Further roof falls resulted in a total of 2179 hours of lost production (or 25.5 per cent of production delays). These experiences illustrate clearly the significant influence which sub-critical panel dimensions can have on the practical and economic feasibility of 'total' extraction mining beneath massive dolerite sills.

Following these experiences, a review of the elastic thin plate model was undertaken by Wagner and Galvin (1977). On the basis of this review, detailed in Appendix VIII.2.2, the researchers established a relationship between the depth:thickness ratio, \( \frac{D_y}{t_D} \), of a sill and the stress at which a sill failed. In the light of this relationship the 'Refined Elastic Thin Plate Model' was developed. This model is defined by the equation:

\[
s = \sqrt{1400 \frac{t_D}{D_y} - \frac{800}{D_y} t_D^2}, \quad (m)
\]

where \( s \) is the minimum panel dimension (m) required to induce failure of a dolerite sill (the numerical values of 1400 and 800 having units of metres (Appendix VIII.2)).
Although the model has been utilized extensively to date it has not proven applicable to all conditions. In particular, application of the model in the Highveld Coalfield has produced unreliable results.

Longwall mining operations beneath a massive dolerite sill were initiated in the Highveld Coalfield at Bosjespruit Colliery in 1980. On the basis of the refined elastic thin plate model, Eqn. (13), the minimum panel dimension required to break the sill was calculated to be 177 m. However, investigations since the formulation of this model in 1977 had indicated that the parting thickness between a seam and a dolerite sill also influences the minimum panel dimension. An attempt was made to approximate this influence and the minimum panel dimension was revised to 200 m. For technical and operating reasons, the face length of the first longwall panel was extended to 222 m. Nevertheless, the dolerite did not fail until the face had advanced over 700 m.

The lack of success in inducing a dolerite sill to fail when longwall mining operations are extended to a new coalfield raises serious doubts about the validity of the refined elastic thin plate model under all conditions. In particular, it is reasonable to question whether the behaviour of the massive dolerite sill which overlies proposed thick seam mining panels in the South Rand Coalfield can be predicted sufficiently accurately by the model. Therefore, it is necessary that the behaviour of massive dolerite sills be reviewed and reassessed in the light of experience gained from the longwall mining of more than 25 panels beneath such sills during the last 15 years.
9.4 **Current Investigations and Theories**

9.4.1 **Approach to current research**

Unfortunately, although more than 25 longwall panels have been extracted beneath massive dolerite sills, very little detailed information about the failure mode of sills has been obtained. Invariably, surface subsidence observations have been made over the panels but in only two instances have borehole extensometers been spaced at regular intervals throughout the sill. Consequently, investigations to date have relied heavily on surface subsidence observations and, to a much lesser extent, on measurements and observations made in surface boreholes over under-mined panels. Thus, the development and, in particular, the verification of new models and theories is restricted by the time interval associated with the instrumenting and mining of further longwall panels.

Nevertheless, a re-analysis of measurements and observations presented in literature in the light of experiences gained during the 15 years of longwall mining beneath dolerite sills, in conjunction with recent measurements and observations, does enable some significant advances to be made in the theory of the behaviour of dolerite sills. Research conducted in this regard is presented in detail in Appendix VIII and only the important findings which influence the implementation of thick seam mining methods in the South Rand and Vereeniging-Sasolburg Coalfields are noted in this chapter.

9.4.2 **Research conclusions**

An assumption associated with the original elastic thin plate model, defined by Eqn. (12), is that 'all sills possess similar mechanical properties'. In the light of the consistent geologic conditions associated with South
African coalfields, Appendix VI, and of observations of dolerite sills made in incline shafts in the Klip River, Vereeniging-Sasolburg, South Rand and Highveld Coalfields, it was considered reasonable to accept this assumption in the initial stages of conducting this research into dolerite behaviour. Subsequent detailed investigations into the structure of dolerite sills, reported in Appendix VIII.7, support this assumption.

One of the most significant points which has emerged from the re-analysis of all available information relating to dolerite behaviour (Appendix VIII) is that the effective unsupported span of a sill is significantly influenced by the caving angle, $\theta$, and the parting thickness, $t_p$, of the strata between a seam and a sill. By definition, the caving angle, $\theta$, is measured relative to the plane of the seam ahead of the face, Fig. 41. Typical caving angles associated with strata overlying longwall panels at Durban Navigation, Sigma, Coalbrook and Bosjesspruit Collieries are recorded in Table 30. It is apparent from Fig. 41 and Table 30 that the effective span, $S_{eff}$, over which an unfailed sill bridges is not equal to the panel dimension, $S$, but is defined by the equation:

$$S_{eff} = S - t_p \tan(\theta - 90) \text{ (m)}$$  \hspace{1cm} (14)

**TABLE 30** Caving angle, $\theta$, to the base of a dolerite sill.

<table>
<thead>
<tr>
<th>Colliery</th>
<th>Caving Angle, $\theta$, (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNC</td>
<td>110</td>
</tr>
<tr>
<td>Sigma</td>
<td>117</td>
</tr>
<tr>
<td>Coalbrook</td>
<td>110</td>
</tr>
<tr>
<td>Bosjesspruit</td>
<td>119</td>
</tr>
</tbody>
</table>
FIGURE 41 Influence of caving angle, $\beta$, and parting thickness, $t_p$, on unsupported dolerite span, $S_{\text{eff}}$. 
In the light of these findings the 'Refined Elastic Thin Plate Model', defined by Eqn. (13), has been updated to the 'Effective Span Elastic Thin Plate Model' (Appendix VIII.4), defined by the equation:

\[
S = \sqrt{1165t_D - 935\frac{t_p^2}{D_D} + 2t_p\tan(\delta-90)} \quad (m) \quad (15)
\]

The difference between the actual span at which a sill failed and that as calculated by this latter model ranges from one under-estimation of only 3 m to an over-estimation of 33 m. As such, this model currently offers the most accurate means of calculating the minimum panel dimension required to induce a massive dolerite sill to fail.

However, a good appreciation of the caving angle, \( \delta \), is required in order to obtain an accurate solution, especially when the parting thickness, \( t_p \), is large. In addition, the equation has yet to be verified for sills exceeding 75 m in thickness or sills exceeding a depth (to the base) of 140 m.

It is doubtful whether this model can be considered as an elastic thin plate model. Although the model has been developed from the original elastic thin plate model through a number of logical refinements to the latter, it has also been derived on the basis of field data. In addition, it is to be questioned whether the elastic thin plate theory as applied to massive dolerite sills, is valid (Appendix VIII.5). Measured displacements often do not agree with those prescribed by elastic thin plate theory whilst the actual failure mode of a sill may also be incompatible with this theory.

Thus, the 'Effective Span Elastic Thin Plate Model' must be viewed only as a reasonably accurate means of
calculating the minimum panel dimension required to induce a sill to fail and not as a model which describes the actual failure mode of a sill. This minimum panel dimension can be calculated quickly from Figs. 42(a) and 42(b). Under conditions falling within the range of those from which the model was derived, the effective unsupported span at which a sill should fail can be read from Fig. 42(a). To this value must be added the increase in span required to compensate for the presence of a parting between the base of the dolerite sill and the mining horizon. This latter value is read from Fig. 42(b), the sum of the two figures being the required minimum panel dimension.

A feature of Fig. 42(a) is that the effective span, $S_{\text{eff}}$, as defined by the equation

$$ S_{\text{eff}} = \sqrt{\frac{1165t_D - 935t_D^2}{D_D}} \quad (m) \quad (16) $$

is a maximum at a $D_D/t_D$ ratio of 1,605, whilst the effective span, $S_{\text{eff}}$, becomes very insensitive to increasing $D_D/t_D$ ratio once this ratio exceeds about 2.2. This behaviour is currently the subject of further research. It appears that the $D_D/t_D$ ratio is a compensating factor for applying a thin plate model to a set of conditions which approximate a composite thick plate. A subject of further research is also the actual failure mode of a dolerite sill, since this mode can influence significantly mine design, the selection of mining equipment and mining operations.

### 9.5 Application of Research Findings

On the basis of Eyn. (15) brief consideration can be given to the influence which massive dolerite sills have on 'total' extraction thick seam mining methods previously identified.
(a) Effective unsupported span.

(b) Parting span.

FIGURE 42 Graphical method for calculating the minimum panel dimension.
(Chapter 7) as being potentially feasible in the South Rand and Vereeniging-Sasolburg Coalfields. The following discussion applies to situations where thick seam mining has to take place beneath an unfailed sill. It is only intended to highlight some of the more important factors relating to each method. A final decision on the applicability of each method can only be made in the light of a detailed analysis of conditions and alternatives associated with a specific site. The discussion is facilitated by considering the Vereeniging-Sasolburg Coalfield first.

9.5.1 Vereeniging-Sasolburg Coalfield

The minimum panel dimension required to induce failure of dolerite sills in the Vereeniging-Sasolburg Coalfield ranges from about 180 m to 235 m. Of those ‘total’ extraction methods potentially suitable in the coalfield, Table 25(C), non-simultaneous multi-slice longwall mining in descending slices is the only method well suited to such panel widths. In full face longwall mining the panel width is usually restricted to about 80 to 110 m, primarily to minimise strata control problems by maintaining a relatively rapid rate of retreat. Similarly, the success of pillar extraction operations also depends on extracting pillars quickly and maintaining a fast rate of retreat. For the range of depth and seam thickness which occur in the coalfield, panel width would need to be restricted to about 5 to 6 pillars, corresponding to 120 to 180 m. However, longwall mining experience in the coalfield have highlighted that panel widths of 150 to 180 m are non-critical. Whilst, in any case, such panel widths are to be avoided under most circumstances because of the high abutment stress which exist throughout the mining life of a panel, the presence of extremely incompetent immediate roof strata in the upper seams of the Vereeniging-Sasolburg Coalfield, Appendix VI.5, makes it essential that panel widths associated with
pillar extraction operations are not sub-critical. As such, full face pillar extraction operations are probably only feasible when panel widths are restricted to less than 120 m.

Therefore, it is apparent that mine design associated with full face 'total' extraction mining methods must be based on the fact that failure of an overlying massive dolerite sill will not be induced, at least whilst mining operations are in progress. In order to limit strata displacement associated with the higher abutment stresses induced by a bridging sill, especially in view of the large mining height (+4 m), panel width will have to be restricted to the order of 100 m. On the basis of the interpanel pillar design procedure for local conditions proposed by Wagner (1980), these pillars will need to be of the order of 50 to 80 m wide in order to protect adjacent panel roadways from high abutment stresses and to provide regional support to the bridging sill. Thus, most of the increased panel percentage extraction achieved by utilizing 'total' extraction mining methods will be negated by the 30 to 45 per cent of reserves sterilized in the form of interpanel pillars. It is reasonable to conclude, therefore, that unless dolerite failure has been induced by preceding upper seam (or slice) mining operations, full face mining methods find limited, if any, application in areas of the Vereeniging-Sasolburg Coalfield overlain by massive dolerite sill.

The limited mining height associated with multi-slice pillar extraction (and, to a certain extent, pillar extraction with top- or bottom-coaling) reduces the adverse effects of high abutment stresses on strata control. If dolerite failure induced during upper slice mining operations interpanel pillars need only be of the order of 30 to 50 m wide, whilst the panel width associated with each subsequent slice need only be
reduced slightly in order to locate the outer roadways beyond the zone of high abutment stress associated with the interpanel pillar (refer section 4.3.1). If dolerite failure is not induced, interpanel pillars in the upper slice again need to be of the order of 50 to 80 m wide. With subsequent slices interpanel pillar width must be increased considerably, with the result that panel width is reduced further. It is apparent from previous considerations that the potential for implementing this latter option in areas where dolerite failure has not occurred is extremely limited.

If sublevel caving and drawing is utilized and failure of a dolerite sill is not induced, interpanel pillars will need to be of the order of 60 to 100 m wide whilst panel width will have to be restricted to 120 to 150 m. Thus, less than 40 per cent extraction, excluding geologic losses, will be achieved. Alternatively, if failure of a dolerite sill is to be induced, high abutment stresses prior to the failure of the sill will give rise to severe strata control problems unless mining height is restricted. This may be achieved indirectly using underhand stoping, whereby the mining height in each sublevel is restricted and mining in an upper sublevel precedes mining in a lower sublevel, Fig. 43. Thus, the working face in the uppermost slice is the only face exposed to the high abutment stresses. However, underlying portions of all sublevel entries will be exposed to high abutment stresses and so entries will have to be well supported in these regions, Fig. 43. The overall mining height could be influenced by the need to provide a sufficient protective cushion of caved strata to the failing sill (section 9.2.3).

The preceding discussion indicates that of the 'total' extraction thick seam mining methods potentially feasible in areas of the Vereeniging-Sasolburg Coalfield overlain by unfailed massive dolerite sills, non-
**FIGURE 43**

Schematic illustration of abutment stress contours when underground stoping is employed beneath a bridging dolerite sill.

Note: The diagram shows the relationship between the dolerite sill and the surrounding strata, indicating stress concentrations in specific regions. The text describes the necessity for support in those areas.
simultaneous multi-slice longwall mining in descending slices exhibits the greatest potential for implementation. The method is suited to face lengths of 180 to 235 m required to induce failure of an overlying sill. The adverse effects of high abutment stress prior to failure of a sill are minimised by the restricted mining height. Subsequent slicing operations take place under destressed ground whilst the coal reserve that is sterilized in the form of interpanel pillars is minimised. Alternatively, for similar reasons to those just noted, many of the other potentially feasible methods could find application if failure of massive dolerite sills was induced by preceding mining operations in the upper No. 3 Seam or in the upper horizon of the No. 2 Seam.

9.5.2 Area AGS, South Rand Coalfield

In area AGS of the South Rand Coalfield the thickness and depth of the dolerite sill (or sills) fall in the upper limit of the conditions on which Eqn. (15) was derived. A minimum panel dimension (width) ranging from 220 to 290 m is required in order to induce failure of the sill in this area. Reference to Table 24(C) shows that 'total' extraction thick seam mining methods based on pillar extraction and stope mining are potentially suitable in the area. No overlying mineable seams occur in the area and so, unless conventional mining methods (mining height: 2-3 m) are employed in the upper horizon of the Main Seam, thick seam mining methods offer the only means of inducing the dolerite sill (or sills) to fail.

Similar to the Vereeniging-Sasolburg Coalfield, because of the need to restrict panel dimensions to achieve an acceptable rate of pillar extraction, it is most unlikely that failure of a dolerite sill can be achieved utilizing full face pillar extraction techniques. As a
result, interpanel pillars will need to be of the order of 50 to 80 m wide which, for a 100 to 120 m wide panel, will only result in 15 to 18 per cent extraction, excluding geologic losses, from the 18 to 23 m thick seam. This percentage extraction is not significantly higher than that achieved currently from bord and pillar mining methods which maintain the integrity of the roof strata. Thus, it may be concluded that the potential for utilizing full face pillar extraction operations beneath an unfailed sill is limited.

The limited mining height associated with slicing pillar extraction operations reduces the adverse effects of high abutment stresses. However, in view of the large panel pillar size (22 to 34 m) required at depths of 140 to 190 m, panel dimensions must be restricted to the order of 110 to 170 m to minimise strata control problems associated with a slow rate of pillar extraction. Under these conditions, failure of a dolerite sill will not be induced and 50 to 80 m wide interpanel pillars will have to be left between panels. In the case of multi-slice bord and pillar mining with pillar extraction, the size of this pillar will have to be increased with each subsequent slice extracted.

The success of open stoping depends on maintaining the integrity of the roof strata whilst stope mining operations are in progress. High abutment stresses associated with a bridging dolerite sill can adversely affect the stability of the roof strata. Furthermore, since a working height in excess of 6 m is also exposed to these stresses, severe coal strata displacement may occur, resulting in the deterioration of roadways, the 'cut-off' of drilling holes, excessive spalling and slabbing of the stope face and associated problems in the recovery of this coal. The severity of these problems will increase prior to dolerite failure as adjacent stopes are mined. Thus, it is not practically
feasible to induce dolerite failure utilizing open stoping. But, it is also impractical to utilize the method if it is proposed not to induce dolerite failure, since at large mining heights (+10 m) extremely large (-100 m) interpanel pillars would have to be left between stopes. Thus, the potential for utilizing open stoping beneath an unfailed sill in area ACS of the South Rand Coalfield is extremely limited.

However, many of the drawbacks associated with open stoping may be overcome with sublevel caving and drawing, especially if underhand stoping techniques are employed, Fig. 43. Panel dimensions are not restricted by the need to maintain the integrity of the roof strata, whilst the effective working height is restricted by the use of underhand stoping. Problems associated with hole 'cut-off' face slabbing and spalling and associated difficulties in coal recovery may be restricted to upper sublevels. Nevertheless, detailed consideration still needs to be given to panel design and mining operations if it is proposed to induce failure of a sill since, prior to failure, extremely high abutment stresses will be associated with a sill that is capable of bridging over panels up to 290 m wide. The need to provide a sufficiently thick cushion of caved material to the failing sill could govern the overall mining height.

9.3.3 Conclusions

Thick seam mining methods are not well suited to inducing failure of dolerite sills in the Vereeniging-Sasolburg and South Rand Coalfields. This is primarily because panel widths must be limited in order to maintain a relatively fast rate of retreat, thereby minimising strata control problems, especially when mining heights are large. As such, the presence of an overlying massive dolerite sill severely restricts
the potential of mining methods previously recognised as being feasible (Chapter 7). However, if failure of dolerite sills were to be induced by an upper seam or upper slice mining operation, not necessarily thick, the potential exists to utilize these methods.

In the Vereeniging-Sasolburg Coalfield, dolerite failure may be induced by longwall mining in the No. 3 Seam or in an upper slice in the No. 2 Seam. In the Sigma basin, dolerite failure has been achieved in one instance utilizing conventional pillar extraction operations to a height of about 3 m. However, severe strata control problems were encountered. Recently, successful trials were conducted utilizing rib-pillar extraction techniques (Laybourne et al., 1981). Such techniques appear to offer a viable alternative to longwall mining, especially in areas where it is desired to induce failure of overlying dolerite sills.

In the South Rand Coalfield, the presence of numerous geologic discontinuities prevents the application of longwall mining. Pillar extraction operations in the coalfield have yet to induce failure of overlying dolerite sills because panel widths have been limited. However, the potential exists to utilize rib-pillar extraction techniques in an upper slice of the Main Seam in area AGS to induce failure of the dolerite sill.

It should be noted that trials are currently being conducted overseas to evaluate the potential of multi-slice rib-pillar extraction techniques for extracting thick seams (6 m). In the light of the success of conventional rib-pillar extraction trials in South Africa recently, such a method may offer the best means of extracting thick seam reserves in area AGS of the South Rand Coalfield.
9.6 Conclusions

The presence of a massive dolerite sill in the superincumbent strata of mine workings has a significant influence on the distribution of stresses around mine workings. In particular, such sills usually result in increased abutment stress. When mining methods which maintain the integrity of the roof strata are employed, the presence of a massive dolerite sill in the superincumbent strata can easily be taken into consideration using analytical and numerical techniques. In general, stress magnitude; associated with such methods tend to be low since either the workings are at a shallow depth and/or the percentage extraction is low. However, when 'total' extraction methods are employed, abutment stresses may be very high if failure of the sill is not induced. Thus, panel widths must either be limited to restrict the magnitude of abutment stresses or else panel widths must be sufficiently large to induce failure of a sill very soon after the commencement of mining operations.

It is crucial that panel dimensions associated with 'total' extraction mining method are not sub-critical, resulting in very high abutment stresses throughout the mining life of a panel. Currently, the most accurate means of calculating the minimum panel dimension required to induce failure of a sill is provided by the 'Effective Span Elastic Thin Plate Model'. This model is defined by the equation -

\[
S = \sqrt{\frac{1165 t_D - 935 \frac{L_p^2}{D_p}}{D_p} + 2 t_p \tan(8-90)}, \quad \text{(m)} \quad (17)
\]

where:  
- \( S \) is the minimum panel dimension (m),  
- \( t_p \) is the thickness of dolerite sill (m),  
- \( D_p \) is the depth to base of sill (m),  
- \( t_p \) is the thickness of parting between base of sill and seam (m),  
- \( \theta \) is the caving angle of strata between seam and base of sill (degrees),  

with the numerical values of 1165 and 935 having units of metres.
The equation has yet to be verified for sills exceeding 75 m in thickness or sills exceeding a depth (to the base) of 140 m. Furthermore, a good appreciation of the caving angle, \( \beta \), is required in order to obtain an accurate solution, especially when the parting thickness, \( t_{p} \), is large. However, this problem will be encountered with any analytical model.

Although Eqn. (17) may provide a reasonably accurate means of calculating the minimum panel dimension required to induce a sill to fail, it is doubtful whether it accounts for the failure mode of a sill. This aspect warrants further research since the actual failure mode of a sill can influence significantly mine design and mining operations.

The potential for implementing feasible 'total' extraction thick seam mining methods in areas of the South Rand and Vereeniging-Sasolburg Coalfields where overlying dolerite sills have not failed is limited. This is primarily because the panel width associated with many of these methods is insufficient to induce failure of a dolerite sill. Consequently, large interpanel pillars must be left to protect adjacent panel roadways from the effects of high abutment stress and/or to provide regional support to the bridging sill. As a result, the overall percentage extraction achieved will not be significantly higher than that achieved by methods which maintain the integrity of the roof strata.

In the South Rand Coalfield, sublevel caving and drawing finds potential application in areas where the dolerite sill has not failed, whilst under similar circumstances in the Vereenining-Sasolburg Coalfield non-simultaneous multi-slice longwall mining in descending slices offers the greatest potential. Sublevel caving and drawing also finds application in thin coalfield.

The adverse influence of an overlying massive dolerite sill on many potentially feasible thick seam mining methods may be overcome by inducing the sill to fail through extracting an
upper coal seam or coal slice prior to implementing such mining methods. Currently, the greatest potential for achieving this aim in the South Rand Coalfield is by utilizing rib-pillar extraction techniques. Recent trials in the Vereeniging-Sasolburg Coalfield indicate such techniques have considerable potential under the conditions that exist in both coalfields. In particular, it may be concluded that because of:

1) the lack of established thick seam mining methods which are feasible in the South Rand Coalfield,

2) the success to date of local trials of rib-pillar extraction techniques beneath massive dolerite sills,

3) the suitability of existing equipment and bord and pillar mining experience to the method, and

4) the success of overseas thick seam mining trials with the method,

local research should be conducted into multi-slice rib-pillar extraction. Furthermore, the results of this research may currently find application in all four potential thick seam coalfields.
Author  Galvin J M
Name of thesis  The mining of South African thick coal seams - rock mechanics and mining considerations  1981

PUBLISHER:
University of the Witwatersrand, Johannesburg
©2013

LEGAL NOTICES:

Copyright Notice: All materials on the University of the Witwatersrand, Johannesburg Library website are protected by South African copyright law and may not be distributed, transmitted, displayed, or otherwise published in any format, without the prior written permission of the copyright owner.

Disclaimer and Terms of Use: Provided that you maintain all copyright and other notices contained therein, you may download material (one machine readable copy and one print copy per page) for your personal and/or educational non-commercial use only.

The University of the Witwatersrand, Johannesburg, is not responsible for any errors or omissions and excludes any and all liability for any errors in or omissions from the information on the Library website.