

1996

Mining the coal reserves under the Cataract Reservoir

Mitchell Jakeman
University of Wollongong

Recommended Citation

Jakeman, Mitchell, Mining the coal reserves under the Cataract Reservoir, Master of Engineering (Hons.) thesis, Department of Civil and Mining Engineering, University of Wollongong, 1996. <http://ro.uow.edu.au/theses/2427>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

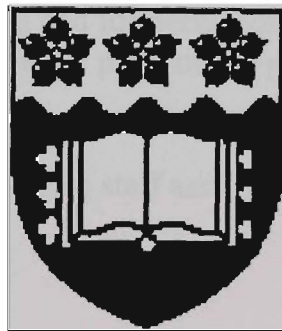
Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

MINING THE COAL RESERVES UNDER THE CATARACT RESERVOIR

**A thesis submitted in fulfilment of the requirements for
the award of a degree of
Master of Engineering (Honours)**

from

UNIVERSITY OF WOLLONGONG



by

**Mitchell Jakeman
BE (UNSW), MAUSIMM, M CMMMA
9588 493**

**Department of Civil and Mining Engineering
June 1996**

ACKNOWLEDGEMENTS

I am grateful for the helpful contributions received by a number of people in the preparation of this thesis.

My sincere thanks goes to:

Professor R N Singh

Professor of Mining Engineering, Department of Civil and Mining Engineering,
University of Wollongong for his supervision and guidance in this thesis
preparation.

Traian Netescu

Consultant Mining Engineering and formerly from Austen & Butta for his
meticulous design work in the early parts of the program.

Russ Phillips

Manager Technical Services, whose staff assisted in the many areas of
monitoring and analysis.

Dr Gladwin

Research Scientist - CSIRO for providing to strain data to determine the effects
on the Dam wall.

Angela Paine/Barbara Lourie

My assistant who helped me to organise my time to complete this thesis so they
could get it ready for submission.

Members of the Dam Safety Committee and Sydney Water

Who have assisted in the active discussions, agreed on approvals and looked on
with active interest into all monitoring programs.

AFFIRMATION

I hereby certify that the work presented in the thesis entitled "Mining the Coal Reserves Under the Cataract Reservoir" for fulfillment of the requirements for the award of the degree of Masters of Engineering, submitted in the Department of Civil and Mining Engineering, University of Wollongong, is my own work carried out under the supervision of Prof. R N Singh. The thesis contains no material previously published or written by another person except where due reference is made through the text.

MITCHELL JAKEMAN

ABSTRACT

Mining beneath ground water, reservoirs, rivers, seas and harbours has been successfully carried out in numerous countries for many decades. The risks and engineering considerations have been refined over a long time to enable safety and geotechnical outcomes to be defined and adequately controlled.

The experience in Australia has been a prolonged debate over three decades between the mining industry and numerous sectionalised Government Departments. The first major step forward was the Reynolds Inquiry recommendations in the 1970's which determined the limitations to which mining could proceed under stored waters. In 1978, the NSW Government enacted the Dam Safety Act and established a Dams Safety Committee to oversee applications of mining within these areas.

Over 3 years from 1990 - 1992 South Bulli worked with the Dam Safety Committee to gain approval for mining the restricted zone beneath Cataract Reservoir for the ongoing viability of its operations. This was the first real test of the recommendations that were handed down by Justice Reynolds Inquiry, and the entire area was divided into zones to determine more accurately some of the engineering factors of subsidence, stress, strain and how the geometry of mine design interacted. These zones would be approved depending on the results of monitoring these parameters in a controlled manner. This thesis analyses the results to date from Stage I and partial Stage II extraction zones and has been used to supplement reports to the Dam Safety Committee.

Mining to date has consisted of the extraction of 2.5 million tonnes of raw coal, via development of 30 km of underground roadways within the Cataract area (six longwalls developed), and the extraction of four longwall panels, each of 110m width, separated by 66 m wide coal pillars which provide support to the overlying strata.

A wide-ranging monitoring programme has been developed and implemented on the surface, in the overburden, and the mine workings, which includes:-

- Surface Geological Mapping
- Underground Mapping
- Geophysical Surveys
- In-Seam Longhole Drilling
- Surface Subsidence
- Surface and Sub-Surface Strains
- Groundwater
- Mine Water Inflow/Outflow
- Pillar Stability

The results from these programs confirm that the strata response to mining operations has been very small, which is very close to original expectations.

This is significant in that greater confidence can now be placed in the "Stage II" design. Since the initial predictions were made, various additional work has been carried out. The most significant of these investigations have been reported and discussed in this thesis and contribute to the high confidence in the Stage II mine design.

Stage II Application was to develop and extract the next seven mini-longwall blocks, from Longwall 508 up to and including Longwall 514. The mine layout is essentially the same as the Stage I Application, with longwalls retreating approximately from East to West, and development of panels progressing northward.

The main change in layout is an increase in extraction width from the current 110m to 120m from Longwalls 511 onwards, and a decrease in chain pillar width from an existing value of 66m to 60m. The reduction in pillar width is in line with the reduction of cover depth, consistent with the Reynold's Inquiry guidelines. Work described gives a high level of confidence in the assertion that the proposed layout is still conservative and will not threaten the integrity of the Reservoir. This will be confirmed by continuing the existing monitoring and investigation programs, and supplementing them by additional programs to cater for the requirements of the Stage II. The proposed Stage II Monitoring programs are detailed elsewhere in this thesis.

The predicted values of surface subsidence and strain for both Stage I and II are detailed below where:

- a) maximum subsidence will go from 200 mm (Stage I) to 280 mm (Stage II)
- b) maximum tensile strain will go from 0.6 mm/m (Stage I) to 0.8 mm/m (Stage II).
- c) maximum compressive strain will go from 0.6 mm/m (Stage I) to 1.2 mm/m (Stage II).

The most important of these parameters is tensile strain. Test work carried out has indicated that the tensile strain failure of the base of the reservoir (in the Hawkesbury Sandstone) is between 3.0 and 7.0 mm/m, which is at least 3.5 times greater than the anticipated strain, and is a sufficient factor of safety to protect the reservoir.

As all mining at South Bulli is now concentrated in the Cataract area, continuity of production is vital if the viability of the mine is to be maintained. The Stage II layout extends the mine life by 2.5 years, providing an annual export revenue of \$65 million.

Table of Contents

	Page No
Acknowledgements	i)
Affirmation	ii)
Abstract	iii)
Table of Contents	vi)
List of Figures	viii)
List of Tables	xi)

Chapter 1 Introduction

1.1 Overseas Experience	1
1.2 Utilising Resources - Mining and Water Storage	7
1.3 Bellambi Collieries - Southern Coal District of NSW	17

Chapter 2 Cataract Case Study - Stage 1 Extension

2.1 Introduction	20
2.2 Mine Layout	20
2.3 Monitoring/Investigation Programs & Results	20
2.4 Survey Investigators and Results	22
2.5 Geomechanical Testing	24
2.6 Subsidence Surveys and Results	25
2.7 Discussion and Results	27
2.8 Conclusion	34

Chapter 3 Strata Monitoring, Investigations and Results Stage I

3.1 Introduction	36
3.2 In-situ Strain	36
3.3 Numerical Modelling	38
3.4 Chain Pillar Stability Monitoring	41
3.5 Results	42
3.6 Conclusion	44

Chapter 4 Hydrology

	Page No
4.1 Introduction.....	45
4.2 Mine Water.....	45
4.3 Ground Water.....	46
4.4 Water Source Analysis & Testing.....	46
4.5 Piezometer Results.....	48
4.6 Conclusions	51

Chapter 5 Mine Design - Stage II Extraction

5.1 Introduction.....	52
5.2 Geological Appraisals	52
5.3 Mine Design	54
5.4 Surface Subsidence Prediction.....	56
5.5 Chain Pillar Stability.....	66
5.6 Monitoring Programs	74
5.7 Conclusions	79

Chapter 6 Conclusions and Recommendations

6.1 Introduction.....	80
6.2 Conclusions	80

References	82
-------------------------	----

List of Figures

	Following Page No
CHAPTER 1 - Introduction	
1.1 North East Area - Undersea Collieries.....	1
1.2 Geological Map of North East Coalfield.....	3
1.3 Effect of Draw Angle on Width of Marginal Zone.....	9
1.4 Notification Area of Southern Coalfields.....	11
1.5 Components of Mining Subsidence.....	12
1.6 Schematic Depictions of Stress Zones in Underground Mining.....	13
1.7 Generalised Depiction of Strata Behaviour with Total Extraction Mining.....	13
1.8 Location of South Bulli Colliery.....	18
1.9 Location of South Bulli Colliery - Approval Area.....	19
1.10 Mine Workings Updated to April 1996.....	19
1.11 South Bulli Safety Performance.....	19
1.12 Longwall and Development Productivity.....	19
CHAPTER 2 - Cataract Case Study - Stage I Extension	
2.1 Cataract Case Study - Stage II Extraction.....	20
2.2 Stage I Surface Geology.....	21
2.3 Stage I Underground Geology.....	21
2.4 In-seam Seismic Survey I.....	22
2.5 In-seam Seismic Survey II.....	22
2.6 Bulli Seam Floor Strata - Location of Section Lines.....	23
2.7 Floor Strata - "R Main" Panel.....	23
2.8 Floor Strata - Cataract Area.....	23
2.9 Floor Strata - Western District Headings.....	23
2.10 Geological Structures.....	24
2.11 Surface Boreholes Drilled During 1994.....	24
2.12 Hawkesbury Sandstone - Geomechanical Tests.....	25
2.13 Location of Stage I Surface Subsidence Lines.....	25
2.14 Line B-B' Subsidence - All Pre-Mining Surveys.....	26
2.15 Line B-B' Strain - All Pre-Mining Surveys.....	26
2.16 Line A-A' Subsidence - All Mining Surveys.....	29
2.17 Line A-A' Strain - All Mining Surveys.....	29
2.18 Line B-B' Subsidence - All Mining Surveys.....	30
2.19 Line B-B' Strain - All Mining Surveys.....	30
2.20 Line C-C' Subsidence - All Mining Surveys.....	32
2.21 Line C-C' Strain - All Mining Surveys.....	32
2.22 Line D-D Subsidence - All Mining Surveys.....	33
2.23 Line D-D' Strain - All Mining Surveys.....	33

CHAPTER 3 - Strata Monitoring - Investigations and Results - Stage I

3.1	Location of In-situ Strain Instruments	36
3.2	Stage I MinCad Subsidence Predictions	39
3.3	Stage I MinCad : Predicted Vertical Stresses.....	39
3.4	Stage I Subsidence Results - MinCad Vs. Actual.....	40
3.5	Pillar Monitoring Sites	42
3.6	Pillar Monitoring Results - G503.....	42
3.7	Pillar Monitoring Results - G504.....	43
3.8	Pillar Monitoring Results - Composite Loading Profile (G503/504).....	43

CHAPTER 4 - Hydrology

4.1	Underground Water Monitoring.....	45
4.2	Location of Piezometer Boreholes.....	46
4.3	Groundwater Monitoring Program - Indicative Section	46
4.4	Longwall 501 Piezometer Borehole Construction.....	46
4.5	Longwall 502 Piezometer Borehole Construction.....	46
4.6	Cataract District - Water Collection Sites.....	47
4.7	Longwall 501 Groundwater Monitoring - During LW501 Extraction	48
4.8	Longwall 501 Groundwater Monitoring - During LW501-504 Extraction	48
4.9	Longwall 502 Groundwater Monitoring - During LW502 Extraction	49
4.10	Longwall 502 Groundwater Monitoring - During LW504-504 Extraction	49

CHAPTER 5 - Mine Design Stage II Extraction

5.1	Surface Topography Map.....	52
5.2	Cover Depth to Bulli Seam	52
5.3	Stage II Surface Geology	52
5.4	Stage II Surface Geology	52
5.5	Bulli Seam Floor Contours.....	53
5.6	Bulli Seam Thickness Isopachs.....	53
5.7	Southern Coalfield Subsidence (After Holla, 1988)	58
5.8	Tensile Strain Factor (After Holla, 1988)	59
5.9	Tensile Strain For 380m Cover Depth	59
5.10	Tensile Strain For 300m Cover Depth	59
5.11	Compressive Strain Factor (After Holla, 1985).....	60
5.12	Stage II MinCad Subsidence Prediction.....	61
5.13	Location of MinCad Subsidence/Strain Prediction Line	61
5.14	Stage II MinCad Strain Prediction.....	62
5.15	Stage II CISPM Prediction Lines	62
5.16	CISPM Longwalls 504-513 Crossline Predicted Subsidence.....	62

	Following Page No
5.17 CISPM Longwalls 504-513 Crossline Predicted Strain	62
5.18 CISPM Longwalls 504-513 Longitudinal Predicted Subsidence	63
5.19 CISPM Longwalls 504-514 Crossline Predicted Strain	63
5.29 CISPM Longwalls 505-514 Crossline Predicted Subsidence	63
5.21 CISPM Longwalls 505-514 Crossline Predicted Strain	63
5.22 CISPM Longwalls 505-514 Longitudinal Predicted Subsidence	63
5.23 CISPM Longwalls 505-514 Longitudinal Predicted Strain	63
5.24 CISPM Contoured Predicted Subsidence	64
5.25 CISPM Isometric Predicted Subsidence	64
5.26 CISPM East-West Contoured Predicted Strain	64
5.27 CISPM East-West Isometric Predicted Strain	64
5.28 AMIRA Project - Bulli Coal Laboratory Strength Envelope	67
5.29 Rectangular-Square Pillar Conversion (60m Pillar)	68
5.30 AMIRA Project - Load Distribution At Peak Load	68
5.31 AMIRA Project - Pillar Strength Measurements	68
5.32 Typical Chain Pillar Loading	69
5.33 MinCad : Pillar Loading Contour Map	70
5.34 MinCad : Pillar Loading Contour Detail G510	71
5.35 MinCad : Pillar Loading Contour Detail G512	71
5.36 MinCad : Pillar Loading Profile G510	71
5.37 Attributable Pillar Area	71
5.38 AMIRA Pillar Stability - Factor of Safety	73
5.39 Squat Pillar Stability - Factor of Safety	73

List of Tables

Table		Page No
1.1	Insitu Coal Reserves Under Storage Reservoirs in the Southern Coalfields.....	8
1.2	Insitu Coal Reserves Under Storage Reservoirs plus the 35° Angle of Draw.....	8
2.1	Parameters of Stage I Layout Including Depth of Cover.....	15
2.2	Geomechanical Rock Test Results.....	20
2.3	Roof and Floor Strata Results	20
2.4	Comparative Results - Subsidence, Compressive & Tensile Strain.....	22
3.1	Location / Depth of Strain meters.....	32
3.2	Extensometer Location and Depths.....	33
4.1	Water Analysis Results.....	43
5.1	Main Parameters for Individual Longwall Panels	55
5.2	Pillar and Panel Parameters	57
5.3	Subsidence Results from South Coast Mines	58
5.4	Subsidence Predictions for Longwalls 508-514.....	58
5.5	Summary of Results for 3 Modelled Layouts.....	61
5.6	Pillar Loading - AMIRA vs Squat Pillar Predictions	72

CHAPTER 1 - INTRODUCTION

1.1 Overseas Experience

Mining has been carried out quite successfully under ground water, reservoirs, rivers and under the sea in countries outside of Australia. They have overcome and adequately dealt with stability, safety and mining engineering problems while mining under water bodies. When mining underground there is always the potential risk of water entering the workings from both surface water and ground water. However when mining under stored water, there is the increased risk of water entering the mine due to the presence of this constant source of water. Many underground mines overseas have successfully been able to avert water away from their workings to prevent the problems associated with water in mines. Protective layers and barrier are one such method that has been employed to prevent water from entering the mine or to minimise the flow.

Several of the mines in the North East of England have worked under rivers, the sea and underground reservoirs without any incidents of water inundations despite the presence of conduits. In the undersea workings, mining under the water has been one challenge combined with other significant features which could influence the water flow. This includes mining in close proximity to old abandoned water logged workings of collieries that worked the same seam in the past. Aquifers located in the coal measures have also provided a path and source of water. There is also outcropping aquifers in the west which could supply as a water source when surface water recharged them. Subsidence caused by mining creates a distressed zone around the excavation which can allow water to flow due to its distressed nature. These mines have also coped with the presence of faults, dykes and joints which act as conduits.

The extraction of coal from workings under the sea in the North East of England has been successful in many instances (Watson, 1979). Large quantities of water have been associated with these workings but the coal is of a good quality and this water has been pumped out to obtain the coal from the seams in this area. The entry of water into the longwall workings under bodies of water has occurred due to the combination of many factors which directly relates to the zone above the caved mine excavations.

There were a total of ten mines with workings (now closed 1990-1994) operating under the sea in this area. These mines range in capacity, producing 1450-5000 tonnes/day with a combined total of 8 million tonnes per year. Figure 1.1 shows the location of these undersea mines in the North East of England. (Watson, 1979.)

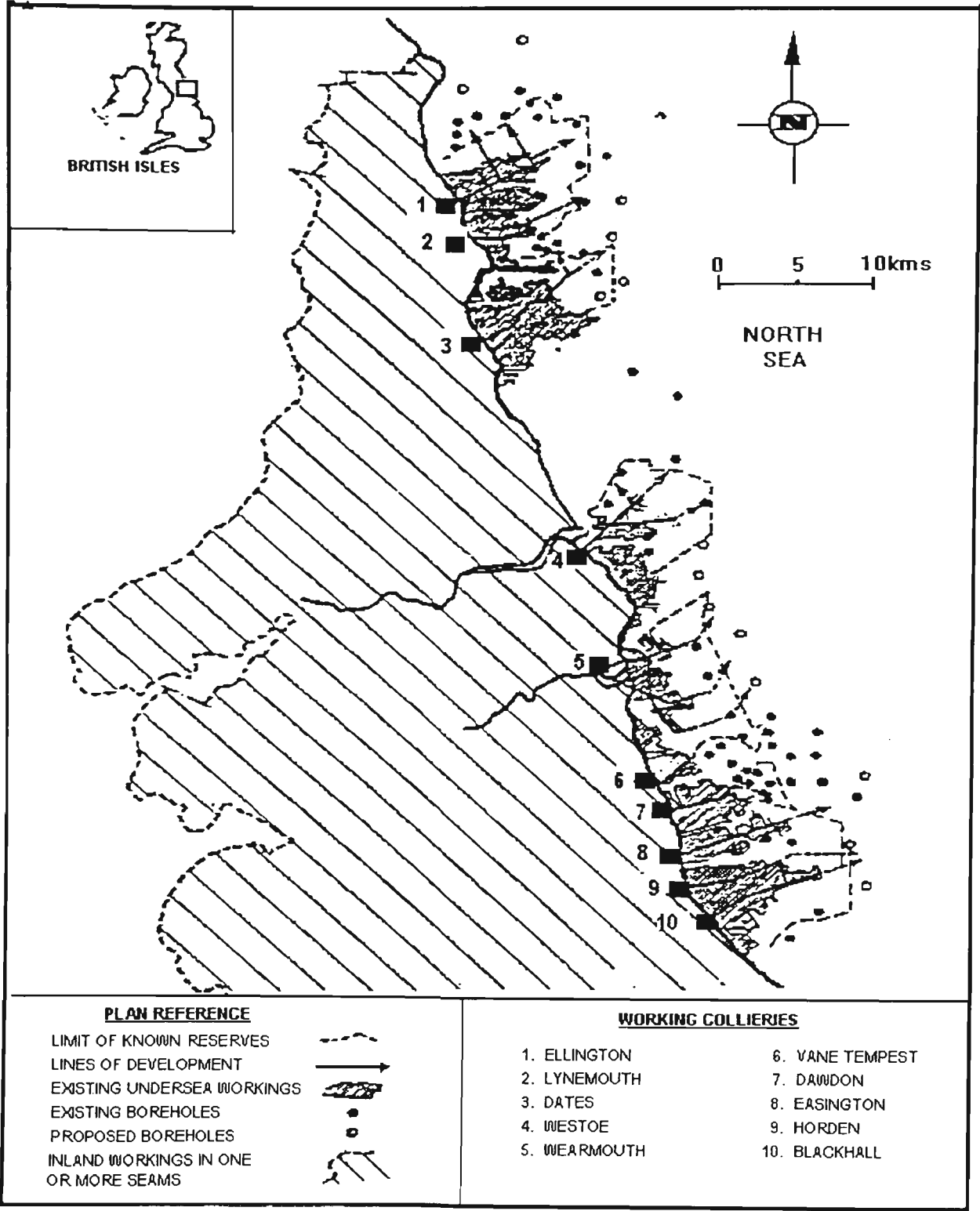


Figure 1.1 North East Area - Undersea Collieries

The depth of mining under the sea in the North East of England varies from approximately 125 m to 410 m. The limit of cover between the sea bed and the site of extraction within the mine determines the selection of mining method. The deeper mines in this area use longwall mining. Face lengths range from 120 m to 250 m with the exception of one mine where the face length is 64 m. Mines with shallow cover have been forced to adopt room and pillar mining to reduce the potential of increased water flow or inrush. The majority of the mines use a combination of Dosco dinthead, Dosco roadheader and continuous miner for development. At greater depths, drill and fire is also used. 70 % of the total output of the ten collieries in this area is obtained from longwall faces and the remaining from the less productive method of room and pillar mining.

There has been no recordings of inrush into workings from sea water. (Whittaker, Aston. 1982.) It has been determined from past experience that the occurrence of water originates from the following sources:

- sea water
- water from Permian aquifers
- water from old mine workings
- water from outcrops percolating down the worked out coal seams

On average, 9.3 tonnes of water is pumped for each tonne of coal extracted in this area. Most of the water problems associated with the water entering the mines can be attributed to water from Permian aquifers or water from old mine workings.

The coal measures in the North of England are 750 m thick and can be divided into two sections: an exposed section in the west and a concealed section in the east. (Refer to Figure 1.2) Overlying the coal measures is the Permian strata which comprises predominantly of magnesium limestone, with yellow sand underlain. The horizon of the Permian which overlies the coal measures consists of unconsolidated sand, sandstone and breccia. It is this strata that forms an important aquifer and source of water to the mine workings. Faults and dykes are major structural features in this area and contain many fissure networks which extend from the coal measures to the Permians. They can be re-charged by the Permians and thus become excellent aquifers. The major faults are capable of acting as water conduits and bringing the Permian strata close to the permeable sandstone bed. This results in this strata becoming recharged and aquifers systems are developed close to the workings. (Whittaker and Aston. 1982.)

A few details of the coal mines extracting under the sea in the North East of England are described below. (Watson, 1979.)

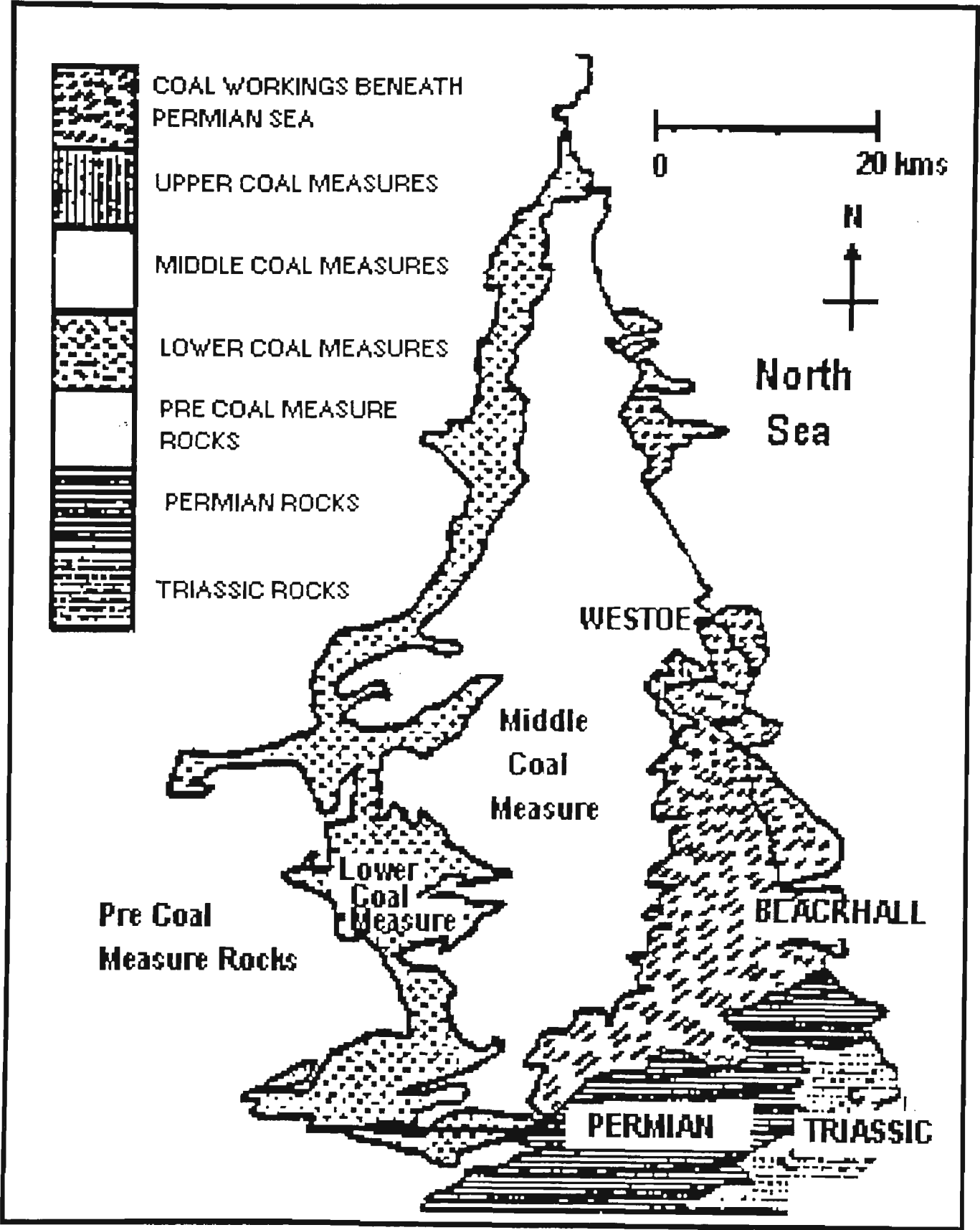


Figure 1.2 Geological Map of the North East Coal Field

Ellington is mined by room and pillar methods at an average depth of 130 m below the sea. Room and pillar was adopted because the cover between the seams and the sea bed was limited and full extraction may have caused water problems. The amount of water pumped out of the Ellington Colliery is $2.8 \times 10^6 \text{ m}^3/\text{year}$. This mine had a production of 1.1 million tonnes per year.

Lynemouth extracted coal by longwall mining and room and pillar methods. Room and pillar was used due to the limited cover when mining two thick seams in this area. It produced 0.9 million tonnes per year. Mining was carried out at an average depth of 125 m below the sea bed. $4 \times 10^6 \text{ m}^3/\text{year}$ of water was pumped out of the mine.

Dawdon Colliery operated at a greater depth of 410 m below the sea. It produced 1.1 million tonnes per year. The mining method they used was longwall mining and the quantity of water which they pump out was relatively less than surrounding pits at $0.3 \times 10^6 \text{ m}^3/\text{year}$.

Horden was another mine operated in the region. It was originally worked using longwall methods but was forced to use room and pillar mining when the limit of cover between the workings and water bearing strata decreased. An increase in the quantity of water resulted from the longwall mining despite attempts to reduce the face width of 55 m.

Blackhall was another colliery that had workable coal reserves under the sea. The workings were also at considerable depth at an average of 390 m. Longwall mining was used for extracting the coal and a total of $5.5 \times 10^6 \text{ m}^3/\text{year}$ of water is pumped out of the pit.

A comparison of water occurrences was carried out between Blackhall and Westoe Collieries. The occurrence of water was found to be dependent on the hydrogeology, structural features and subsidence aspects of each colliery. Both coal mines experienced water problems but to varying degrees. In 1979 Blackhall was pumping $12.3 \text{ m}^3/\text{min}$ of water out of the mine. Of this they could attribute $10.3 \text{ m}^3/\text{min}$ to the 35 faces in the Low Main seam. In total 51% of the faces experienced water. Water was experienced when the predicted tensile strain of 9 mm/m at the base of the Permian occurred. However faces with strains of 7 mm/m have had no such problems with water and remained dry. Faults have been the most significant feature in the occurrence of water in mining this area. Problems were experienced when mining occurred near a major E-W fault or perpendicular to it.

Westoe Colliery pumped $8.0 \text{ m}^3/\text{min}$ of water out of the mine which consisted of 63 faces in three seams. Approximately 18% of the Westoe faces had experienced water.

Base of Permian strata of 14 mm/m in areas of multi-seam extraction have not experienced any water problems and remained dry. However in single extraction areas, Base of Permian strata of 6 mm/m have experienced water. Faults in Westoe have been the most significant feature in the occurrence of water. Water problems have been experienced when working close to or perpendicular to a major E-W fault.

The amount of strata cover between the sea bed and workings in Westoe and Blackhall is relatively the same. For both wet and dry faces, the amount of cover at Blackhall ranged from 91 - 140 m for the Low Main seam to Base of Permian. At Westoe the cover ranged from 113-177 m for the Main Seam to Base of Permian.

Although the amount of cover is usually the most important condition when considering the occurrence of water into the workings, it is more likely that the occurrence of water as noted in these two coal mines is affected by the structural features and strata lithology in the coal measures. Faults in particular have had a major influence on the occurrence of water. Faults in both regions have been responsible for bringing water bearing strata into close proximity with the strata overlying the working areas and thus allowing recharging. Induced subsidence from mining can also affect secondary structural features related to the fault and this will also be related to water occurrences at the faces.

Water was sampled from both mines and hydrochemically analysed (Aston, 1982.) It was determined that the water originated from either the Permian or overlying coal measures aquifers and that the transmission of this water to the workings was dependent on the local lithology, structural features and the tensile strain zone which occurs due to extraction. This zone extends above the areas of extraction and the magnitude of this zone depends on the parameters of the face.

To reduce the inflow of water into the mine workings at Blackhall, a number of measures were instigated. The direction of advance of the coal face was changed after previous directions encountered wet conditions. When the face was advanced parallel to the main fault, the occurrence of wet faces decreased to 40%. The width of the face was reduced for two reasons. One was to reduce the rate of inflow of water as when the face was narrowed, the rate decreased. Narrower faces decreased the amount of strain developing in the Permian strata and sea bed and thus resulted in less inflow of water through secondary fissures developed from this strain. Mudstone and siltstone strata layers were utilised where possible to reduce the flow of water as these strata are aquicludes and aquitards and were located between the workings and the source of water, they act as a barrier.

Another mine extracting under the sea in the North East of England was also faced with hard strata, an aquifer with high hydraulic head, massive sandstone incropping

within 60 m of the major aquifer, old workings 90 - 140 m below the present workings and a fault heading over the coal face. The mine was designed with a minimum thickness of protective barrier between the coal seam and base of the Permian. The selection of mining method was determined by the one which would produce the least amount of subsidence on the surface and thus have the least disturbance to the overlying strata. The mine extracted a longwall face width of 190 m at a thickness of 2 m. To ensure water would not flow from the Permian strata into the workings, a reduced face length was installed with a barrier pillar of 50 m. This reduced the strain in the Permian strata caused by the fracture zone from extraction and reduced the chance of water flowing into the workings.

In conclusion, many mines have worked below the sea, lakes and water bearing strata. throughout many coalfields in Britain and other areas around the world. Although specific criteria associated with the rock types and geological conditions will vary with each location, a number of criteria will enable successful mining to occur. This criteria will enable successful mining to occur. This criteria is based on the width of the extraction zone, the height of caving, depth of cover and the width of the gate road pillars to create a stable mining void which does not interact with the surface.

1.2 Utilising Resources - Mining & Water Storage

Mining under stored bodies of water is possible without serious consequences when properly undertaken and planned. There are however risks and it is because of these risks that restrictions are applied to mining operations. These risks concern the mining operation, the community and the environment. There is a concern for the environmental damage to water courses that may occur due to mining if the operation is on a water catchment area. Environmental considerations are becoming more important but the major concerns are the safety of the mine workings and the loss of water from the stored body.

Damage to the integrity of the dam structure may result from mining beneath this feature. Distortion, cracking and failure may also result and cause: (Singh, 1994.).

- Increased seepage
- Loss of safe yield of water
- Complete loss of water
- Inrush into the mine workings
- Risk of damage to the dam wall

If these situations were to arise, the loss of life or property on the surface or underground are very possible. Restrictions to mining operations have thus been implemented to minimise these risks.

As mining under stored bodies of water was not permitted, coal reserves have been sterilized. With the depletion of easily accessible coal these areas of previously sterilized coal are having to be considered. However, even when these reserves are made accessible there is still the limitation on mining operations under the stored body of water which can make the operation infeasible. Financial implications will arise from the sterilization of coal required to remain for mine barriers and pillars. These are to provide protection to both the safety of the workings and any structure related to the stored water and to prevent the loss of water.

There are coal seams under reservoirs and dams within New South Wales that are economically viable. Figure 1.3 indicates the boundary of economic reserves in the Water Board Water Supply Catchment areas in New South Wales. Previously mining was not permitted under stored bodies of water until the Reynolds Inquiry established a zone around the stored body of water. Reynolds, 1976.) This zone defines a restricted area in which mining can occur.

The Reynolds Inquiry was initiated to determine the limitations to which mining operations could proceed under stored bodies of water. The following limitations resulted from this inquiry:

- (i) No mining in areas of 60 m or less cover.
- (ii) Bord and pillar mining is allowed at depths of greater than 60 m. The bords may have a maximum width of 5.5 m and pillars may have a minimum width of fifteen times the extraction height (or one tenth the depth of cover, whichever is greater).
- (iii) Panel and pillar mining is allowed at depths greater than 120 m. The panel sizes are to be no greater than a third of the depth of cover. The pillar sizes are to be of a length co-extensive with that of the panel extracted and a width not less than one fifth of the depth cover, or fifteen times the height of extraction, whichever is greater.
- (iv) The marginal zone around stored waters should be determined by an angle of draw of 26.5° taken down from the boundary of the stored water at full storage level.
- (v) There should be no mining or driving of access roads beneath a dam structure within a coal pillar at a point 200 m way from the edge of the structure and an angle of draw of 35° .

However, since this inquiry there have been amendments to the criteria for mining under stored bodies of water. The following limitations are now applicable to mining operations:

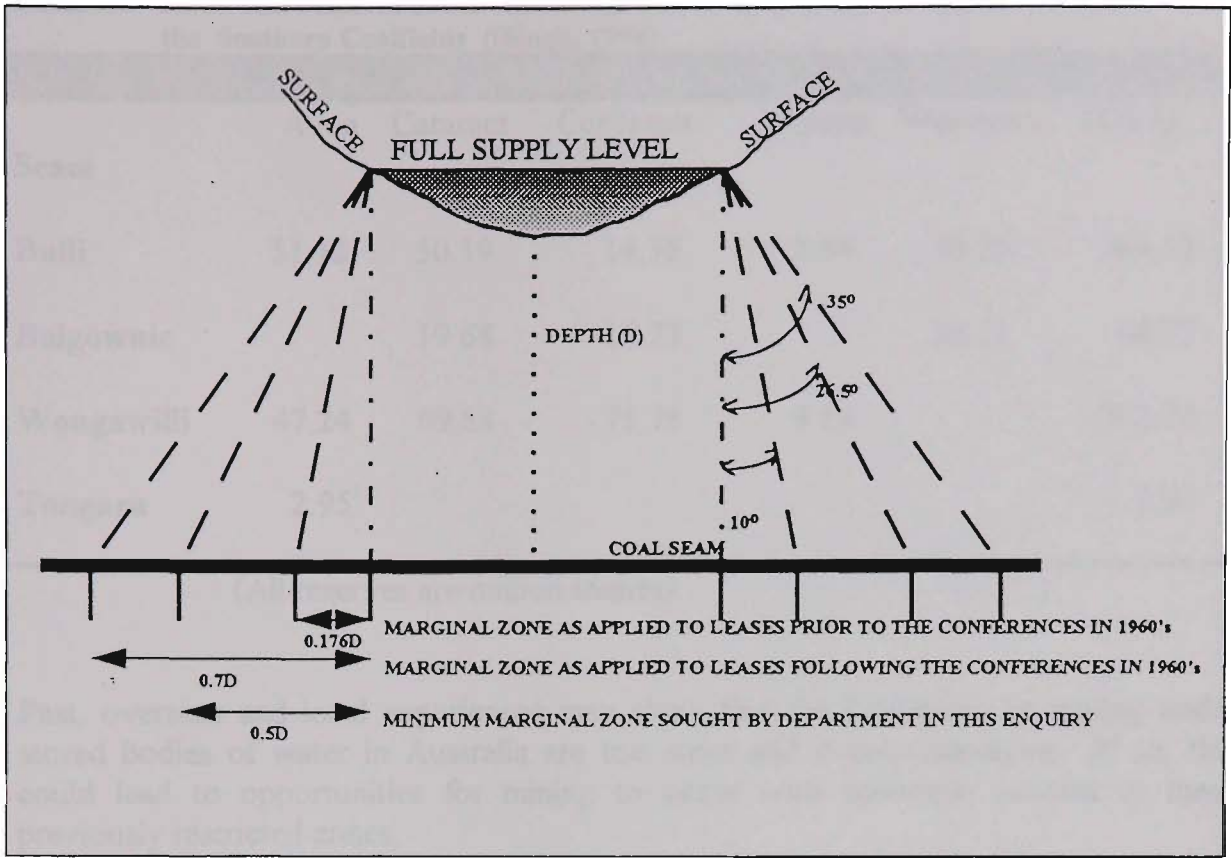
- (i) Panel and pillar mining are allowed with widely spaced cross-cuts to allow underground development.
- (ii) The depth used in the panel width calculation is taken as the least solid cover. For the pillar width calculation, the greatest solid cover is used. The result of this amendment is a reduction in recovery rates.
- (iii) The marginal zones were increased to 35° from the top of the water level. At the intercept of that angle with the seam, a further distance of half the depth from the bottom of the seam to the top water level is used as a restricted zone.

A Dam Safety Act was introduced in 1978 by the New South Wales Government to outline the procedures that are necessary when mining under water bodies. This is to ensure protection from the potential damage that may arise from mining operations. Any proposed mining operation must be submitted to the Dams Safety Committee who is responsible for the restricted zones as shown in Figure 1.3.

The restricted zone, as determined from the Reynolds Inquiry, (Reynolds, 1976) is the 35° angle of draw and half the depth from the bottom of the seam to the top water level. The Dams Safety Committee considers the application which contains all details of the proposed operation, and makes a recommendation to the Department of Mineral Resources who will issue an approval, conditional approval or rejection. (See Figure 1.3).

If approval is granted for mining in the restricted zone, there are conditions which the mining company will need to comply with.

These are determined from the Reynold's Inquiry and directly effect the amount of reserves that can be recovered. Although extraction can commence protection barriers must be left and the monitoring of tensile strain is an essential condition. The result is increased costs and decreased recovery. Another consideration is to provide protection for the water courses if mining under stored water means locating facilities on a catchment area. Increased costs may also result because of this.



Within New South Wales there are several reservoirs with underlying coal seams of economic significance that contain substantial reserves. Table 1.1 and Table 1.2 illustrates the extent of the reserves contained in these areas. (Figure 1.4.)

Table 1.1 - Insitu Coal reserves under the storage reservoirs in the Southern Coalfields (Singh, 1994)

Seam	Reservoir					TOTAL
	Avon	Cataract	Cordeaux	Nepean	Woronora	
Bulli	21.65	20.67	6.89	0.79	9.84	59.84
Balgownie		5.91	7.38		6.89	20.18
Wongawilli	19.68	23.62	30.51	3.44		77.25
Tongara	0.89					0.89

Table 1.2 - Insitu coal reserves under the storage reservoirs plus the 35° angle of draw in the Southern Coalfields ((Singh, 1994)

Seam	Reservoir					TOTAL
	Avon	Cataract	Cordeaux	Nepean	Woronora	
Bulli	51.18	50.19	14.76	2.46	46.25	164.85
Balgownie		19.68	16.73		30.51	66.92
Wongawilli	47.24	69.88	75.78	9.84		202.74
Tongara	2.95					2.95

(All reserves are million tonnes)

Past, overseas and local experiences may show that the limitations to mining under stored bodies of water in Australia are too strict and overconservative. If so, this could lead to opportunities for mining to occur with economic success in these previously restricted zones.

The risks and problems that are present when mining under stored water arise from the behaviour of the strata overlying the coal that is being extracted. A generalised explanation is presented to explain the theory behind the limitations on mining under stored water.

Water entering the workings is affected by the mining geometry, sub-surface and surface subsidence patterns and the hydrology of the strata separating the workings from the surface. Underground mining affects the surrounding and above rock by inducing stresses in an area that was previously in equilibrium. This redistribution of stresses causes surface and sub-surface subsidence. As a result, the surface and sub-surface flow pattern of water and the sub-surface water table is affected. This may cause serious water inflow problems into a mine due to this change in the ground water hydrology.

Subsidence occurring on the surface can be divided into three zones. These zones include:

- zone of full subsidence
- zone of compression
- zone of elongation

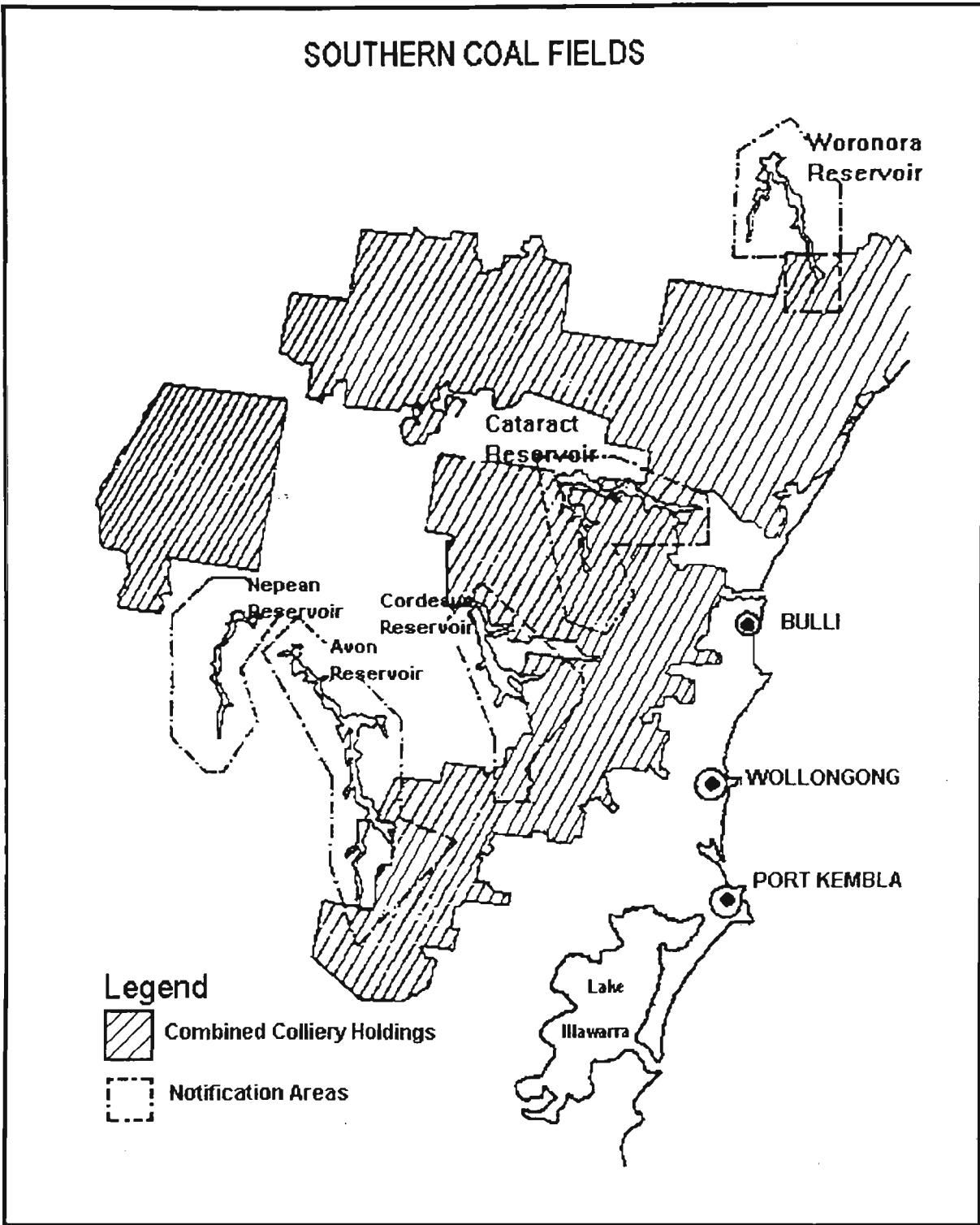


Figure 1.4 Notification Area of Southern Coalfields

Figure 1.5 illustrates the components of mining subsidence when total extraction is involved.

The components of sub-surface subsidence are classified into three de-stress zones. These three distinct zones are depicted in Figure 1.6 and include:

- zone of vertical compression
- zone of vertical extension
- zone of incomplete convergence

The behaviour of the strata above a longwall excavation in underground mining is affected by the surface and sub-surface subsidence. When excavation occurs, the stress zones described are formed. As a result the permeability of the strata is changed. This change in permeability can be divided into three major zones. These include:

- Fracture zone
- Aquiclude zone
- Zone of surface cracking

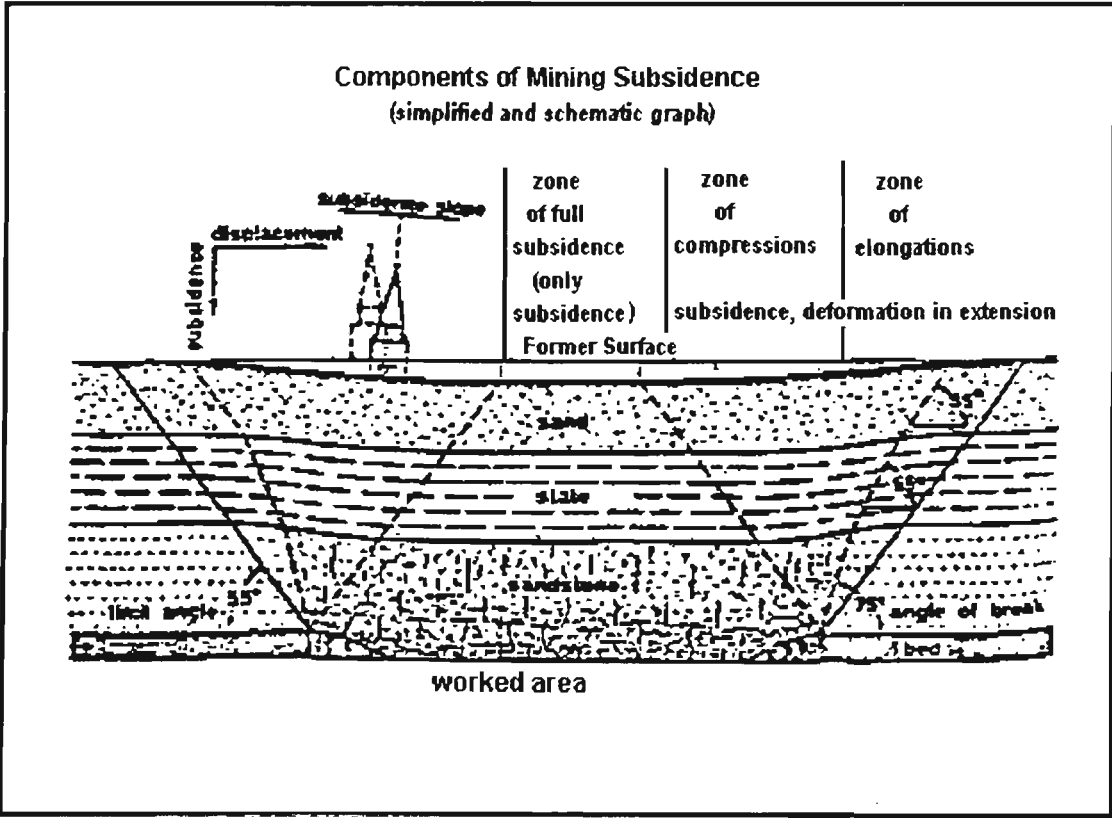


Figure 1.5 Components of Mining Subsidence

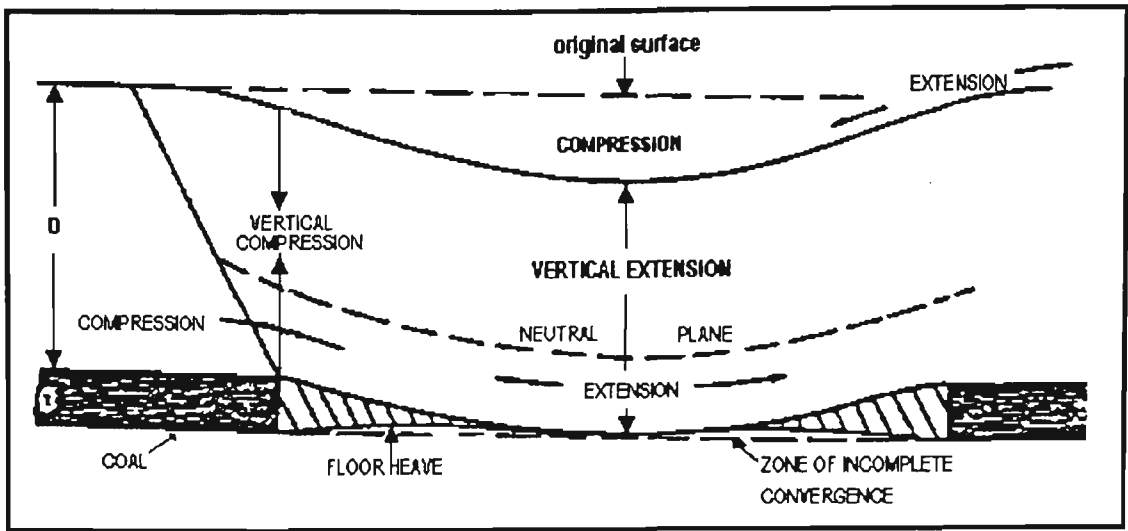


Figure 1.6 Components of Subsurface Subsidence

Figure 1.7 depicts the formation of these three zones. The fracture zone occurs immediately above the seam being extracted. It extends vertically upwards from the extraction horizon for a distance of 30 to 58 times the thickness of the seam. In this zone there is also a caved zone that extends 3 to 6 times the thickness of the seam from the extraction horizon. This zone is related to the area required to fill the void left from extraction and consists of many induced fractures. Above the fractured zone is the aquiclude zone. In this zone, the strata tends to bend or flex so the presence of induced fractures is not high. This zone consists of constrained strata that has little change in permeability. It extends from 30 times the thickness of the seam above the extraction horizon, to 15 m from the surface. The zone of surface cracking extends from the surface to a depth of 15 m.

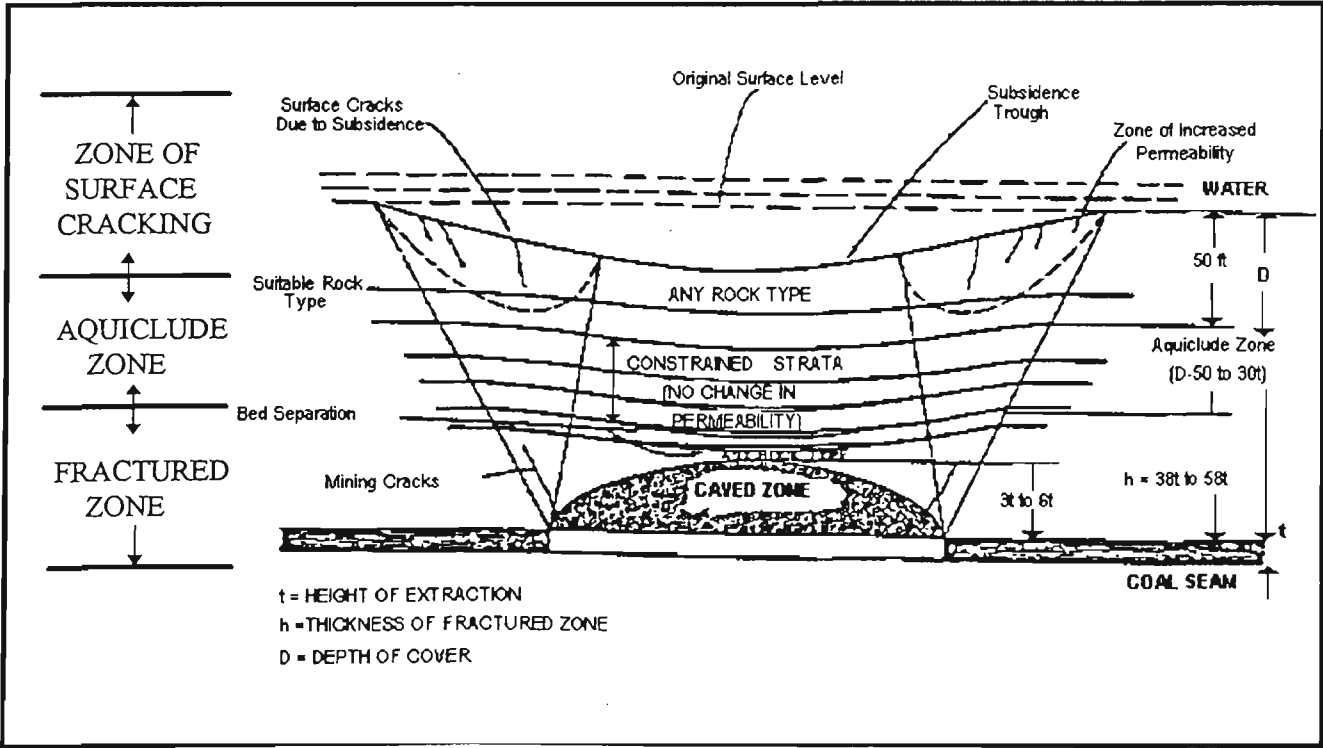


Figure 1.7 Generalised Depiction of Strata Behaviour with Total Extraction Mining

Total extraction causes the development of these three zones. Once extraction begins the strata above this area caves into the void left from extraction. The overlying strata, within the zone of influence of this extracted region, is affected by this disturbance. The result of this disturbance is subsidence on the surface. The development of surface cracks may also appear depending on the depth to seam thickness ratio and other related factors. The strata layers above the caved zone experience compressive and tensile stresses. The tensile strain in the vertical direction causes bed separation and horizontal strains tend to open up joints. Any joints that are opened up or formed present a path for the flow of water. The flow of water through these conduits can be of a very high magnitude.

When mining underground Figure 1.7 a fracture zone pattern occurs above the caved mine workings. When mining under bodies of water, an effective barrier can be calculated to protect the mine workings. In the zones above the mining horizon, there is an increase in permeability of the rock in the amount of 40-80 times that of the intact rock permeability. Thus if water is present in regions above this zone, large amounts are able to flow. Above this caving zone, is the bed separation zone and the horizontal conductivity of this strata is greatly increased. Due to the cavities in the bed separations, large amounts of water are capable of forming and drain into the workings below. However a compressional zone (Aquiclude) between the mine workings and the surface trough is able to act as a barrier against the flow of water from the surface because in this zone the strata is in compression and does not create a vertical linked fracture pattern. In effect it acts as a protective barrier. Problems may arise if the strata is hard and brittle as subsidence cracks at the surface may propagate down to greater depths.

It can be expected that the ground movement associated with surface subsidence will affect the hydrology. The zone of elongation can become a zone of increase permeability due to mining subsidence and this strata, if forming the groundwater bed of an unconfined aquifer, may allow increased inflow of groundwater through it. This may result in an inrush of water to the mine workings. If the strata is plastic and able to resist the movement without breaking, then water may accumulate on the surface.

If the strata beneath the surface is limestone or dolomites then the formation of sink holes is a possibility. Modification of the ground water flow due to mining subsidence can result in these formations. Fissures may accelerate the process.

The extent of subsidence is dependent on the dimensions of the excavation and the extent of disturbance to the strata. If the natural stress field is greatly disturbed, subsidence results on the surface. Once the rock has caved into the void left by extraction, the effect of the strata pressure on this material consolidates the caved material. This has the effect of reducing the permeability and reduces or eliminates the flow of water into the mine. The higher the pressure from the overlying rock, the more the flow of water through this area can be reduced.

Mining under bodies of water is possible and operations have successfully recovered reserves from these areas. Such bodies of water include oceans, lakes, rivers, ponds, streams, large underground aquifers and abandoned workings. Therefore relating these operations to mining under stored bodies of water is quite similar. Mining under water is similar to other mining operations but requires careful planning to ensure that no damage is caused to structures such as dam walls from surface subsidence or depletion of water supplies.

A factor that needs to be considered when planning a design for workings under water is the size of the body of water. Working under smaller amounts of water may not pose such a high risk as large amounts of water that have the potential of causing major inrushes and resulting in danger to life and property or totally destroying the mine. The inrush of water from a stored body of water is of a high potential as there is a large accumulation of water. However for inrush to occur, there must be a low resistance route for the water to move from the stored body to the workings and the hydraulic pressure should exceed the threshold pressure to cause inrush.

The nature of the strata separating the body of water and the mine workings is an important factor to consider together with any structural features within the sequence that may present potential flow paths. Aquifers occurring in the intervening strata can cause constant inflows of water if they are recharged. There is a strong possibility of this due to the fact that approximately 40 % of coal measures rock is aquiferous. This is due to layers of sandstone units that occur in the layers of coal, shale and mudstones that otherwise make up the coal measures. Sandstones are aquifers and if they outcrop on the surface, due to their porous nature, are able to be recharged and cause inflow into the mine. However, the shale layers when intact are impervious to the flow of water and will form aquitards.

In the fractured zone above the excavation region as previously mentioned, the permeability of the rock is increased and can be 40 - 80 times the intact rock permeability. Serious water problems can be experienced on the face when longwall mining. Joints are an integral feature of coal measures but their size, orientation and spacing are unique to each region. It should be noted that despite the disturbance to strata, very few new joints are created. Subsidence movement occurs on the pre-existing joints and cracks. Joints need only a 35 microns opening as observed in numerous locations in the Southern Coalfields region to transmit water but the nature and characteristics of joints are dependent on many factors. If these joints provide a path connecting a water source to the workings then water problems may arise. Thus, the thickness of the intervening strata is an important factor to consider when designing workings under stored bodies of water as the aquiclude zone must be large enough to separate the fractured zone from the surface crack zone.

In the design of workings under stored bodies of water there are specified regulations stating the maximum strain that is allowed for a given amount of subsidence. Tensile

strain should not exceed 6 - 10 mm/m at the surface or aquifer bed. When structures are located on the surface, there is a limit to the amount of subsidence that is permitted to ensure that these structures are not damaged in any way. The width of workings to depth is an important factor in determining the maximum strain.

1.3 Bellambi Collieries - Southern Coal District of NSW

South Bulli Colliery is located in the Southern Coal District of N.S.W. some 80 km south of Sydney and 14 km from the Port Kembla Coal Terminal (Figure 1.8). The colliery is operated by Bellambi Collieries Pty. Ltd which is a wholly-owned subsidiary of the Shell Company of Australia Limited.

The mine is over 100 years old and has produced over 54 million tonnes of coal since it commenced production. During the 1980's the operations were concentrated in the Bulli seam in an area located to the west of the Cataract Reservoir, hereafter referred to as the "Western District".

Following on from a geological investigation, a study conducted in 1990 concluded that the coal quality in the Western District of the mine would no longer meet the specifications of the export contracts and the financial position of the operation would deteriorate significantly. At that time the best quality remaining reserves within the colliery lease were located beneath the Cataract Reservoir.

Based on the guidelines recommended in the Inquiry into Coal Mining Under Stored Water conducted by Justice Reynolds the company applied for the permission to mine the coal reserves under Cataract Reservoir. In May 1991 the Minister consented, based on the recommendations of the N.S.W. Dams Safety Committee to the extraction of the first seven panels and the development of the eighth panel, referred to as the Bellambi-6 area (Figure 1.9). The Chief Inspector of Coal Mines subsequently approved the extraction of the first seven panels by the longwall method.

The mining of development roadways in the Cataract District commenced in March 1992 and by March 1993 the development of the first longwall panel was complete.

Mining conditions in the Western District deteriorated faster than original expectations and this led to a decision in January 1993 to withdraw from the West. Longwall extraction on Longwall 212 ceased in June 1993, which coincided with the commencement of Longwall 501, the first Cataract Longwall. A restructuring program for the operation of the mine was implemented in January 1993 to conform with the new mine plan.

Currently the extraction of Bulli seam coal in the Western District and/or other existing seams in the colliery lease (ie. Balgownie and Wongawilli) is not considered economic under forecast market conditions. Therefore the existence of the mine depends exclusively on the extraction in the Cataract District.

Since July 1993 all of South Bulli's development and coal production has come from the Cataract District, and to date 6 panels have been developed and the first four longwalls extracted (Figure 1.10). During this period 2.5 million tonnes of raw coal have been mined with superior washability characteristics, having an 83% yield, 80% of which is a coking coal fraction. Gross Revenue from the Cataract since July 1993 has been approximately \$92 million.

Significant improvements in safety and productivity have been realised since relocating operations from the Western District, in part due to the improvement in mining condition. This is shown in the Lost Time Injury Frequency Rate (Figure 1.11) and longwall and development productivity rates (Figure 1.12).

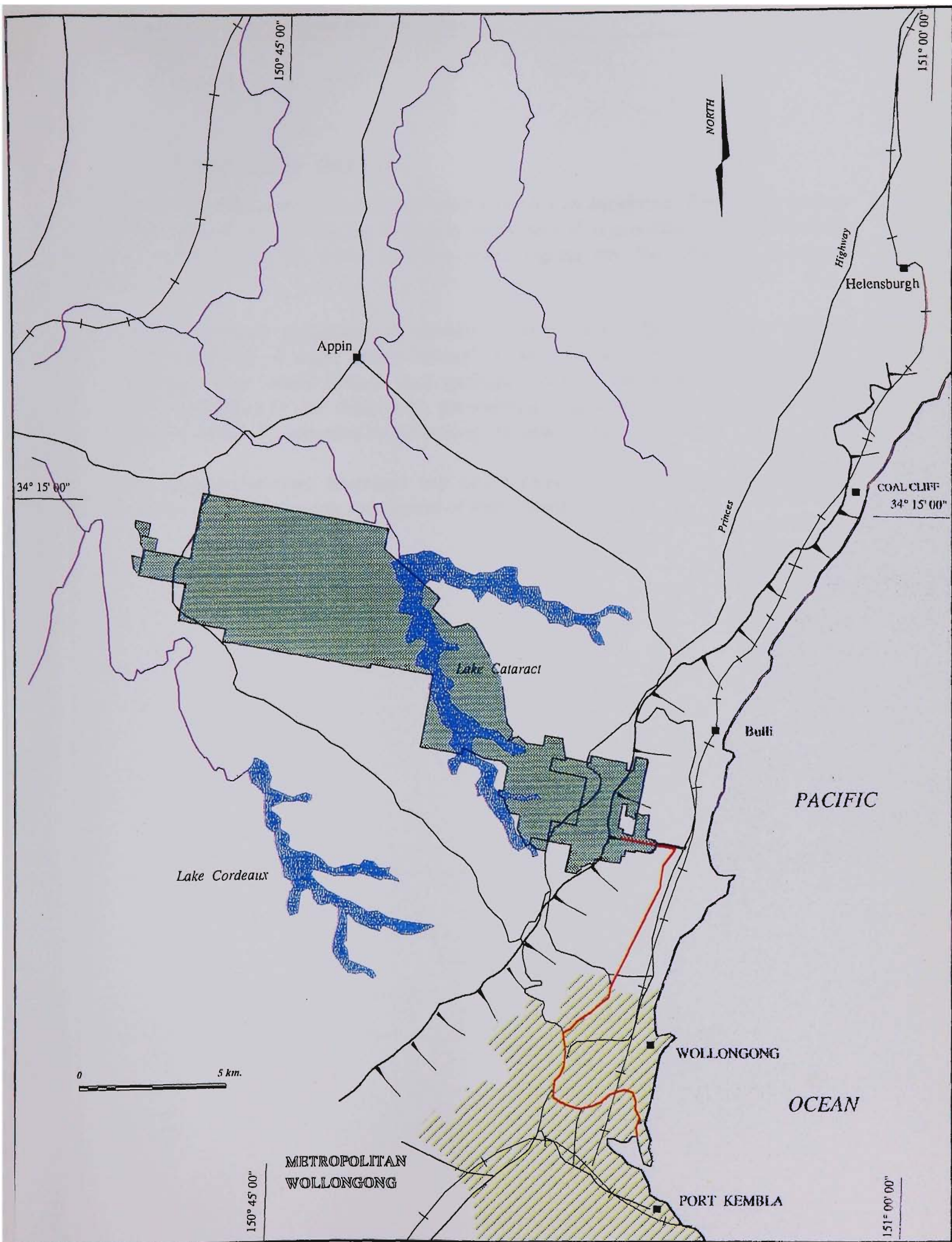
Due to the high quality of the coal and the favourable mining conditions under reservoir the company has improved its position in an unfavourable international coal market. In doing so it secures 315 jobs for the local community through direct employment, with the viability of about 1000 other jobs in the area also depending on the continued operation of the colliery. Approximately \$52M per annum are injected to the economy through employees remuneration, the purchase of goods and services, and State and Federal taxes.

1.4 Scope of the Thesis

The present thesis has been prepared and used by the mine to substantiate work already done. It will also be used to justify modifications that are required to test other parameters that will be used to further maximise the resource recovery and also determine specific parameters for the South Coast region.

It contains a review of the Stage I extraction to date, the geology of the new area, the proposed mining layout and its implications, as well as a proposed monitoring programme for Stage II.

Although the extraction of all currently approved panels has not yet been completed, approval of the new application is required well in advance of completion of the approved layout. This is due to the long lead times necessary to prepare longwall panels in general, and, in particular, the scheduling restrictions imposed on South Bulli by existing workings.



LOCATION OF SOUTH BULLI COLLIERY

1.5 Mining and Water Storage

The aim of mining beneath a body of water (whether an aquifer or "free" water such as a river, lake or sea) is to safely extract as much mineral as possible, without disturbing the overburden to the extent that any water ingress into the workings is beyond control.

There are two main possibilities to consider in relation to an inflow of water:- the first is the possibility of water inflow through a pre-existing extensive discontinuity or weakness. This would include such geological features as faults and dykes. The second possibility is that there is no pre-existing extensive weakness existing in the strata which may be activated by the mining operation itself.

Both possibilities were examined and where relevant, measures are proposed for identification, investigation and control of their effects.

SOUTH BULLI COLLIERY STAGE I APPROVAL AREA

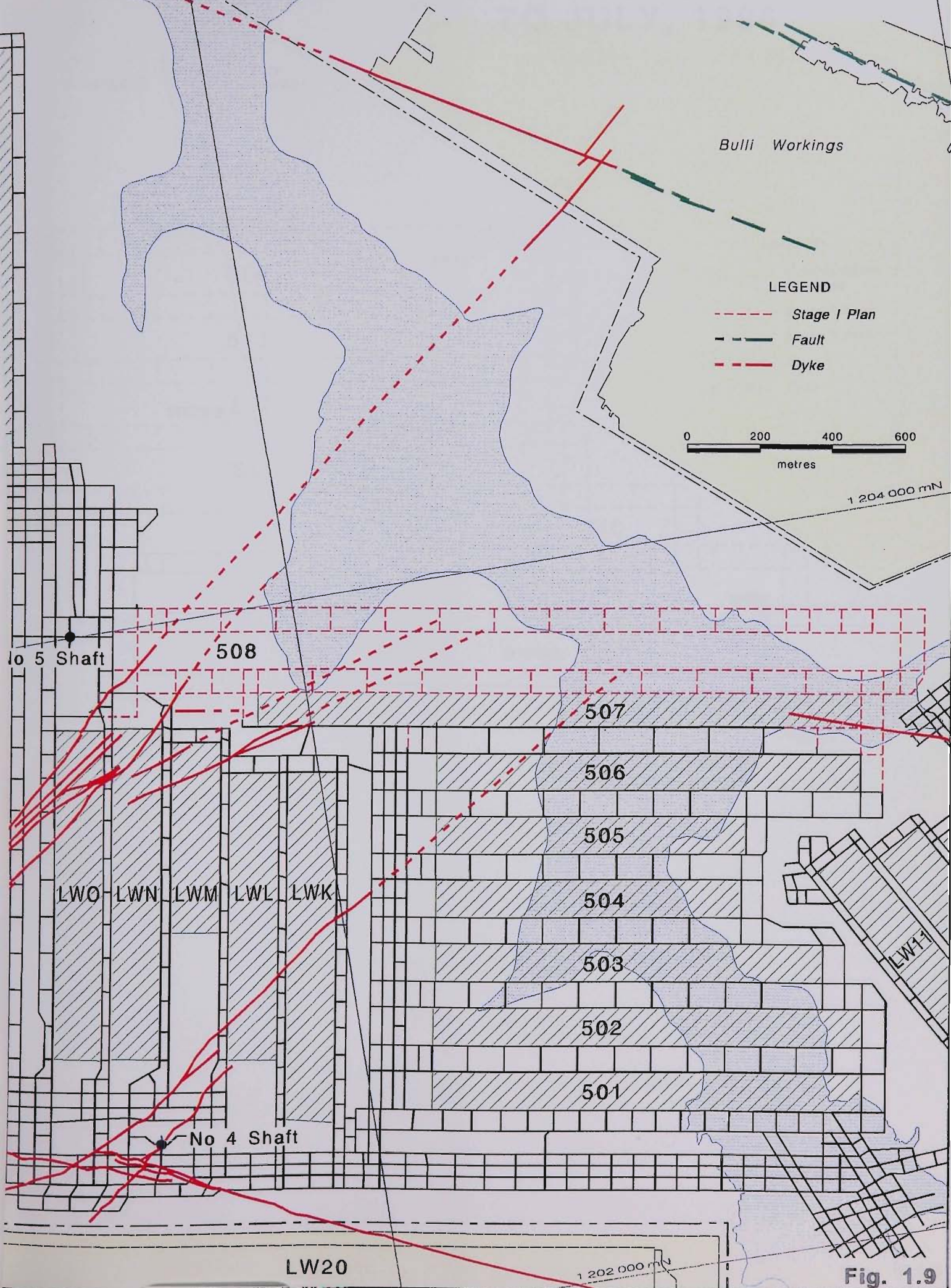


Fig. 1.9

SOUTH BULLI COLLIERY

MINE WORKINGS UPDATED TO JULY, 1996

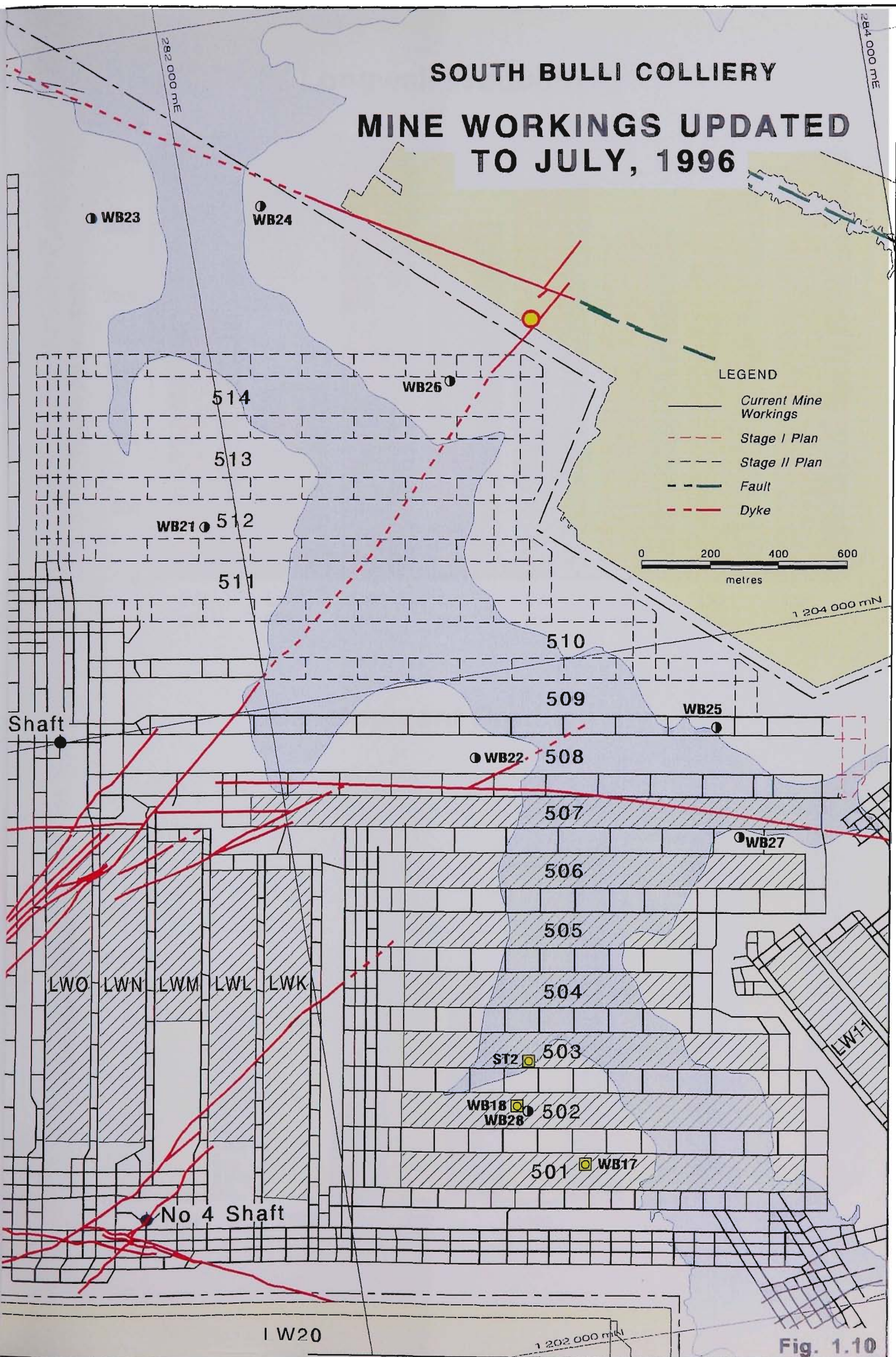
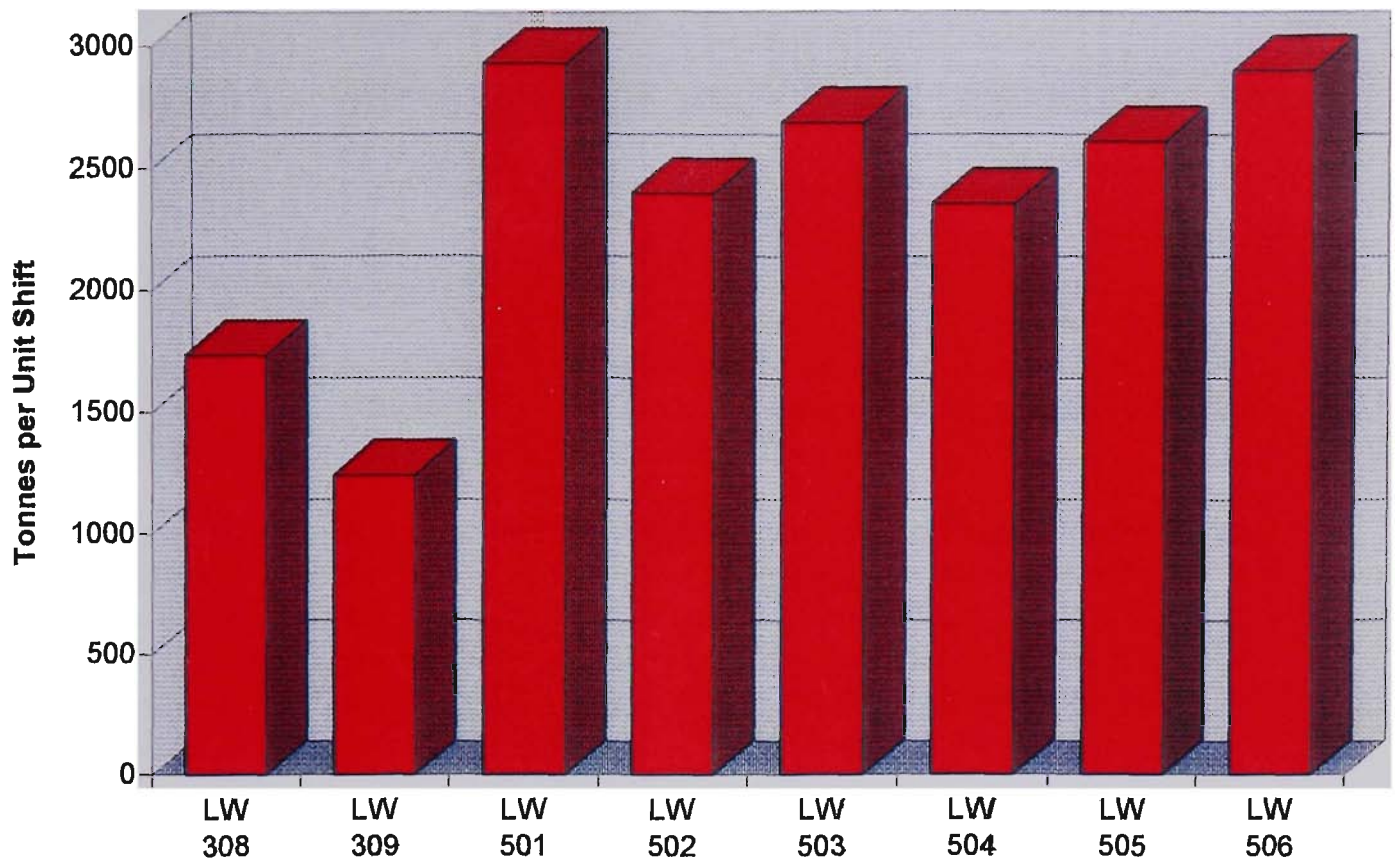


Fig. 1.10

Longwall Productivity



Development Productivity

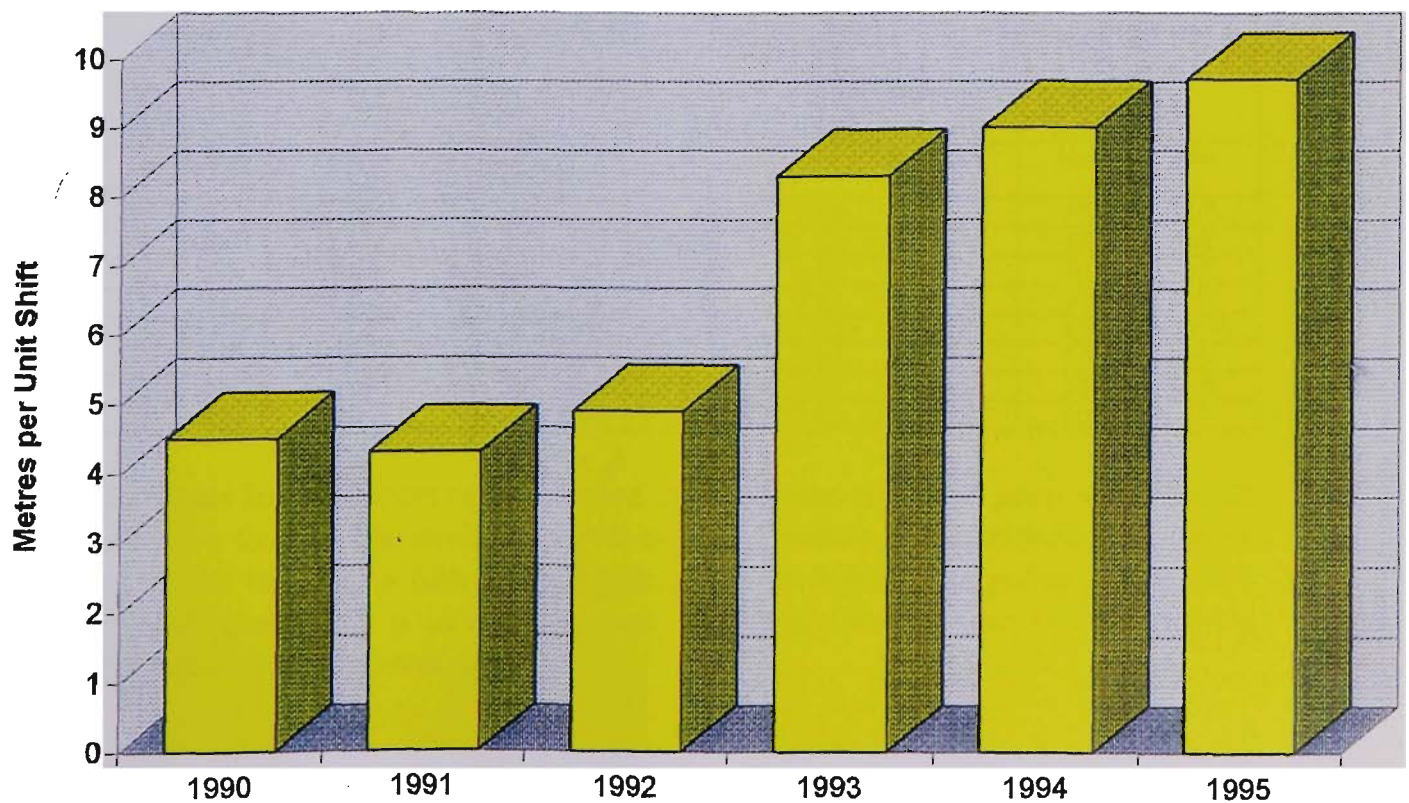


Fig. 1.12

CHAPTER 2 - CATARACT CASE STUDY STAGE I EXTENSION

2.1 Introduction

The Stage I mine layout developed was as proposed in the initial application, and to date only minor variations to the layout have been made, on the approval of the Chief Inspector of Coal Mines and the NSW Dam Safety Committee.

The minor variations up to Longwall 507 consisted of some alterations to the layout which did not affect the two most important parameters, the panel and pillar width (which ultimately impacts upon the safety of the storage). Based on the monitoring results and re-evaluation of these parameters, a new proposal for the mine layout involving a change in the width of the G507 chain pillars and the width of Longwall 508 in February 1995 (Figure 2.1) has been sought.

2.2 Mine Layout

The parameters of the Stage I layout including the latest depth of cover calculations are shown below in Table 2.1.

Table 2.1 - Longwall Design Parameters.

	Cover Depth (m)			Panel Width (m)	Pillar Width (m)	Ratios (rounded)			
	Reservoir		Plateau			Panel Width/ Cover Depth		Pillar Width/ Cover Depth	
Panel Number	Bottom	F.S.L.	Maximum			Min.	Max.	Min.	Max.
501	325	335-370	445	110	66	1/3	1/4	1/5	1/7
502	325	330-360	410	110	66	1/3	1/4	1/5	1/6
503	330	335-360	430	110	66	1/3	1/4	1/5	1/7
504	335	340-370	445	110	66	1/3	1/4	1/5	1/7
505	340	330-360	440	110	66	1/3	1/4	1/5	1/7
506	325	325-365	425	110	66	1/3	1/4	1/5	1/6
507	295	315-355	415	100	60	1/3	1/4	1/5	1/7
508	305	310-350	445	100	60	1/3	2/9	1/5	1/7

The Reynolds Inquiry report recommended the maximum allowable panel width should not exceed a third of the minimum cover depth. Similarly, the minimum pillar width should not be less than a fifth of the maximum cover depth. The policy of the NSW Dam Safety Committee is to examine every mining application with respect to these recommendations on its own merit.

2.3 Monitoring/Investigation Programs and Results

An extensive program of monitoring has been designed to verify and confirm the actual parameters for stress, strain and subsidence against theoretical modelling predictions.

SOUTH BULLI COLLIERY

CATARACT CASE STUDY STAGE I EXTRACTION

Bulli Workings

LEGEND

--- Development

Longwall extraction

Panel/Pillar size:
centreline to centreline (m)

Roadway width 4.9m

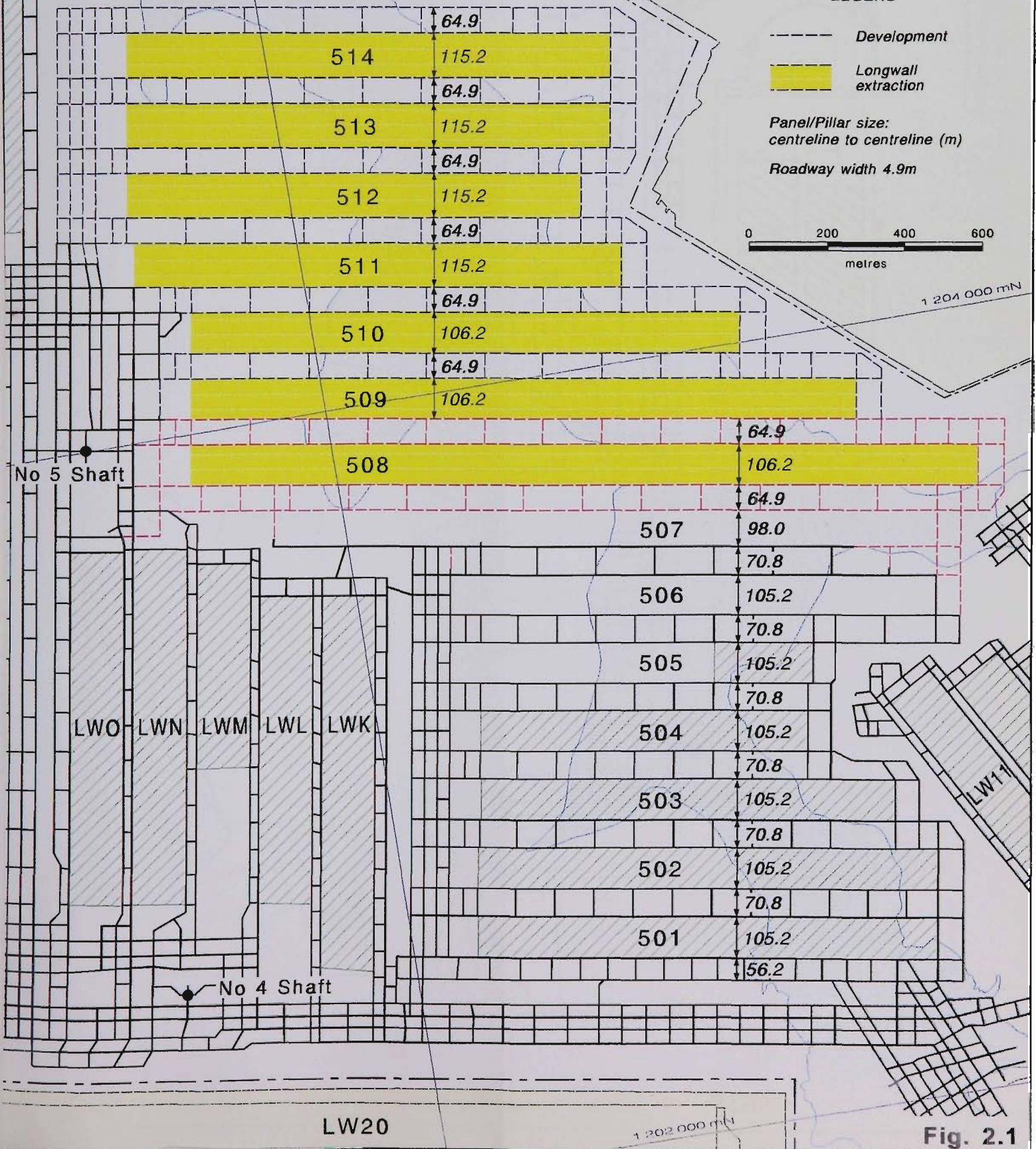
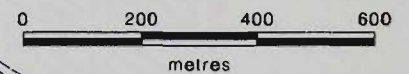
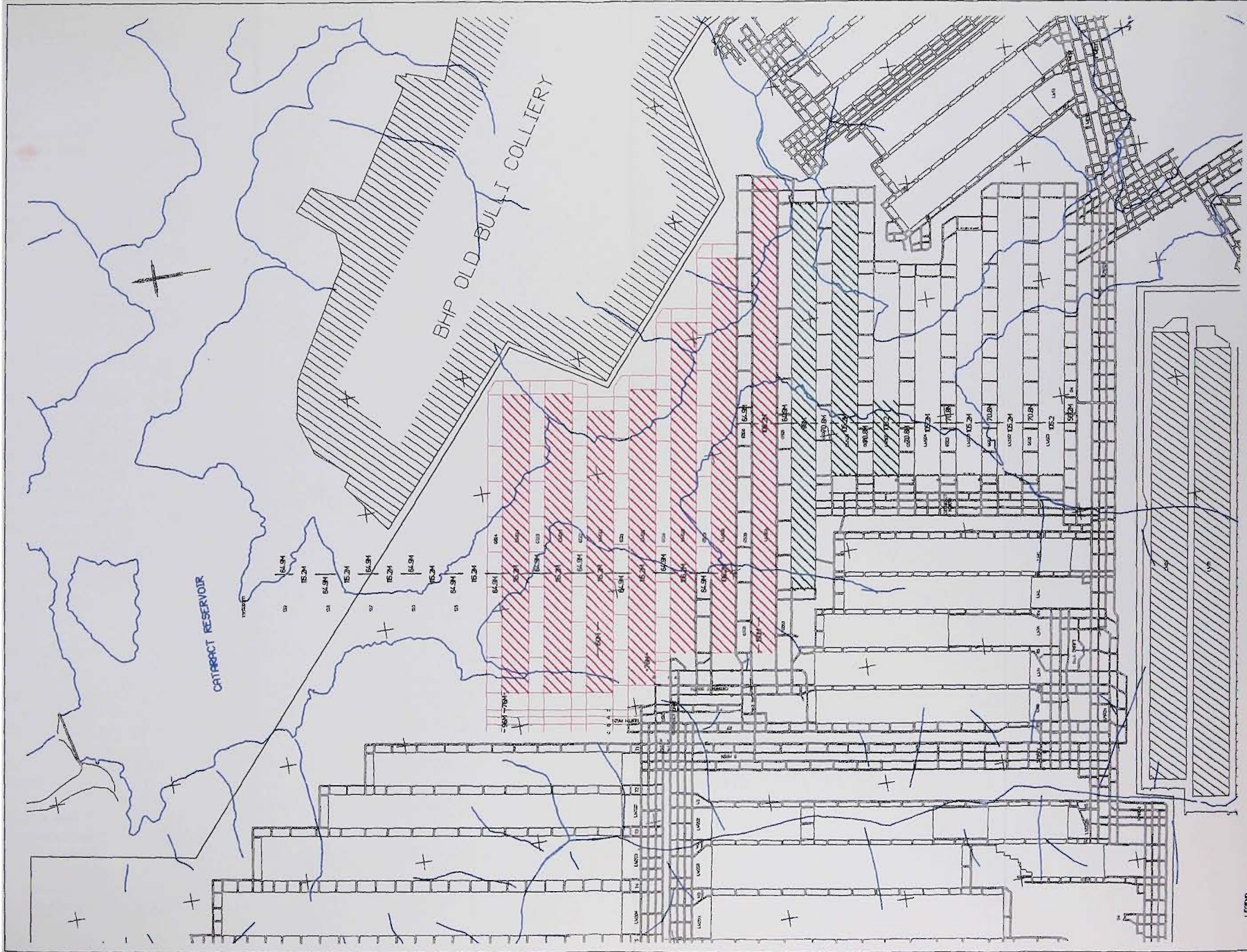


Fig. 2.1



LEGEND
 STAGE 1 APPLICATION (SHIPPED)
 STAGE 2 APPLICATION
 FULL STORAGE LEVEL
 SURFACE CONTOUR
 SURFACE CONTOUR 5M INTERVALS



This knowledge is critical in understanding how the strata responds to the extraction of the Bulli seam and the controls that limit the rate and manner of extraction below the reservoir.

A number of additional analyses, tests and investigations were completed to improve the knowledge / interpretation of the seam and overburden characteristics. These included such items as:-

- geotechnical testing of samples
- in-seam longholes
- aerial magnetic survey
- surface exploration boreholes
- a study of the composition and variation of the seam floor

A description of the programs and their results are presented below.

2.3.1 Surface Geological Mapping

A number of relatively thin dykes have been detected in the Bulli Seam. All these dykes have been altered to clay in old panels and only one dyke appears to have a surface expression;- a lineament running parallel to the 0.9 m dyke in Q district of old South Bulli workings can be identified along the shore line of Lake Cataract as a group of very strong joints. A photograph of this surface feature is clearly marked on the 1:2,000 scale surface geology map (Figure 2.2). A 1.0 m to 1.5m gap between two straight joints is followed by an intermittent stream bed. The gap may have been formed by the erosion of soft dyke material. Interpretation of the aerial magnetic survey attributes a very slight anomaly to this lineament, whereas the westward continuation of the dyke appears to be very restricted (according to the last in-seam seismic survey).

2.3.2 Underground Seam Mapping

Underground geological mapping is continuous, keeping pace with mine development, and up-dated copies of the map are regularly appended to monthly geological reports to review our knowledge base in relation to the mine layout and any changes that may affect the stability of our extraction plan.

The following features and variables are summarised on the 1:2,000 scale map (Figure 2.3):

- Spot seam thicknesses
- Discontinuities such as igneous intrusions, faults, shear planes, clay dykes, and major jointing, with a description of physical dimensions
- Roof lithology and position of erosive sandstone channels; features affecting roof continuity such as roof rolls
- Floor irregularities (eg. floor rolls)

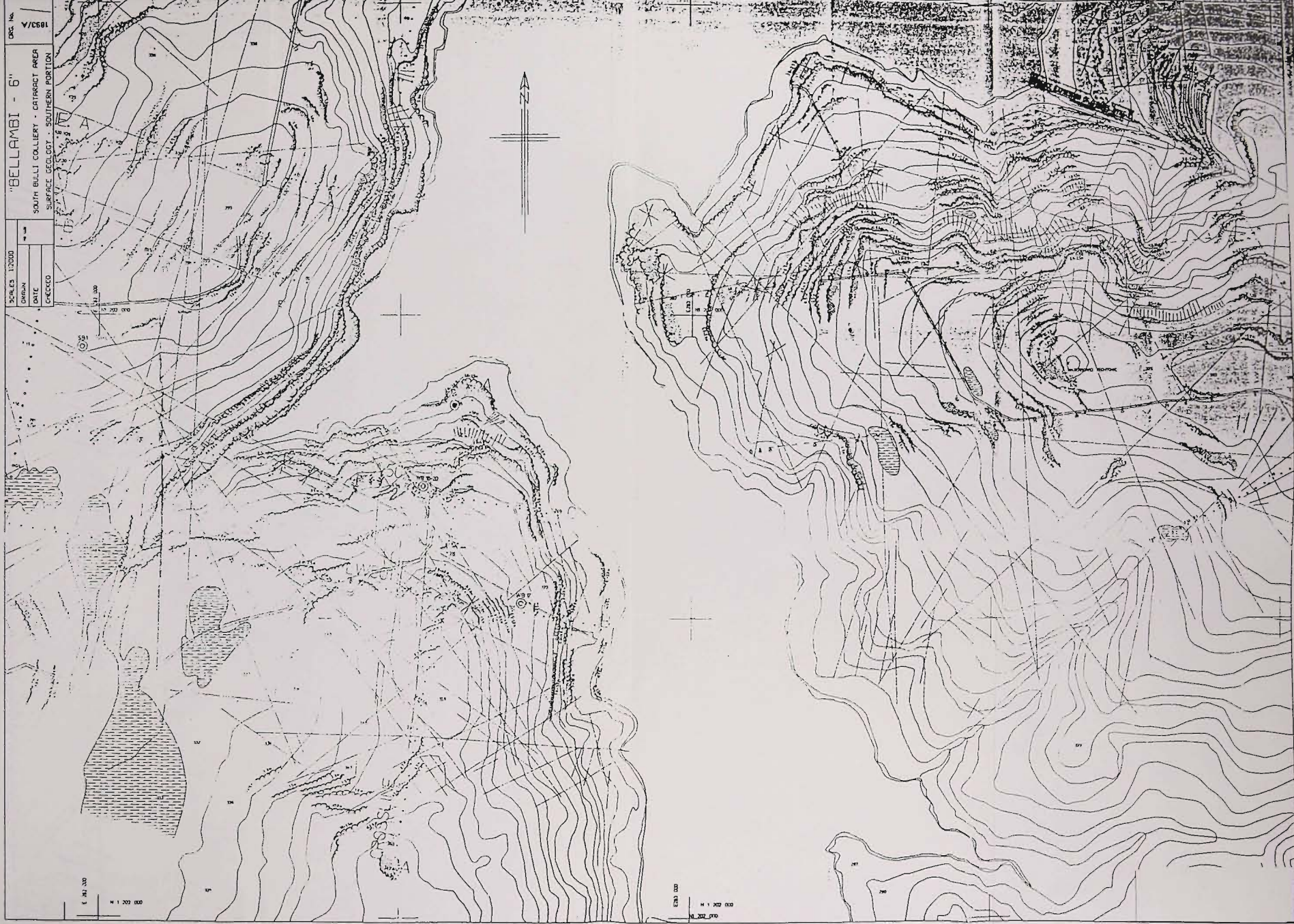
000. 44

"BELLAMBI - 6"

1953/ VCS/ 1951
SOUTH BULLI COLLIERY - CATHARTIC AREA
SURFACE GEOLOGY - SOUTHERN PORTION

328.03 12000

DATE
CXCXCO



- Roof falls and floor heaves occurring at an early stage of development work
- Major water drippers
- Location of underground drilling sites: roof holes and floor holes
- Position of surface boreholes
- Coal sample sites; rock sample sites; various measurement stations (joints/cleats/seam lithotypes).

Additional data on faults and igneous intrusions, water drips, and major anomalies has been and is currently being provided in monthly reports.

Predictions formulated for the area being mined during Stage I were proved correct. As mining took place within a confined area framed by old workings on three sides, no surprises were anticipated or found concerning geological structures.

Commitments relative to geological work underground and on surface, and reporting were fulfilled, and routine day-to-day monitoring activities and periodical investigations (eg. in-seam seismic surveys) were accompanied by surface and underground exploration work which, though mainly targeting the future potential mining areas further north, also provided a better knowledge of the remainder of the area covered by Stage I mining.

Unusually good roof and floor conditions were enjoyed in the area, and the only disturbances to development work were large floor and roof rolls which are exclusively seam-level disturbances with no vertical extensions. Features with potential vertical extensions, such as dykes, were thinner than expected and their lateral extensions shorter than anticipated in the area mined.

The prediction/monitoring/re-prediction cycle continued on a block-by-block basis, and extraction-oriented forecasts were improved, as are interpretations of in-seam seismic surveys, as a distinction of seam-level features of sedimentary origin from tectonic/intrusive features cutting across strata is now easier, due to a better familiarisation with local conditions. Thus, even without any major technical improvement, it is believed that future remote-sensing surveys will be even more successful, owing to better interpretations based on experience.

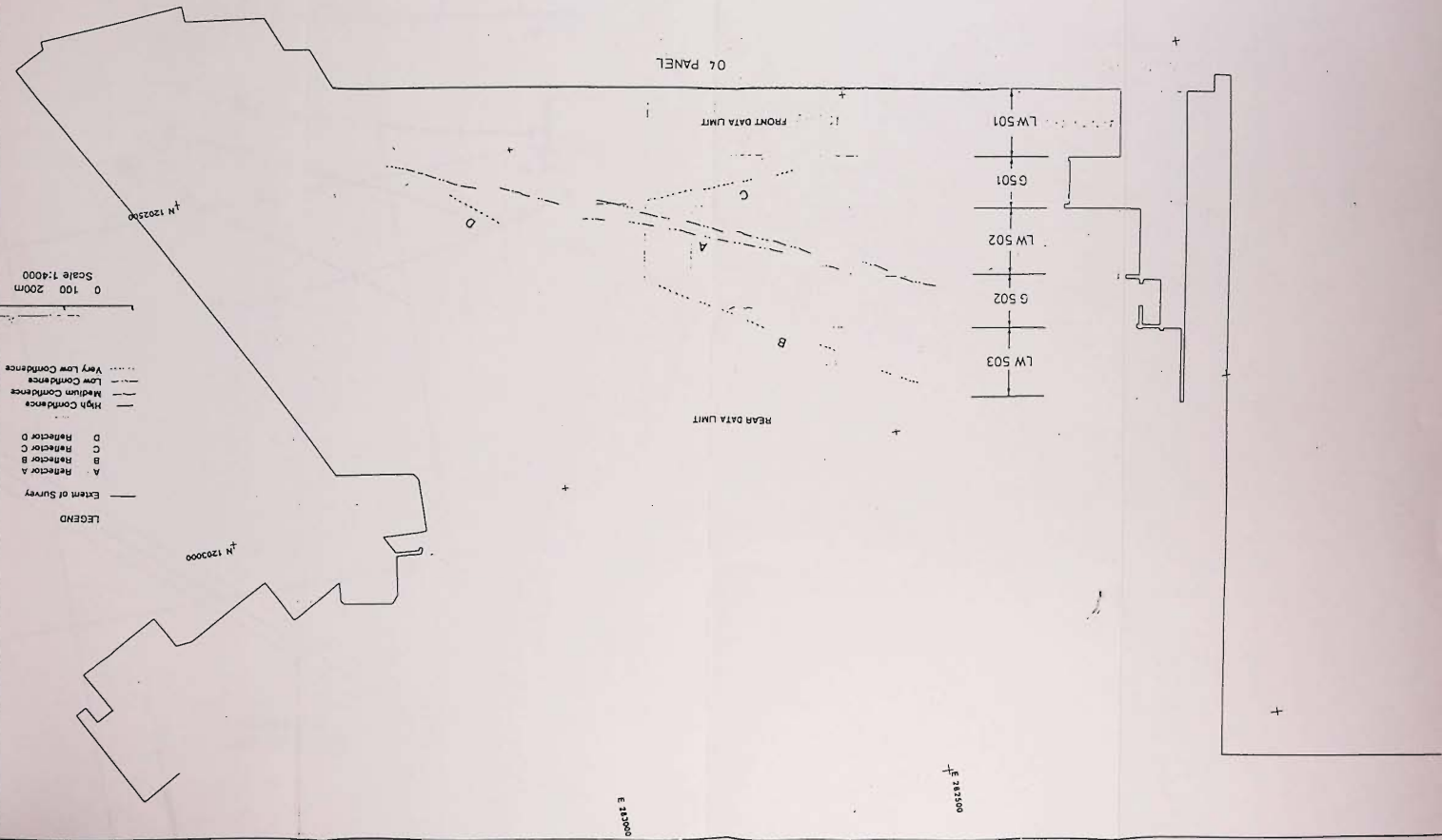
2.4 Survey Investigations & Results

2.4.1 In Seam Seismic Surveys (ISS Surveys)

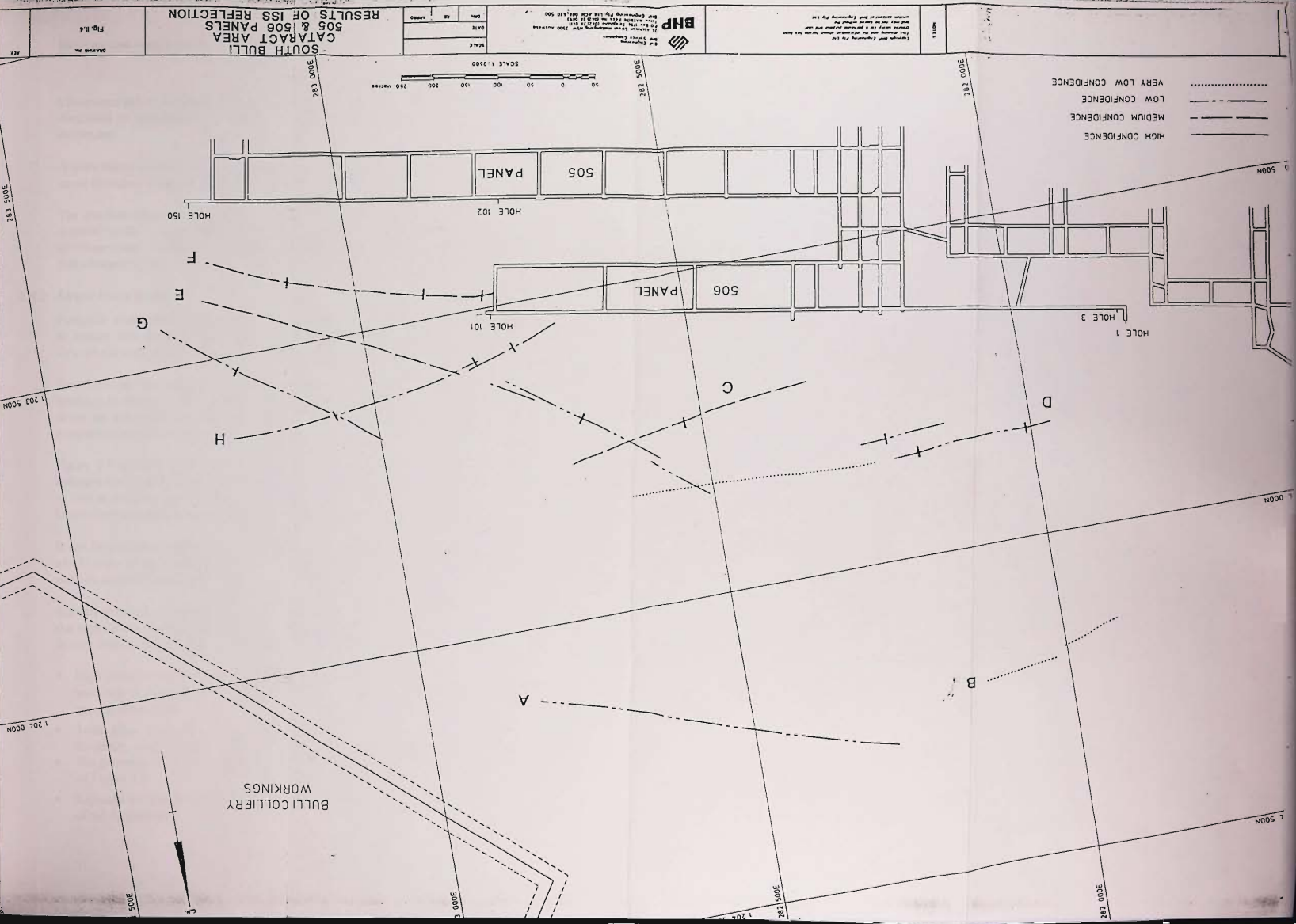
The first in-seam seismic survey was run in July 1992 using the existing O4 Panel, and covering the longwall blocks 501-503. The attached Figure 2.4 summarises the findings of this survey in an area that proved to be free of any geological discontinuity.

BHP ENGINEERING

Fig. 11.3



HIGH CONFIDENCE
 MEDIUM CONFIDENCE
 LOW CONFIDENCE
 VERY LOW CONFIDENCE



SOUTH BULLI
 CATARACT AREA
 505 & 506 PANELS
 RESULTS OF ISS REFLECTION

Fig. B.6
 DRAWING NO.
 REF.

BHP
 BHP Engineering Pty Ltd
 100-110-120-130-140-150-160-170-180-190-200-210-220-230-240-250-260-270-280-290-300-310-320-330-340-350-360-370-380-390-400-410-420-430-440-450-460-470-480-490-500-510-520-530-540-550-560-570-580-590-600-610-620-630-640-650-660-670-680-690-700-710-720-730-740-750-760-770-780-790-800-810-820-830-840-850-860-870-880-890-900-910-920-930-940-950-960-970-980-990-1000-1010-1020-1030-1040-1050-1060-1070-1080-1090-1100-1110-1120-1130-1140-1150-1160-1170-1180-1190-1200-1210-1220-1230-1240-1250-1260-1270-1280-1290-1300-1310-1320-1330-1340-1350-1360-1370-1380-1390-1400-1410-1420-1430-1440-1450-1460-1470-1480-1490-1500-1510-1520-1530-1540-1550-1560-1570-1580-1590-1600-1610-1620-1630-1640-1650-1660-1670-1680-1690-1700-1710-1720-1730-1740-1750-1760-1770-1780-1790-1800-1810-1820-1830-1840-1850-1860-1870-1880-1890-1900-1910-1920-1930-1940-1950-1960-1970-1980-1990-2000-2010-2020-2030-2040-2050-2060-2070-2080-2090-2100-2110-2120-2130-2140-2150-2160-2170-2180-2190-2200-2210-2220-2230-2240-2250-2260-2270-2280-2290-2300-2310-2320-2330-2340-2350-2360-2370-2380-2390-2400-2410-2420-2430-2440-2450-2460-2470-2480-2490-2500-2510-2520-2530-2540-2550-2560-2570-2580-2590-2600-2610-2620-2630-2640-2650-2660-2670-2680-2690-2700-2710-2720-2730-2740-2750-2760-2770-2780-2790-2800-2810-2820-2830-2840-2850-2860-2870-2880-2890-2900-2910-2920-2930-2940-2950-2960-2970-2980-2990-3000-3010-3020-3030-3040-3050-3060-3070-3080-3090-3100-3110-3120-3130-3140-3150-3160-3170-3180-3190-3200-3210-3220-3230-3240-3250-3260-3270-3280-3290-3300-3310-3320-3330-3340-3350-3360-3370-3380-3390-3400-3410-3420-3430-3440-3450-3460-3470-3480-3490-3500-3510-3520-3530-3540-3550-3560-3570-3580-3590-3600-3610-3620-3630-3640-3650-3660-3670-3680-3690-3700-3710-3720-3730-3740-3750-3760-3770-3780-3790-3800-3810-3820-3830-3840-3850-3860-3870-3880-3890-3900-3910-3920-3930-3940-3950-3960-3970-3980-3990-4000-4010-4020-4030-4040-4050-4060-4070-4080-4090-4100-4110-4120-4130-4140-4150-4160-4170-4180-4190-4200-4210-4220-4230-4240-4250-4260-4270-4280-4290-4300-4310-4320-4330-4340-4350-4360-4370-4380-4390-4400-4410-4420-4430-4440-4450-4460-4470-4480-4490-4500-4510-4520-4530-4540-4550-4560-4570-4580-4590-4600-4610-4620-4630-4640-4650-4660-4670-4680-4690-4700-4710-4720-4730-4740-4750-4760-4770-4780-4790-4800-4810-4820-4830-4840-4850-4860-4870-4880-4890-4900-4910-4920-4930-4940-4950-4960-4970-4980-4990-5000-5010-5020-5030-5040-5050-5060-5070-5080-5090-5100-5110-5120-5130-5140-5150-5160-5170-5180-5190-5200-5210-5220-5230-5240-5250-5260-5270-5280-5290-5300-5310-5320-5330-5340-5350-5360-5370-5380-5390-5400-5410-5420-5430-5440-5450-5460-5470-5480-5490-5500-5510-5520-5530-5540-5550-5560-5570-5580-5590-5600-5610-5620-5630-5640-5650-5660-5670-5680-5690-5700-5710-5720-5730-5740-5750-5760-5770-5780-5790-5800-5810-5820-5830-5840-5850-5860-5870-5880-5890-5900-5910-5920-5930-5940-5950-5960-5970-5980-5990-6000-6010-6020-6030-6040-6050-6060-6070-6080-6090-6100-6110-6120-6130-6140-6150-6160-6170-6180-6190-6200-6210-6220-6230-6240-6250-6260-6270-6280-6290-6300-6310-6320-6330-6340-6350-6360-6370-6380-6390-6400-6410-6420-6430-6440-6450-6460-6470-6480-6490-6500-6510-6520-6530-6540-6550-6560-6570-6580-6590-6600-6610-6620-6630-6640-6650-6660-6670-6680-6690-6700-6710-6720-6730-6740-6750-6760-6770-6780-6790-6800-6810-6820-6830-6840-6850-6860-6870-6880-6890-6900-6910-6920-6930-6940-6950-6960-6970-6980-6990-7000-7010-7020-7030-7040-7050-7060-7070-7080-7090-7100-7110-7120-7130-7140-7150-7160-7170-7180-7190-7200-7210-7220-7230-7240-7250-7260-7270-7280-7290-7300-7310-7320-7330-7340-7350-7360-7370-7380-7390-7400-7410-7420-7430-7440-7450-7460-7470-7480-7490-7500-7510-7520-7530-7540-7550-7560-7570-7580-7590-7600-7610-7620-7630-7640-7650-7660-7670-7680-7690-7700-7710-7720-7730-7740-7750-7760-7770-7780-7790-7800-7810-7820-7830-7840-7850-7860-7870-7880-7890-7900-7910-7920-7930-7940-7950-7960-7970-7980-7990-8000-8010-8020-8030-8040-8050-8060-8070-8080-8090-8100-8110-8120-8130-8140-8150-8160-8170-8180-8190-8200-8210-8220-8230-8240-8250-8260-8270-8280-8290-8300-8310-8320-8330-8340-8350-8360-8370-8380-8390-8400-8410-8420-8430-8440-8450-8460-8470-8480-8490-8500-8510-8520-8530-8540-8550-8560-8570-8580-8590-8600-8610-8620-8630-8640-8650-8660-8670-8680-8690-8700-8710-8720-8730-8740-8750-8760-8770-8780-8790-8800-8810-8820-8830-8840-8850-8860-8870-8880-8890-8900-8910-8920-8930-8940-8950-8960-8970-8980-8990-9000-9010-9020-9030-9040-9050-9060-9070-9080-9090-9100-9110-9120-9130-9140-9150-9160-9170-9180-9190-9200-9210-9220-9230-9240-9250-9260-9270-9280-9290-9300-9310-9320-9330-9340-9350-9360-9370-9380-9390-9400-9410-9420-9430-9440-9450-9460-9470-9480-9490-9500-9510-9520-9530-9540-9550-9560-9570-9580-9590-9600-9610-9620-9630-9640-9650-9660-9670-9680-9690-9700-9710-9720-9730-9740-9750-9760-9770-9780-9790-9800-9810-9820-9830-9840-9850-9860-9870-9880-9890-9900-9910-9920-9930-9940-9950-9960-9970-9980-9990-10000-10010-10020-10030-10040-10050-10060-10070-10080-10090-10100-10110-10120-10130-10140-10150-10160-10170-10180-10190-10200-10210-10220-10230-10240-10250-10260-10270-10280-10290-10300-10310-10320-10330-10340-10350-10360-10370-10380-10390-10400-10410-10420-10430-10440-10450-10460-10470-10480-10490-10500-10510-10520-10530-10540-10550-10560-10570-10580-10590-10600-10610-10620-10630-10640-10650-10660-10670-10680-10690-10700-10710-10720-10730-10740-10750-10760-10770-10780-10790-10800-10810-10820-10830-10840-10850-10860-10870-10880-10890-10900-10910-10920-10930-10940-10950-10960-10970-10980-10990-11000-11010-11020-11030-11040-11050-11060-11070-11080-11090-11100-11110-11120-11130-11140-11150-11160-11170-11180-11190-11200-11210-11220-11230-11240-11250-11260-11270-11280-11290-11300-11310-11320-11330-11340-11350-11360-11370-11380-11390-11400-11410-11420-11430-11440-11450-11460-11470-11480-11490-11500-11510-11520-11530-11540-11550-11560-11570-11580-11590-11600-11610-11620-11630-11640-11650-11660-11670-11680-11690-11700-11710-11720-11730-11740-11750-11760-11770-11780-11790-11800-11810-11820-11830-11840-11850-11860-11870-11880-11890-11900-11910-11920-11930-11940-11950-11960-11970-11980-11990-12000-12010-12020-12030-12040-12050-12060-12070-12080-12090-12100-12110-12120-12130-12140-12150-12160-12170-12180-12190-12200-12210-12220-12230-12240-12250-12260-12270-12280-12290-12300-12310-12320-12330-12340-12350-12360-12370-12380-12390-12400-12410-12420-12430-12440-12450-12460-12470-12480-12490-12500-12510-12520-12530-12540-12550-12560-12570-12580-12590-12600-12610-12620-12630-12640-12650-12660-12670-12680-12690-12700-12710-12720-12730-12740-12750-12760-12770-12780-12790-12800-12810-12820-12830-12840-12850-12860-12870-12880-12890-12900-12910-12920-12930-12940-12950-12960-12970-12980-12990-13000-13010-13020-13030-13040-13050-13060-13070-13080-13090-13100-13110-13120-13130-13140-13150-13160-13170-13180-13190-13200-13210-13220-13230-13240-13250-13260-13270-13280-13290-13300-13310-13320-13330-13340-13350-13360-13370-13380-13390-13400-13410-13420-13430-13440-13450-13460-13470-13480-13490-13500-13510-13520-13530-13540-13550-13560-13570-13580-13590-13600-13610-13620-13630-13640-13650-13660-13670-13680-13690-13700-13710-13720-13730-13740-13750-13760-13770-13780-13790-13800-13810-13820-13830-13840-13850-13860-13870-13880-13890-13900-13910-13920-13930-13940-13950-13960-13970-13980-13990-14000-14010-14020-14030-14040-14050-14060-14070-14080-14090-14100-14110-14120-14130-14140-14150-14160-14170-14180-14190-14200-14210-14220-14230-14240-14250-14260-14270-14280-14290-14300-14310-14320-14330-14340-14350-14360-14370-14380-14390-14400-14410-14420-14430-14440-14450-14460-14470-14480-14490-14500-14510-14520-14530-14540-14550-14560-14570-14580-14590-14600-14610-14620-14630-14640-14650-14660-14670-14680-14690-14700-14710-14720-14730-14740-14750-14760-14770-14780-14790-14800-14810-14820-14830-14840-14850-14860-14870-14880-14890-14900-14910-14920-14930-14940-14950-14960-14970-14980-14990-15000-15010-15020-15030-15040-15050-15060-15070-15080-15090-15100-15110-15120-15130-15140-15150-15160-15170-15180-15190-15200-15210-15220-15230-15240-15250-15260-15270-15280-15290-15300-15310-15320-15330-15340-15350-15360-15370-15380-15390-15400-15410-15420-15430-15440-15450-15460-15470-15480-15490-15500-15510-15520-15530-15540-15550-15560-15570-15580-15590-15600-15610-15620-15630-15640-15650-15660-15670-15680-15690-15700-15710-15720-15730-15740-15750-15760-15770-15780-15790-15800-15810-15820-15830-15840-15850-15860-15870-15880-15890-15900-15910-15920-15930-15940-15950-15960-15970-15980-15990-16000-16010-16020-16030-16040-16050-16060-16070-16080-16090-16100-16110-16120-16130-16140-16150-16160-16170-16180-16190-16200-16210-16220-16230-16240-16250-16260-16270-16280-16290-16300-16310-16320-16330-16340-16350-16360-16370-16380-16390-16400-16410-16420-16430-16440-16450-16460-16470-16480-16490-16500-16510-16520-16530-16540-16550-16560-16570-16580-16590-16600-16610-16620-16630-16640-16650-16660-16670-16680-16690-16700-16710-16720-16730-16740-16750-16760-16770-16780-16790-16800-16810-16820-16830-16840-16850-16860-16870-16880-16890-16900-16910-16920-16930-16940-16950-16960-16970-16980-16990-17000-17010-17020-17030-17040-17050-17060-17070-17080-17090-17100-17110-17120-17130-17140-17150-17160-17170-17180-17190-17200-17210-17220-17230-17240-17250-17260-17270-17280-17290-17300-17310-17320-17330-17340-17350-17360-17370-17380-17390-17400-17410-17420-17430-17440-17450-17460-17470-17480-17490-17500-17510-17520-17530-17540-17550-17560-17570-17580-17590-17600-17610-17620-17630-17640-17650-17660-17670-17680-17690-17700-17710-17720-17730-17740-17750-17760-17770-17780-17790-17800-17810-17820-17830-17840-17850-17860-17870-17880-17890-17900-17910-17920-17930-17940-17950-17960-17970-17980-17990-18000-18010-18020-18030-18040-18050-18060-18070-18080-18090-18100-18110-18120-18130-18140-18150-18160-18170-18180-18190-18200-18210-18220-18230-18240-18250-18260-18270-18280-18290-18300-18310-18320-18330-18340-18350-18360-18370-18380-18390-18400-18410-18420-18430-18440-18450-18460-18470-18480-18490-18500-18510-18520-18530-18540-18550-18560-18570-18580-18590-18600-18610-18620-18630-18640-18650-18660-18670-18680-18690-18700-18710-18720-18730-18740-18750-18760-18770-18780-18790-18800-18810-18820-18830-18840-18850-18860-18870-18880-18890-18900-18910-18920-18930-18940-18950-18960-18970-18980-18990-19000-19010-19020-19030-19040-19050-19060-19070-19080-19090-19100-19110-19120-19130-19140-19150-19160-19170-19180-19190-19200-19210-19220-19230-19240-19250-19260-19270-19280-19290-19300-19310-19320-19330-19340-19350-19360-19370-19380-19390-19400-19410-19420-19430-19440-19450-19460-19470-19480-19490-19500-19510-19520-19530-19540-19550-19560-19570-19580-19590-19600-19610-19620-19630-19640-19650-19660-19670-19680-19690-19700-19710-19720-19730-19740-19750-19760-19770-19780-19790-19800-19810-19820-19830-19840-19850-19860-19870-19880-19890-19900-19910-19920-19930-19940-19950-19960-19970-19980-19990-20000-20010-20020-20030-20040-20050-20060-20070-20080-20090-20100-20110-20120-20130-20140-20150-20160-20170-20180-20190-20200-20210-20220-20230-20240-20250-20260-20270-20280-20290-20300-20310-20320-20330-20340-20350-20360-20370-20380-20390-20400-20410-20420-20430-20440-20450-20460-20470-20480-20490-20500-20510-20520-20530-20540-20550-20560-20570-20580-20590-20600-20610-20620-20630-20640-20650-20660-20670-20680-20690-20700-20710-20720-20730-20740-20750-20760-20770-20780-20790-20800-20810-20820-20830-20840-20850-20860-20870-20880-20890-20900-20910-20920-20930-20940-20950-20960-20970-20980-20990-21000-21010-21020-21030-21040-21050-21060-21070-21080-21090-21100-21110-21120-21130-21140-21150-21160-21170-21180-21190-21200-21210-21220-21230-21240-21250-21260-21270-21280-21290-21300-21310-21320-21330-21340-21350-21360-21370-21380-21390-21400-21410-21420-21430-21440-21450-21460-21470-21480-21490-21500-21510-21520-215

Lineaments shown as possible discontinuities or major joints zones by ISS survey were diagnosed by company staff as major stone-rolls, and this has been confirmed by later extraction.

A more recent in-seam seismic survey was run from G505 and G506 panels in order to cover the future longwall blocks 506, 507, 508, and part of 509.

The attached Figure 2.5 summarises the geological interpretation of anticipated dykes detected by the survey, together with the extensions of joint zones which were intruded in outbye areas. In addition a fairly exact outline of the old Bulli goaf to the north east was obtained by this survey at a distance of 700 m.

2.4.2 Seam Floor Study

Particular attention has been paid to the nature of the seam floor in the Cataract area, to ensure that the floor is competent to withstand predicted loadings transmitted through the coal pillars, and able to provide sufficient confinement to the pillars.

Over 30 holes have been drilled in the Cataract panels (Figure 2.6), and in the R-Main headings to the south, to investigate the lithological succession of the floor strata, to allow an assessment to be made regarding the strength/stability of the floor in comparison to other areas of South Bulli.

Figure 2.7 and 2.8 shows the isopachs of the shale/siltstone/laminite sequence, and indicates that a thick (ie. thicker than 2 m) sequence of this strata occurs within a 300 to 500 m wide trough extending in a NW-SE direction, in keeping with the known Upper-Permian palaeo-drainage configuration of the general area.

It can be concluded that the proven, and anticipated floor conditions for both Stage I and II areas of the Cataract are good. It is extremely unlikely that pillar or roadways stability conditions will deteriorate.

Stability problems were experienced in a limited area of the main roadways 1.7 km to the west of the Cataract area, however these were due to a combination of specific factors, none of which apply to the Cataract. The principal factors were:-

- High pillar stresses in the main headings as a result of extensive wide longwall workings to the north and south of the W/T Main headings, supported by (mainly) narrow chain pillars.
- Small pillar dimensions in the Mains area. These pillars were only 26 m wide nominally, and closer to 22-23 m in situ, and were not restrained by goaf material.
- The presence of plastic claystone layers within the uppermost floor strata as shown on Figure 2.9.
- Repeated backbrushing of the affected area, which removed a considerable volume of the original floor.

SOUTH BULLI COLLIERY

FLOOR STRATA - WESTERN DISTRICT HEADINGS

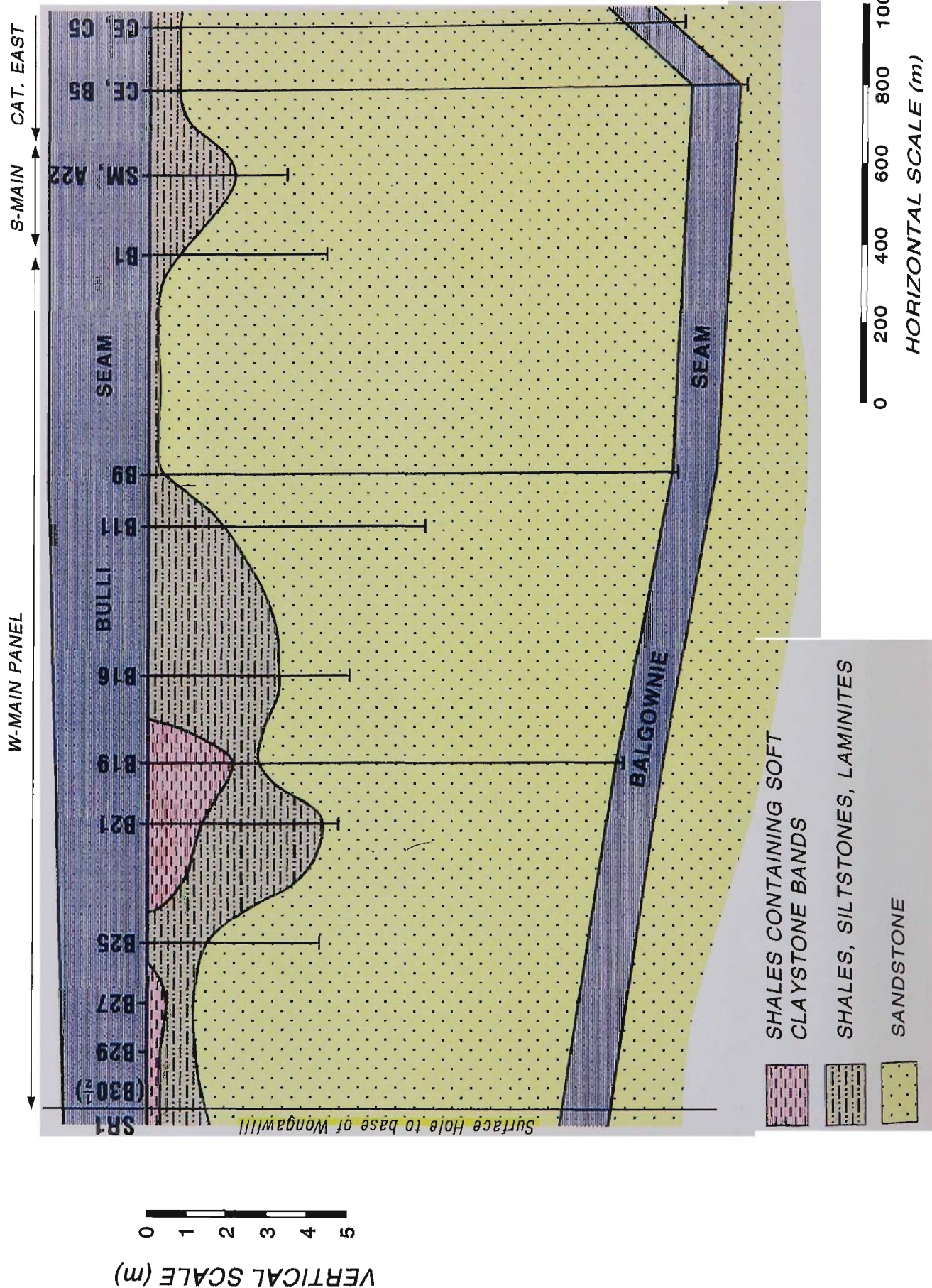
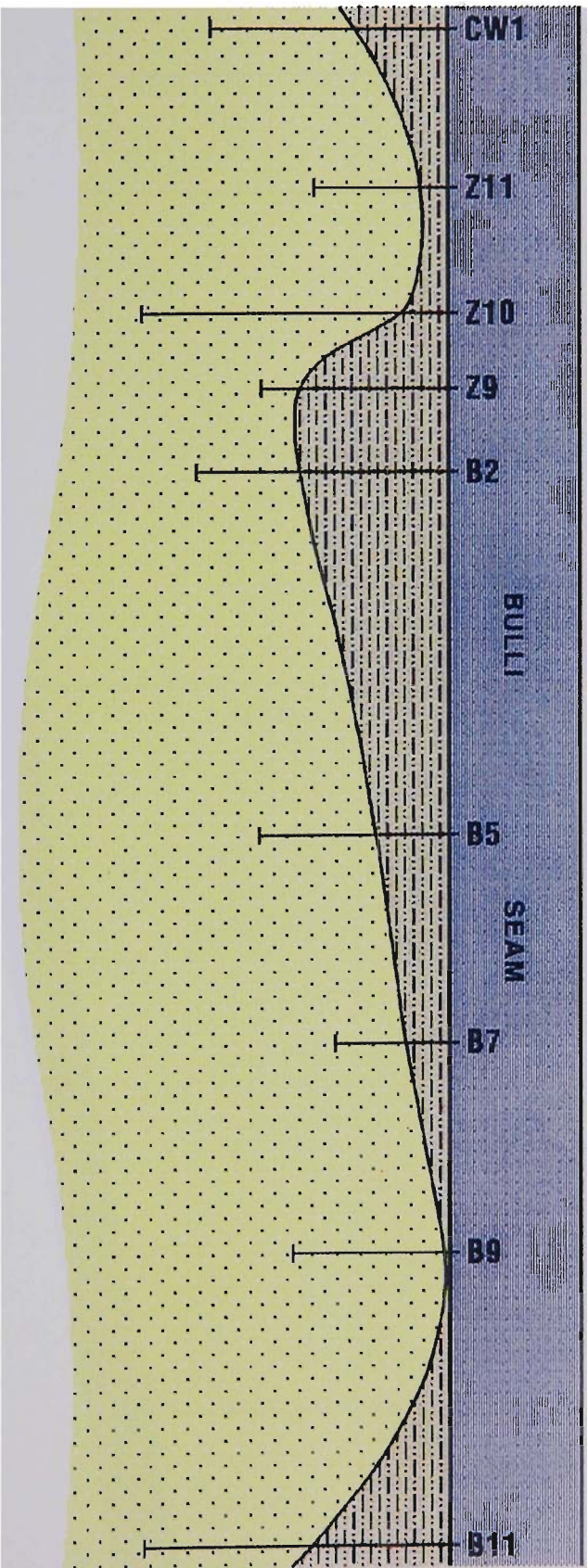


Fig. 2.9

SOUTH BULLI COLLIERY
FLOOR STRATA - CATARACT AREA

CAT. WEST CAT. NORTH G.504 G.503 G.502

VERTICAL SCALE (m)



HORIZONTAL SCALE (m)

0 100 200 300 400 500



SOUTH BULLI COLLIERY FLOOR STRATA - "R MAIN" PANEL

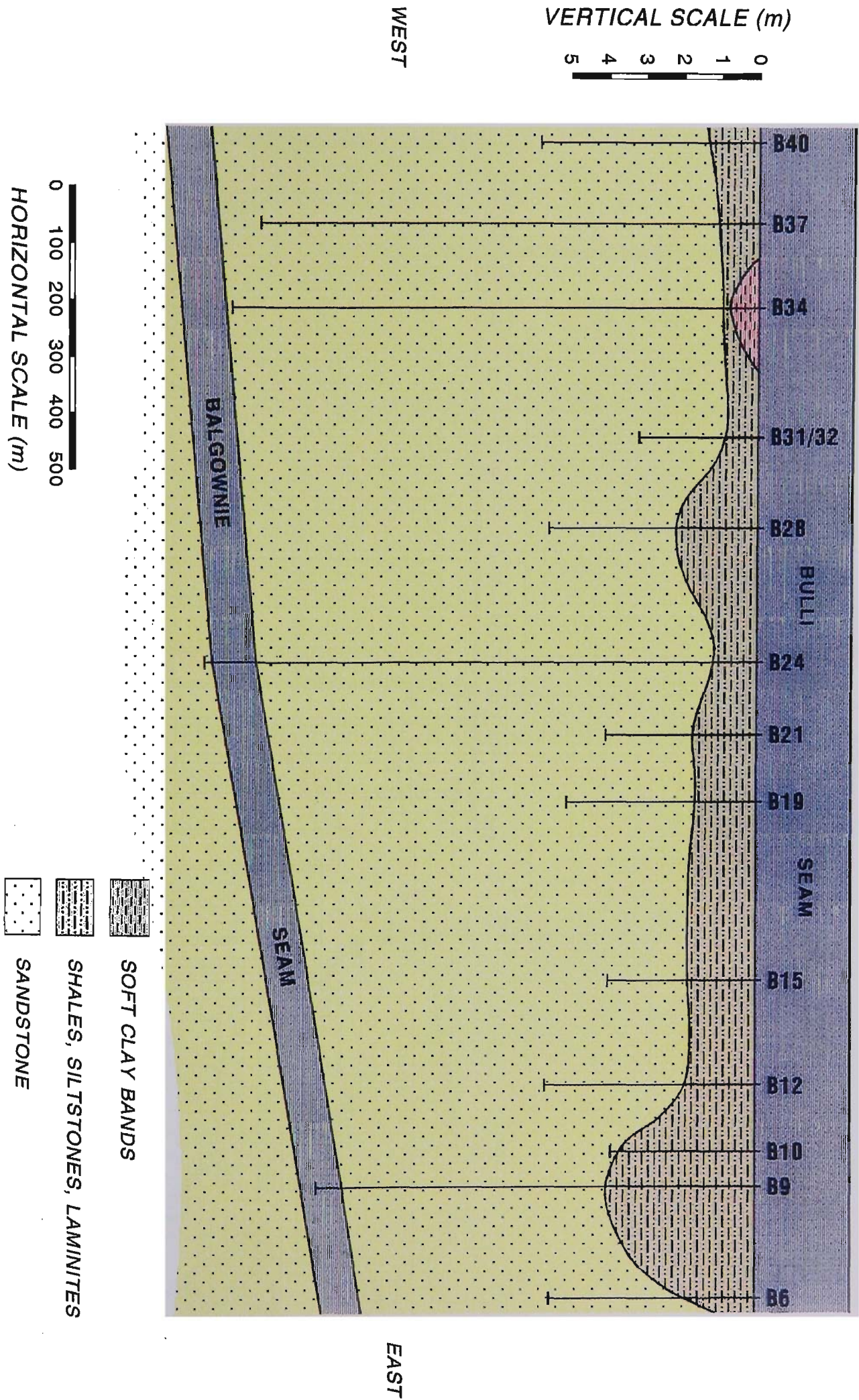


Fig. 2.7

BULLI SEAM FLOOR STRATA LOCATION OF SECTION LINES

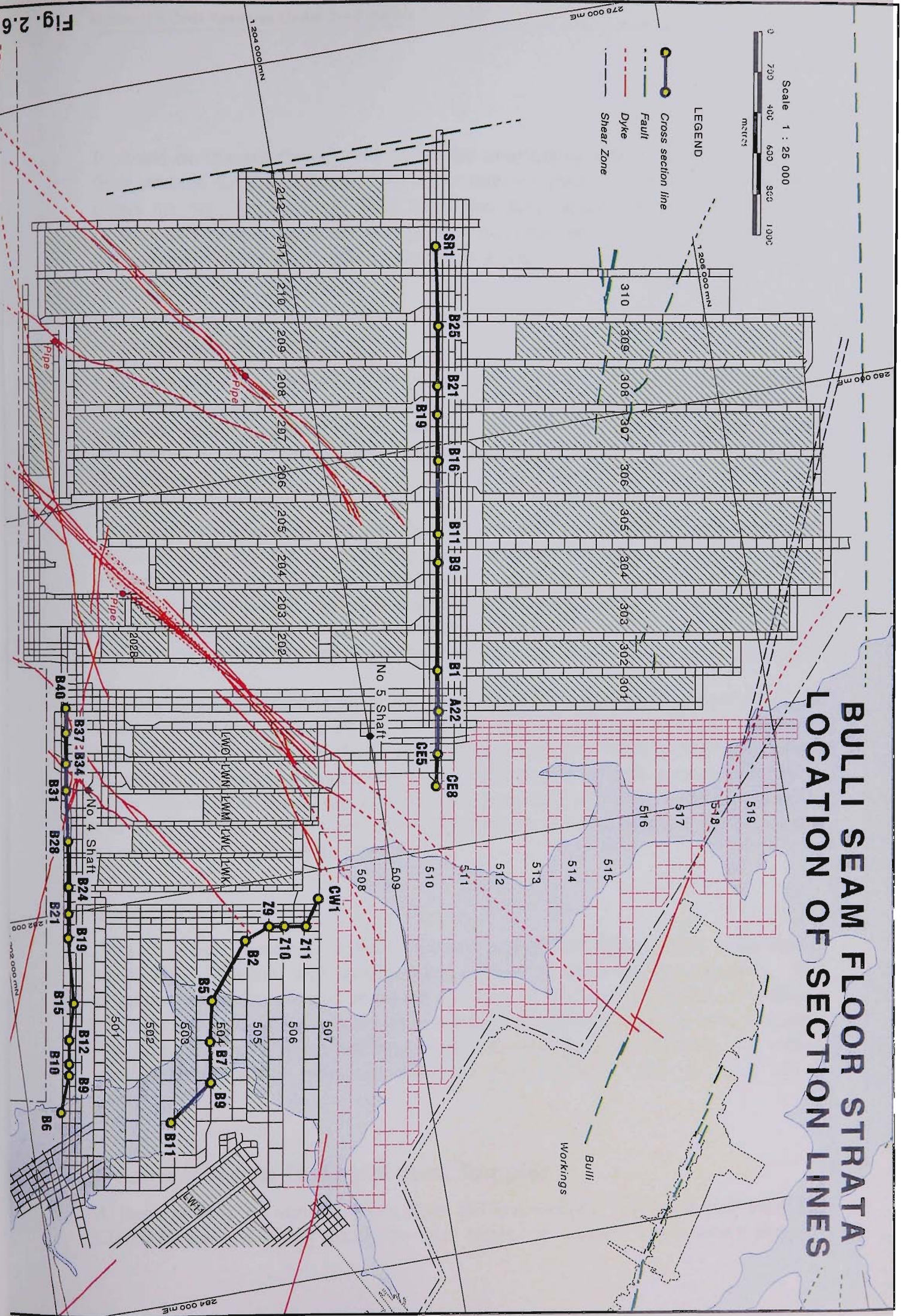
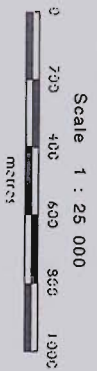


Fig. 2.6

It should be stressed though, that unlike the deteriorated area in W and T Main, the floor strata in the Cataract area does not contain any plastic claystone. Since all chain pillars are significantly larger than chain and main heading pillars in the Western District, as well as being confined by goaf on two sides, and holding much lower loads, the possibility of the chain pillars yielding as a result of foundation problems appears remote.

2.4.3 Aerial Magnetic Survey

Following the survey carried out in 1981/82 which covered the 200's and 300's series of longwall panels as well as the western portion of the Colliery holding, a helicopter-mounted aerial magnetic survey was carried out in 1993 to investigate the occurrence/extent of any major structures (mainly intrusions) in the area covered by the Cataract Reservoir.

The Cataract survey indicated the likely presence of an igneous sill/plug astride the projected longwall panels 511/512, and a number of lineaments with magnetic anomalies, some of which could be dykes. Only some of the known dykes were identified by the survey, and it is also an acknowledged fact that identification was often based on the knowledge of intrusions in workings. The approximate position of main features identified or suggested by the magnetic survey are shown on Figure 2.10.

In-seam longhole drilling is underway to investigate the igneous body and determine whether it is a plug, sill, or cinder, and it is intended that hole-to-hole and surface-to-hole seismic techniques will also be used. Recent modelling work by BHP Engineering suggests an elongated sill is present at the Bulli seam level, with a much wider sill in lower seams. The hypothesis of a diatreme extending vertically is not supported by this study. Once the nature and extent of the feature are determined, it will be possible to consider the impact on the mine plan.

2.4.4 Surface Drilling

Six surface holes have been drilled in the later half of 1994 (Figure 2.11) to the base of the Wongawilli Seam, with samples taken from all the three seams for analysis. This programme has also allowed improved definition of the seam, geotechnical testing of various rock types from the overburden strata, coal quality assessment and gas testing. The holes have also been used for a cross-hole seismic survey to detect the vertical extent of any igneous intrusions and other discontinuities. This survey is still in progress.

2.5 Geomechanical Testing of Rock Samples

A large number of samples taken from the Hawkesbury Sandstone and Bald Hill Claystone cores in recent boreholes were tested for Uniaxial Compressive Strength

SOUTH BULLI COLLIERY

SURFACE BOREHOLES DRILLED DURING 1994

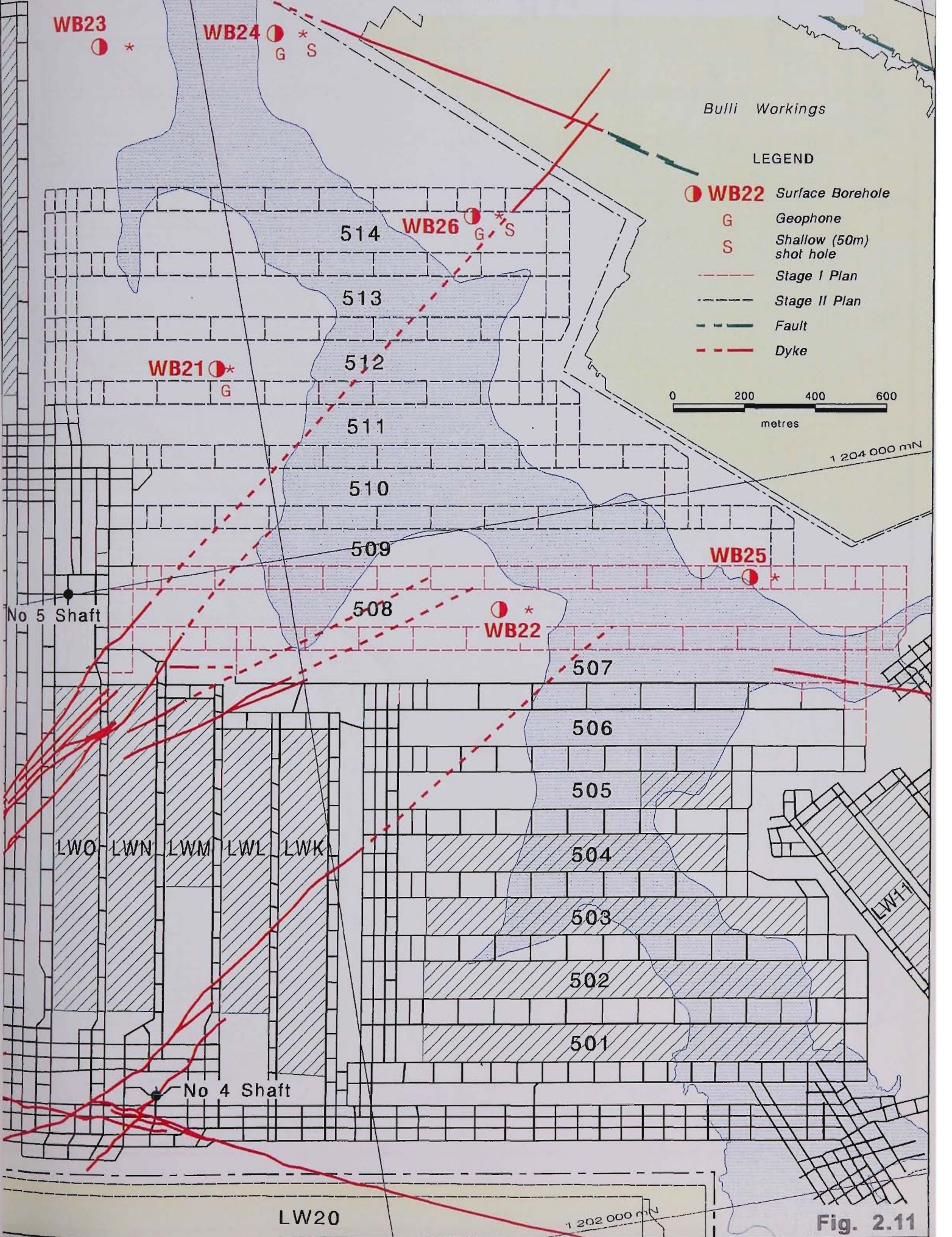


Fig. 2.11



bellambi
BELLAMBI COLLIERIES PTY. LTD.

**SOUTH BULLI COLLIERY
STRUCTURES**

Scale 1 : 25 000



- LEGEND**
- Outburst Location
 - - - Fault
 - - - Dyke
 - - - Shear Zone
 - - - Magnetic Anomaly
 - WB24 Drill Holes
 - ST2 Geotech Holes
 - In-Seam Drilling
 - Core sample for gas determination
 - Cinder zone

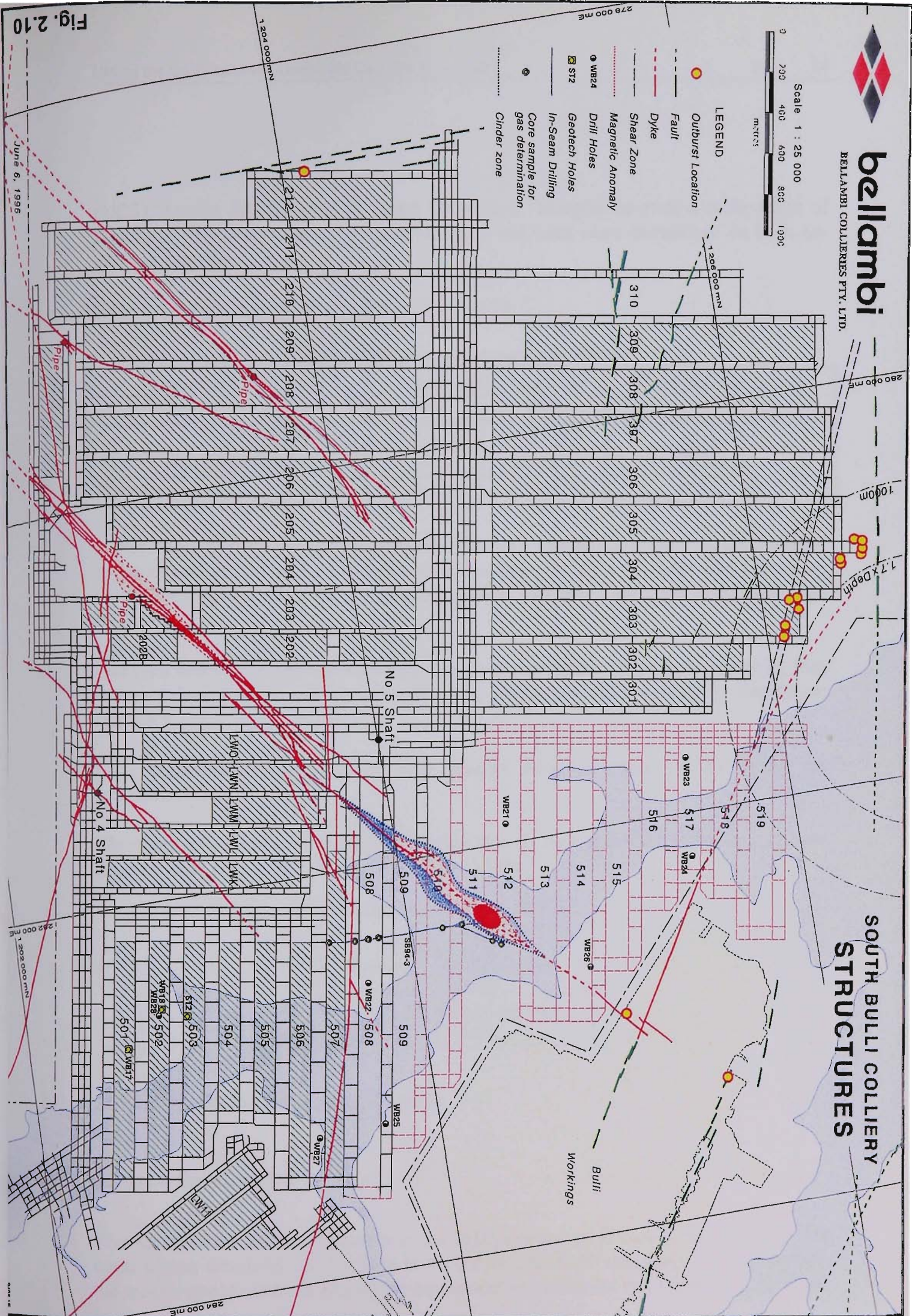


Fig. 2.10

June 6, 1996

(UCS), Tensile Strength and Fracture Toughness. Samples covered a wide range of texture and grain size for the units considered, and tests were carried out on both dry and wet samples.

Results can be summarised as follows (Table 2.2):

Table 2.2 Geomechanical Rock Test Results

Geometrical Test	Hawkesbury Sandstone		Bald Hill Claystone
	Dry	Wet	Dry
UCS (MPa)	24.3-61.9	17.4-49.5	15.9-52.5
Tensile Strength (MPa)	4.0-7.3	2.0-3.4	0.9-3.75
Fracture Toughness (MPaM ^{0.5})	0.42-1.13	0.29-0.59	0.24-0.54

It was deduced from the tests that the Hawkesbury Sandstone is likely to fail violently and suddenly under load with penetrative fractures, whereas the Bald Hill Claystone will fail in a more gradual and progressive manner with brecciation and non-penetrative fracturing.

The tests defined for the sandstones, a "tensile strain failure", expressed in mm/m, that is never less than 3 mm/m, even for wet specimens of Hawkesbury Sandstone (Figure 2.12).

UCS determinations on various core samples from underground drill holes are summarised below

These values support the earlier assumption that all roof and floor strata are stronger than the Bulli coal, which has a UCS of 17-22 MPa.

Table 2.3 Roof & Floor Strata Results

Shales	32 MPa (Approx.)
Mudstones	28-68 MPa
Siltstones	39-51 MPa
Laminites	62 MPa (Approx.)
Sandstones	49-65 MPa

2.6 Subsidence Surveys and Results

2.6.1 Surface Subsidence Survey

Five survey lines were constructed in the configuration as shown in Figure 2.13. The construction details for survey lines in accordance with the topography of the surface, the measurement methods and survey equipment and indicated the expected accuracies.

HAWKESBURY SANDSTONE (Geomechanical Tests)

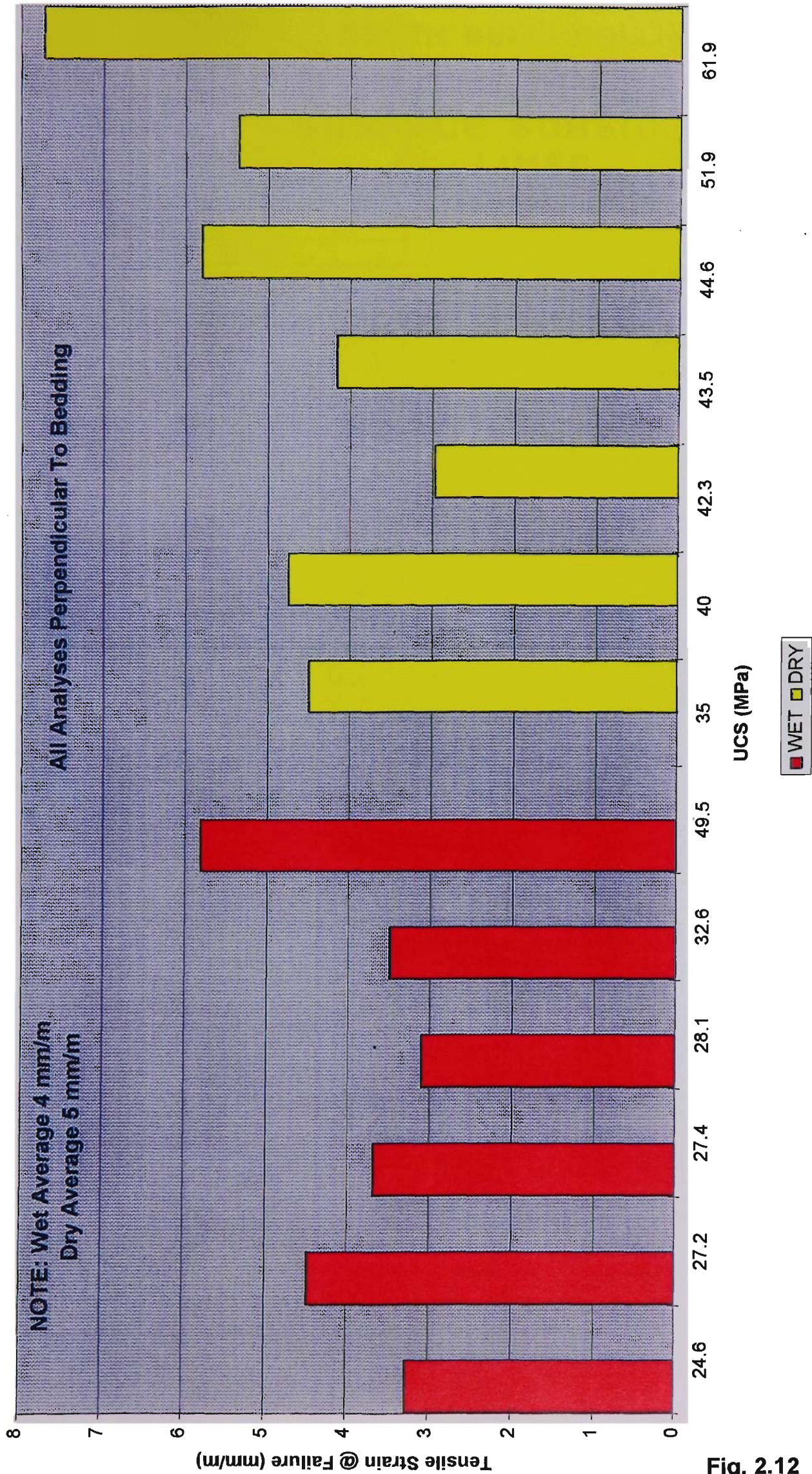


Fig. 2.12

SOUTH BULLI COLLIERY **LOCATION OF STAGE I** **SURFACE SUBSIDENCE** **LINES**

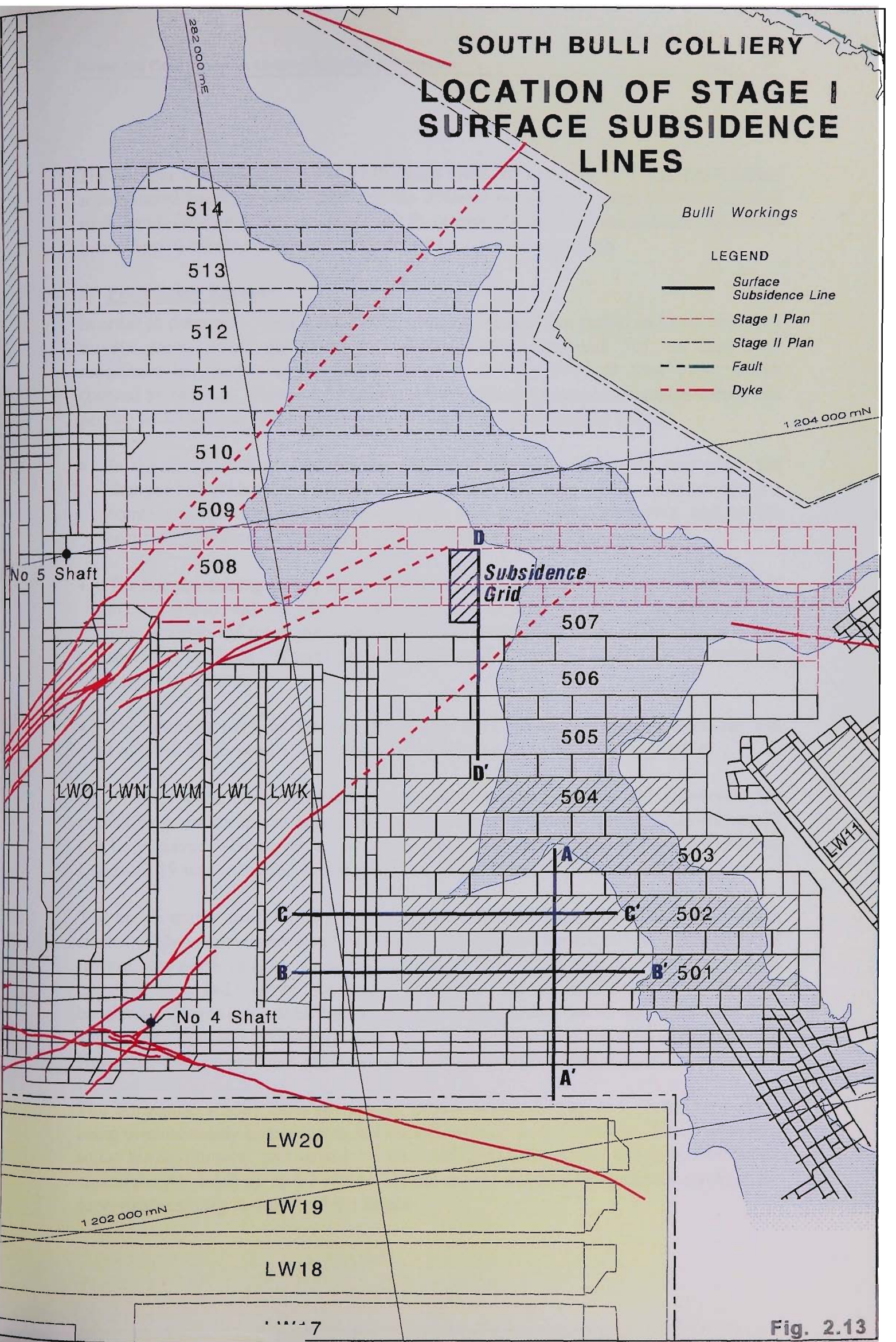


Fig. 2.13

The surveys comprised levelling of the pegs (with an accuracy of 1 mm/km levelled) accompanied by the measurements of the distance between the pegs with a tensioned steel band (accuracy ± 1 mm/bay) or Electronic Distance Measurement (accuracy 5 mm \pm 5ppm) where access was difficult and topography was steep.

a) Pre-mining Surveys

In order to determine the influence of non-mining factors, five partial and four complete surveys were carried out along the western part of Longwall 501, on Line B-B' subsidence line during a pre-mining period from May 1992 to June 1993, which covered all seasons. Figure 2.14 indicates the measured ground movement during this period, with the most important aspects of these surveys described below:

- In the rocky cliff area where the Electronic Distance Measuring was used, the changes in level between surveys were comparatively large. This would be due to a combination of the cliff response to non-mining ground movements, and to the accuracy limitation of the Electronic Distance Measuring instruments.
- The last pre-mining survey (June 1993) indicated an uplift of the ground, eg 10 mm in comparison with the March 1993 survey, or 12 mm with that of November 1992. The accuracy of these measurements could result in an error of ± 4 mm over the surveyed distance. Therefore the actual uplift of the ground could be between 8 mm and 16 mm.
- The western pegs of the line (No's 101-104), which are located over the old Longwall K, showed a reactivation of subsidence up to 4 mm in magnitude.

Correlation of the movement over the not-yet-extracted Longwall 501 panel with the rainfall/evaporation in the region and/or the level of the water in the Reservoir could not be achieved. However it was noticeable that in that period Cordeaux Colliery's Longwall 19 was extracted and its goaf was 600 m from the Cataract subsidence line.

The bench marks used initially were located in the old Longwall 's K-O area which started to show some movement. Consequently, the bench mark has been moved twice towards the north in order to find a stable site. It is now the north-most point of the extended Line D-D' (over Longwalls 505-508). At the establishment of the new benchmark, it was calculated that the previously used bench marks may have moved by approximately 4 mm. This may have been due to surveying error (due to distance). Never-the-less the previous measurements were amended correspondingly.

The horizontal strains from pre-mining period shown in Figure 2.15 indicate strain being predominantly compressive, having values of up to 0.17 mm/m. There were also some tensile strains, particularly in the cliff area (Electronic Distance Measuring measurements used) up to 0.1 mm/m. These are not considered significant because the surveying accuracy is only 0.05-0.1 mm/m.

Line B-B' Strain : All Pre-Mining Surveys

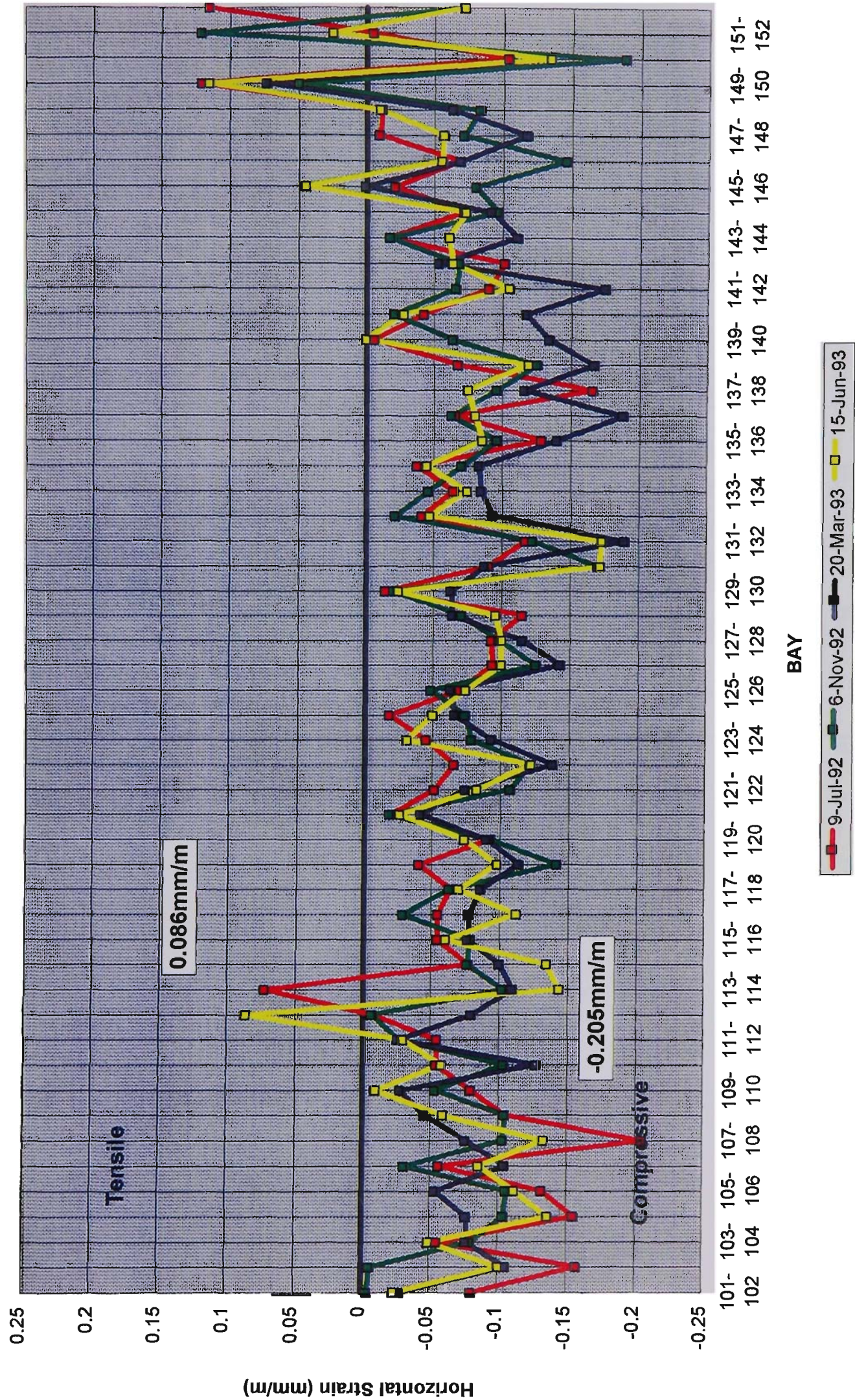


Fig. 2.15

Line B-B' Subsidence - All Pre-Mining Surveys

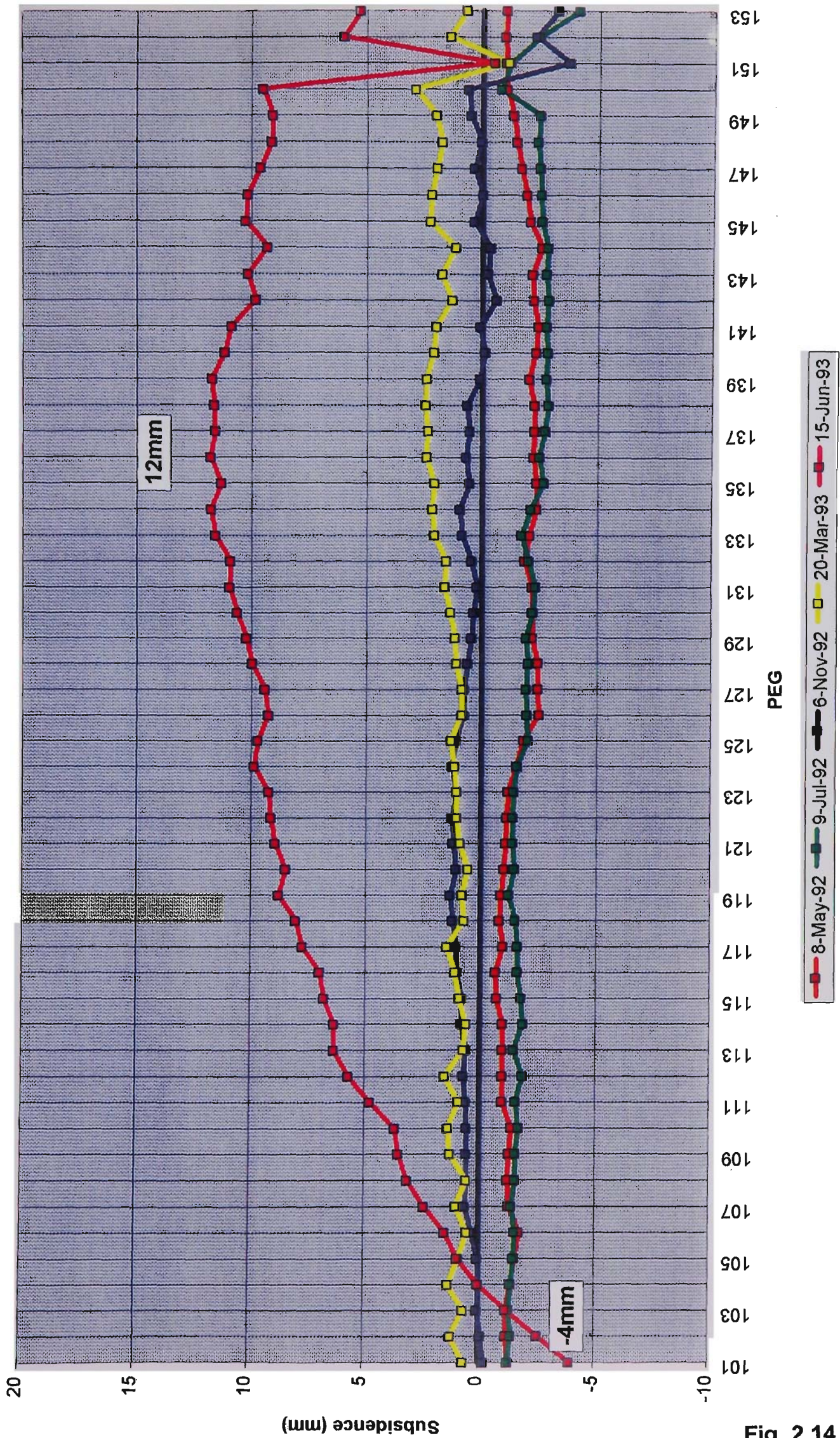


Fig. 2.14

b) **Mining Period Surveys**

This period spans the surveys of Line A-A' (crossline over Longwalls 501, 502 and partially Longwall 503), Line B-B' (surveyed during the pre-mining period) and Line C-C' (along western side of Longwall 502) from September 1993 onwards.

To date measurements of the three subsidence lines have been carried out at the completion of every panel, from 501 to 504, and at mid panel completion for Longwalls 501 and 502.

An important observation is that due to the limited extension of the lines towards the edge of the Reservoir, the complete subsidence profile will not be measured. It is believed however that the maximum subsidence measured following the extraction of Longwalls 501 and 502 was very close, if not equal to the actual maximum subsidence. Unfortunately Line A-A' ends above Longwall 503, so the full cross-line subsidence profile when supercritical extraction is reached will not be measured. Nevertheless, the A-A' surveys suggest that the line extends north sufficiently to measure the maximum subsidence magnitude. A comparison between lines A, B and C suggests that there is little difference between maximum subsidence *measured* along line A-A' and *actual* maximum subsidence.

Results from the extraction of the first four longwalls confirm that the actual strains and subsidence match quite closely with predictions made using the "Holla" curves and the modelling work carried out by MinCad Systems (Table 2.4). (Holla, 1988.)

Table 2.4: Comparative Results - Subsidence, Compressive & Tensile Strain

	Subsidence (mm)	Max. Compressive Strain (mm/m)	Max. Tensile Strain (mm/m)
Actual	178	0.7	0.6
Holla Prediction	200	0.6	0.6
MinCad Prediction	180	0.9	0.4

2.7 **Discussion & Results**

2.7.1 **General Comments Relating to the Mining-Period Surveys**

At the time of the first mining-period survey, when Longwall 501 was half completed, Cordeaux's Longwall 20 was operational and also near the crossline A-A.

From the last pre-mining and mid Longwall 501 surveys it appears that the Cordeaux extraction influenced the ground movement by re-activating the old subsidence of Longwalls K (and possibly L to O) and uplifted the unmined Longwall 501-503 area. From the comparison of the surveys of lines B-B' and C-C' the re-activation of the old subsidence almost fades out at a distance of 600 m. The distance up to where the

ground uplifting occurred is not clear because the extraction of Longwall 20 and Longwall 501 occurred concurrently. However at a distance of 600 m, Longwall 19 may have influenced the movement of Line B-B' by 8 mm or so.

The surface movement over Longwalls 501-503 and the reactivation of subsidence over Longwall K suggests that the extraction of Cordeaux Longwalls at quite a distance has had a long-range effect. It is thought that this is due to a combination of events including :-

- Significant cover depth (440 m).
- The existence of a high proportion of sandstone units (up to 80% of the total overburden strata) between the surface and the seam. In a such situation it is believed that the top of Hawkesbury bends down over the extracted areas and lifts up in surrounding virgin areas.
- "Valley" effect associated with the topography of this area.

At Cordeaux Colliery the pillars did not produce "humps" in the shape of the subsidence trough. If there were no inter-panel chain pillars, then the subsidence should reach a maximum amplitude of 1.5 m (60% of extracted thickness). In fact the Cordeaux pillars of 25 m width limited total subsidence to 0.95 m (40%). In another case, Longwall 's K-O with a similar cover depth and panel width but with pillars of 17 m wide, the subsidence was limited to 1.3 m (45%). These two examples suggest that the smaller pillars deform and undergo compaction, but have a strong effect on subsidence in accordance with their width.

In the Cataract District where the pillars are much wider and panels are narrower it is expected that the uplift in front of an extraction would be much smaller and fade out at a shorter distance. This is an important aspect for panels approaching the Reservoir wall during the Stage III extraction.

The initial survey of the Cataract surface lines was carried out before the extraction of Cordeaux's Longwalls 17-20 had an influence on the ground movements over the Bellambi-6 area, but after stabilisation of the subsidence to the east (Q panels) and west (Longwalls K to O) of the Cataract. Consequently the subsequent uplift of the ground is only attributable to the Cordeaux extraction (prior effects of Longwalls K to O and Q panels are unknown). In comparison with the actual downward subsidence of pegs, the magnitude of the uplift is quite high. However, when this is compared with the maximum subsidence after the extraction of Longwall 504, the uplift is relatively small.

Due to the short extraction life of a panel (3-4 months) with surveys carried out shortly after the completion of the panels, residual subsidence is still occurring when the panel completion survey is carried out. If a time-span of 6 months is considered for the duration of residual subsidence, it is likely that full subsidence will not occur prior to July 1995, although the subsidence between December 1994 and July 1995 (excluding the effects of Longwall 505) is expected to be relatively small in comparison to that which has already taken place.

2.7.2 General Comments on Subsidence Patterns along Line A-A'

Figure 2.16 shows: i) some uplift between the extraction areas of Cordeaux and South Bulli
ii) a maximum subsidence of -178 mm between 501 and 502.

Figure 2.17 shows a peak tensile strain of 0.407 mm/m developed between South Bulli and Cordeaux.

(a) Survey at the Middle of Longwall 501 (September 1993)

The north-most pegs moved up, by up to 16 mm, although they were located approximately 800m north of Longwall 20 and 360 m north of Longwall 501. Ground uplift was almost zero over the southern edge of Longwall 501 and R Main, with subsidence of up to 13 mm above Longwall 20.

(b) Survey at the Completion of Longwall 501 (December 1993)

The most northerly peg (300 m from the edge of Longwall 501 goaf) was further uplifted, to a total of 17 mm. Above the Longwall 501 goaf the ground subsided to 47 mm below its original position, with a smooth transition to 25 mm subsidence over the R Main headings. At the end of the line above Cordeaux's Longwall 20, 98 mm was recorded. Although some empirical data for first panel extraction in the NSW Southern District exists, a comparison with the Longwall 501 subsidence is not considered appropriate because of the influence of Cordeaux and the low reaction of the overburden (residual subsidence is likely to take a significant time to complete).

Tensile strains were recorded to the north of the line and in the vicinity of the edges of the extracted panels (Cataract Longwall 501 and Cordeaux Longwall 20), although the strain profile suggests a high proportion of "noise" in the small strain magnitudes. Tensile strains reached a maximum of 0.37 mm/m. Compressive strains were observed between the tensile zones, which did not exceed 0.3 mm/m.

(c) Survey at the Completion of Longwall 502 (May 1994)

The uplift at the north end of the line (near to the middle of Longwall 503 panel) increased further to 34 mm from the previous survey figure of 17 mm at a distance of 180m from the 502 goaf. The total subsidence due to the extraction of first two panels reached 96 mm, and was located above the middle of Longwall 501. The minimum subsidence above the R Main pillars was 27 mm and increased to a maximum 106 mm above the goaf of Cordeaux's Longwall 20. Compared to the subsidence at the end of Longwall 501, no significant change in subsidence occurred over R Main. The difference of 8 mm between the last surveys for Longwall 20 is considered to be the effects of residual subsidence.

Observed strains were recorded as tensile outside of the extracted area and compressive inside the extracted area, although again the strain profile was very noisy. Tensile

strains reached 0.22 mm/m while the compressive strains reached 0.3 mm/m, with one anomalous exception. Towards the south end of the line tensile strains predominated and increased gradually to 0.58 mm/m above Cordeaux's Longwall 20.

(d) Survey at the Completion of Longwall 503 (September 1994)

As a result of the Longwall 503 extraction, the entire line indicated subsidence. The subsidence along this line increased significantly in comparison with that of the extraction of the previous panel. The maximum subsidence of 157 mm was recorded over the pillar between 501/502 and the subsidence trough had a more blocky appearance than during previous surveys.

It is interesting to observe after the extraction of the first three panels the point of maximum subsidence of this line moved towards the north by approximately 40m for every mined panel. Once the supercritical span is reached after the completion of Longwall 504 the maximum subsidence for the line will still be measured, even though the line ends mid Longwall 503.

The strains along line A-A' were mostly compressive in nature. Again there was a high amount of noise in the data, as shown by the strains alternating between compression and tension from bay to bay in many cases. Maximum tensile strain was 0.302 mm/m, with a maximum compressive strain of 0.713 mm/m.

(e) Survey at the Completion of Longwall 504 (December 1994)

The maximum subsidence on this line increased by approximately 20 mm. If the anomaly at peg 314/315 is disregarded the maximum subsidence was 166 mm. The location of maximum subsidence has remained over the Longwall 501/Longwall 502 pillar. This suggests that the maximum subsidence on this line will be measured even after the extraction of the Longwall 506. At that time the subsidence should have reached a maximum value, not because of reaching the supercritical span, which in fact was achieved with Longwall 504, but by the elapse of sufficient time for the completion of residual subsidence.

Towards the south, beyond the edge of Longwall 501, subsidence continued to increase and the strata overlying the R Main headings lowered a further 7 mm.

The extracted area underneath line A-A' was mostly in compression, recording a maximum strain of 0.4 mm/m and to the south, over the R Main roadways, the surface was in tension with a maximum strain of 0.4 mm/m.

.7.3 General Comments on Subsidence Pattern Along Line B-B'

Figure 2.18 shows a peak subsidence of -149 mm over 501 Panel and further subsidence over the old Longwall K areas.

Figure 2.19 generally shows that strains were compressive over 501 Longwall reaching a peak of 0.309 mm/m and the area between Longwall K and 501 changed from tensile to compressive strains as the longwall move.

Line B-B' Strain - All Mining Surveys

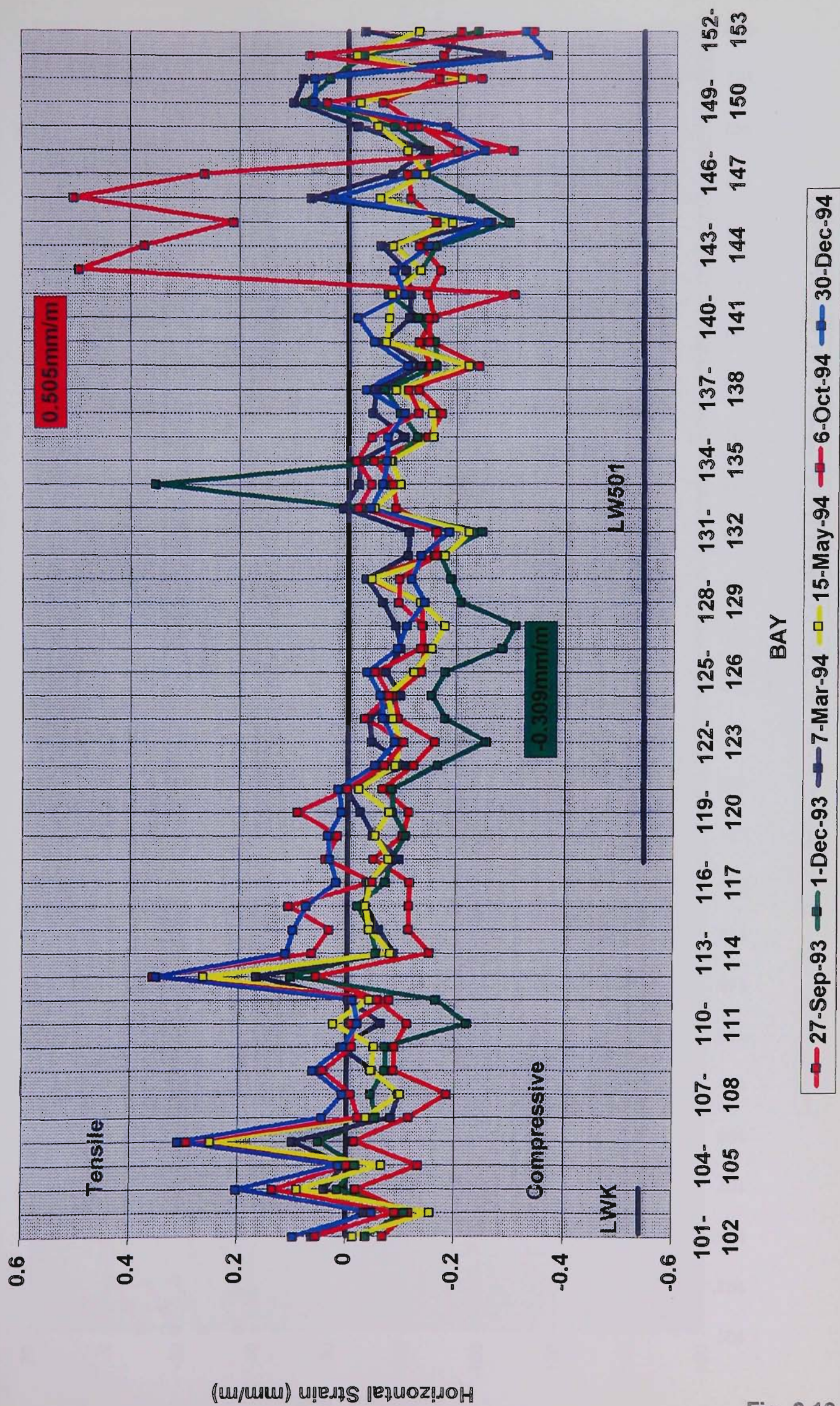


Fig. 2.19

Line B-B' Subsidence - All Mining Surveys

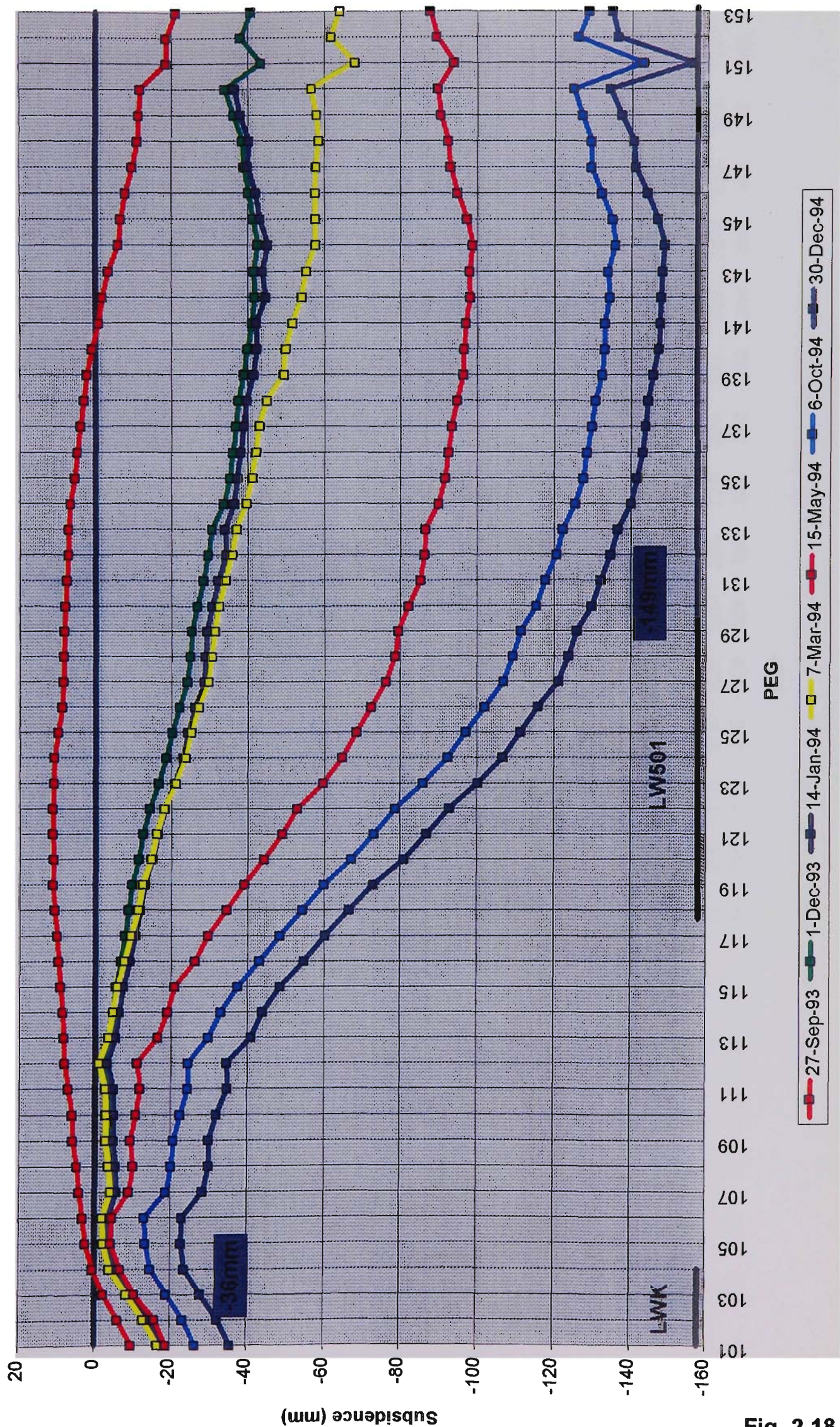


Fig. 2.18

Line A-A' Strain - All Mining Surveys

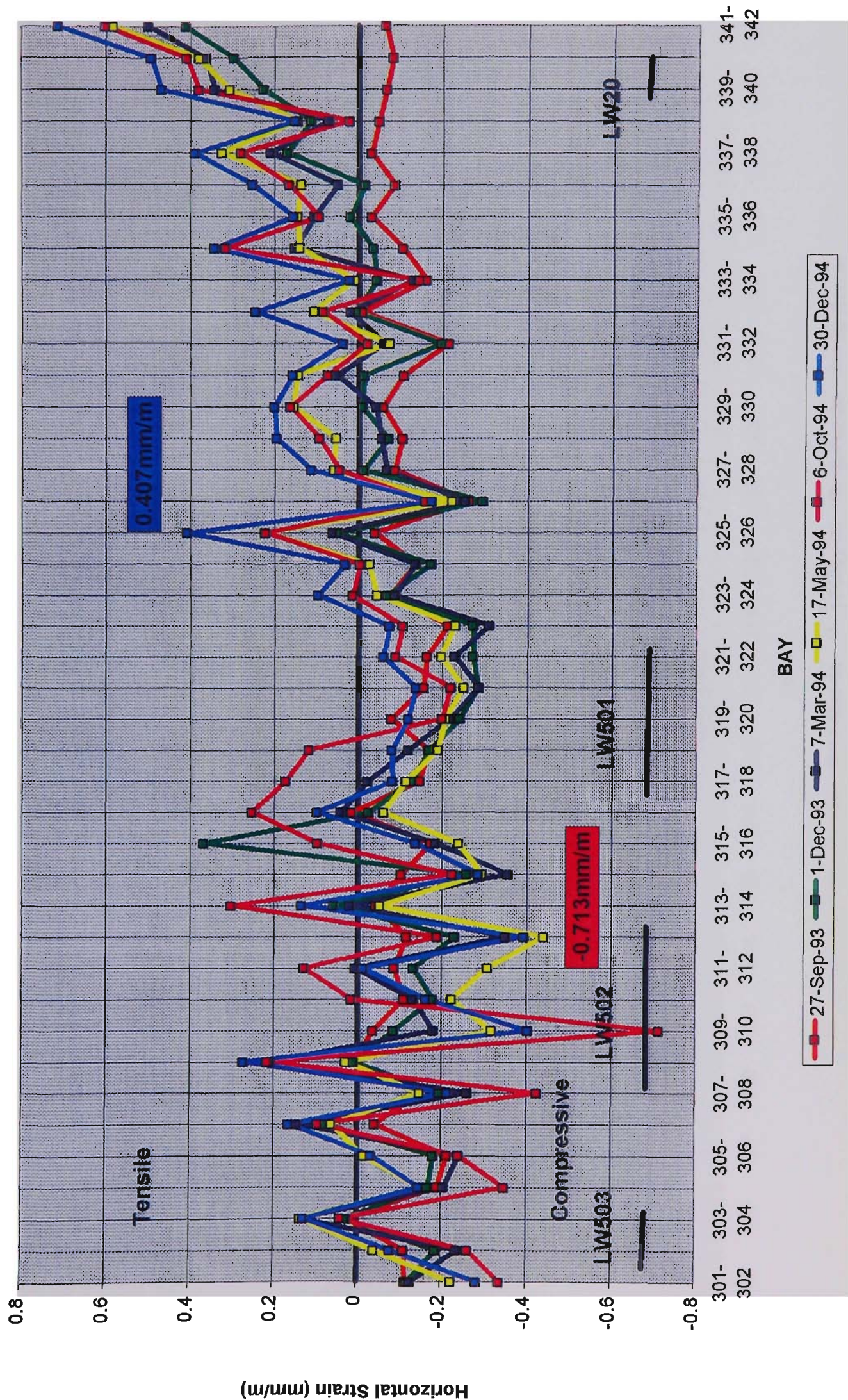


Fig. 2.17

Line A-A' Subsidence - All Mining Surveys

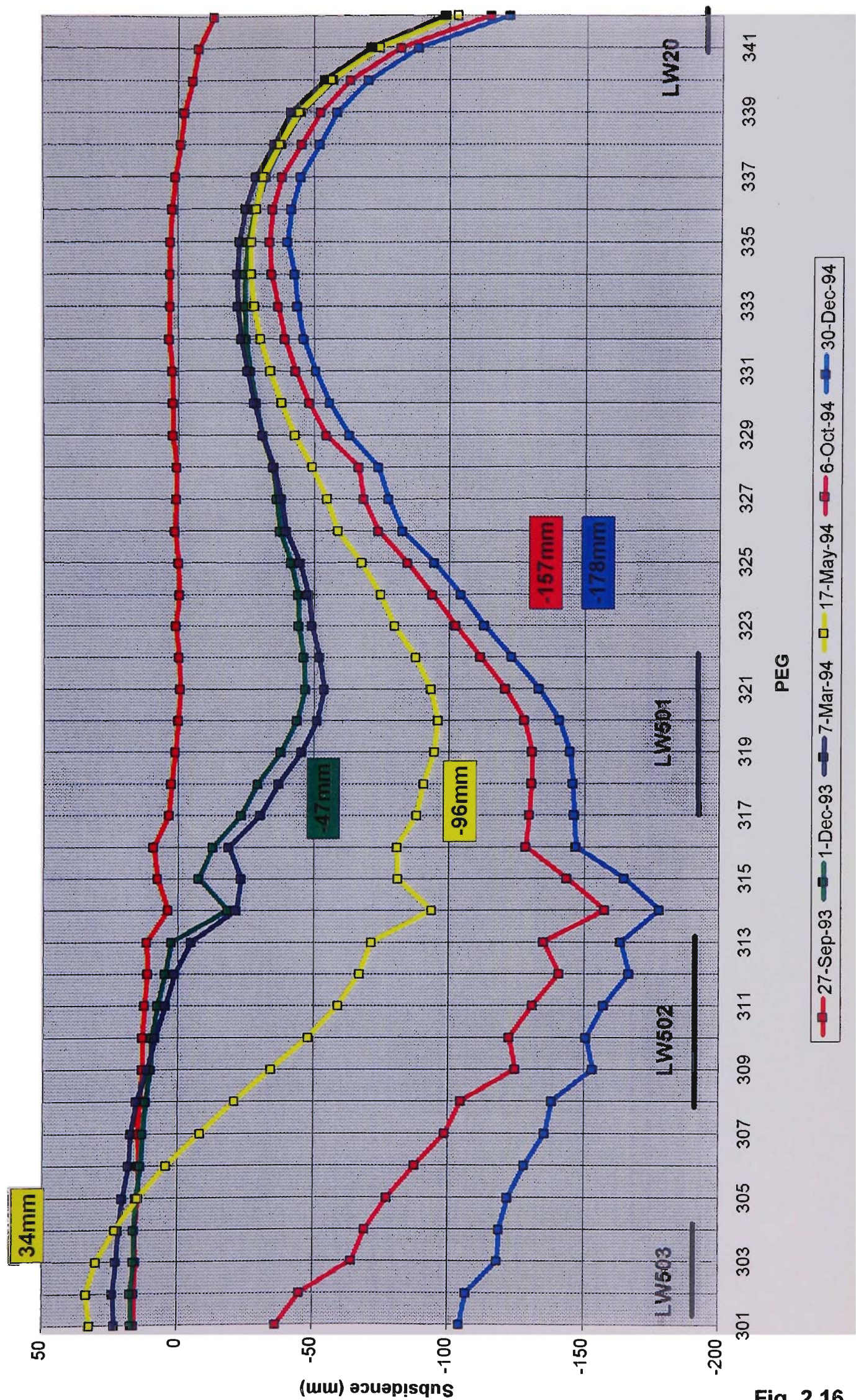


Fig. 2.16

(a) Survey at the Middle of Longwall 501 (September 1993)

The surface over Longwall K subsided further to a maximum of 10 mm at a distance of 440 m from the Longwall 20 goaf and 930 m from the face of Longwall 501. Because of the longer distance and smaller extraction width of Longwall 501 it is believed that this movement is due almost entirely to Longwall 20. From the edge of Longwall K the ground moved up to a maximum of 11 mm over the Cat. North headings, then decreased to zero 160 m from the face position. Subsidence near the reservoir edge was 21 mm.

(b) Survey at the Completion of Longwall 501 (December 1993)

The ground over the old Longwall K subsided by a further 4 mm (a total of 14 mm since the extraction of the Cordeaux Longwalls 19 and 20). If the Electronic Distance Measuring area results are excluded (with justification due to the limits of the instrument), the uniformity of the subsidence suggests that the maximum subsidence (43 mm) over the panel has been measured.

Tensile strain was again observed near the edge of the panels (in this case Longwall K and Longwall 501) with a maximum magnitude of 0.1 mm/m. A value of 0.35 mm/m was recorded some distance from the panel edge, with bays measuring compressive strains on either side, and this value is considered to be anomalous. The compressive strains were similar to those on Line A-A', not exceeding 0.3 mm/m.

(c) Survey at the Completion of Longwall 502 (May 1994)

The maximum subsidence over Longwall 501 following the extraction of Longwall 502 was 99 mm. The west side of the line, over the Cat North pillars experienced a further 5 mm of subsidence, and over the middle of Longwall K subsidence reached 19 mm.

Strains developed as expected, with tensile strains near the edges of the extracted areas, and compressive strains over the extracted areas. The maximum values were 0.26 mm/m for tensile strains and 0.22 mm/m for compressive strains, which are lower than at the end of Longwall 501, probably due to the trough widening out and reducing differential strain in the process.

(d) Survey at the Completion of Longwall 503 (September 1994)

At the west side of the line over Cat North pillars subsidence increased by 10 mm. At the border of the Reservoir subsidence reached 129 mm.

The maximum strains were observed close to the Reservoir, being 0.5 mm/m tensile strain and 0.34 mm/m compressive. The value of tensile strain is quite high in comparison to the maximum predictions, although it occurs on only a couple of bays.

(e) Survey at the Completion of Longwall 504 (December 1994)

At a distance of 470 m from the edge of Longwall 504 goaf, the subsidence in the middle of the line increased by 15 mm.

The maximum subsidence along the line is positioned to the east of Line A-A' but the difference in magnitude is only 3%.

The strains were within the ranges on Line A-A'.

2.7.4 General Comments on Subsidence Patterns along C-C

Figure 2.20 shows that the maximum subsidence was - 154 mm and this was located above 502 Longwall

Figure 2.21 shows

- i) the maximum tensile strain was 0.789 mm/m located between Longwall K and Longwall 502
- ii) the maximum compressive strain was -0.47 mm/m located over Longwall 502.

(a) Mid Panel Survey (September 1993)

The pegs over Longwall 502 were uplifted by a reasonably consistent range of 12-14 mm, except those over Longwall K which showed hardly any movement.

(b) Survey at the Completion of Longwall 501 (December 1993)

The uplift resulting from the influence of Cordeaux and half of Longwall 501 panel extraction remained approximately the same as the previous survey, except at the ends of the line and the middle area where Electronic Distance Measuring was used. In the Longwall K area the subsidence increased to 8 mm, being influenced by the proximity of Longwall 501 to the edge of Longwall K (266 m). At the other areas, measured using Electronic Distance Measuring, uplift of just over 20 mm total was recorded. Again this is probably due to surface topography in combination with surveying accuracy limitations.

The strain profile was again very noisy, with tensile strains recorded in the areas undergoing uplift. Compressive and tensile strains were both in the range 0-0.25 mm/m.

(c) Survey at the Completion of Longwall 502 (May 1994)

In the middle of Longwall K, subsidence reached 11 mm (previously 8 mm). The maximum subsidence of 50 mm occurred one third of the total panel length from the finish line. Near to the western bank of the Reservoir the subsidence decreased to 23 mm which could be due to the higher uplifting of this area as a result of the Longwall 501 extraction.

The change in strains was in line with subsidence change; the maximum tensile strain was 0.31 mm/m and the compressive strain 0.46 mm/m. Both of these were observed in the Electronic Distance Measuring segment of the line.

Line C-C' Strain - All Mining Surveys

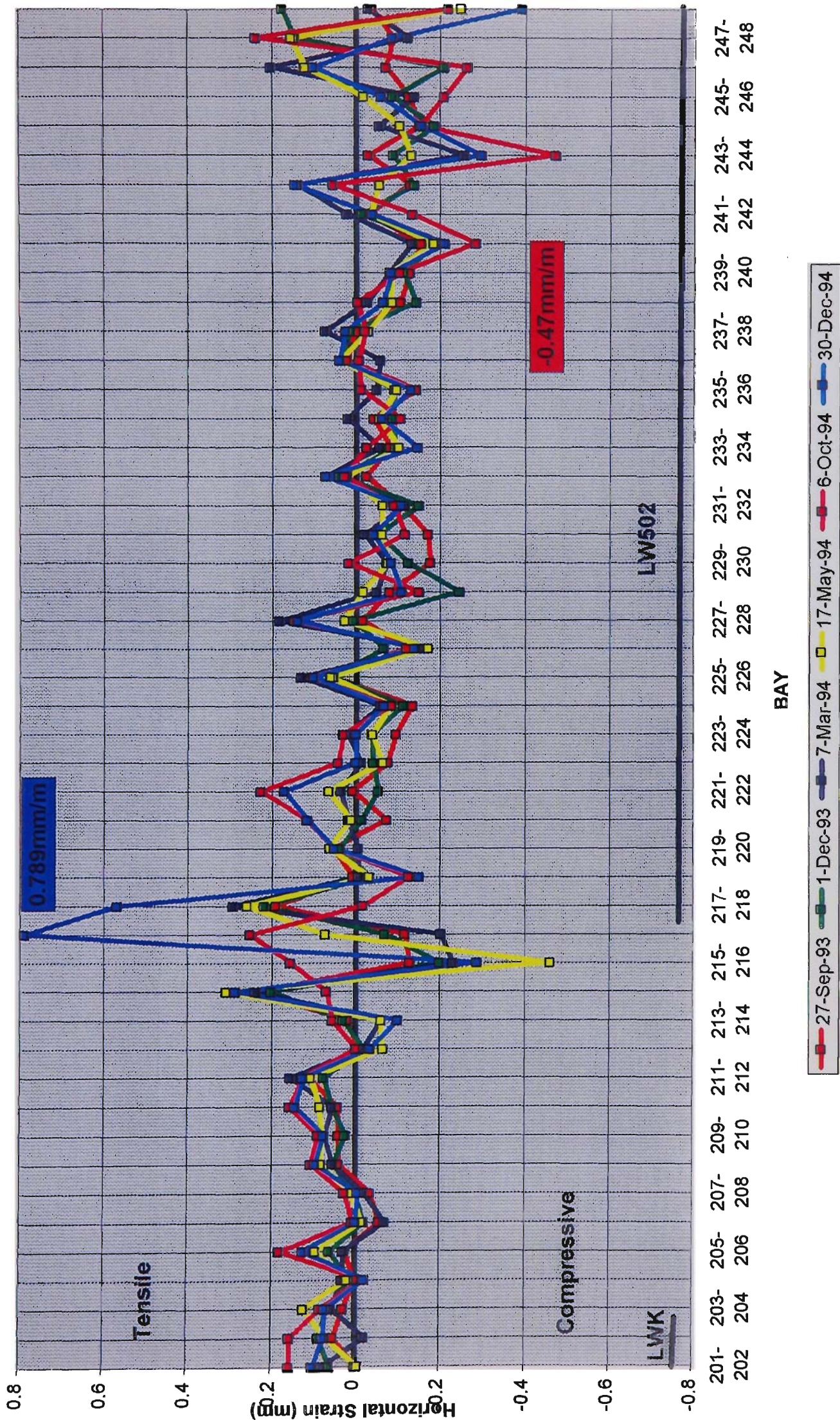


Fig. 2.21

Line C-C' Subsidence - All Mining Surveys

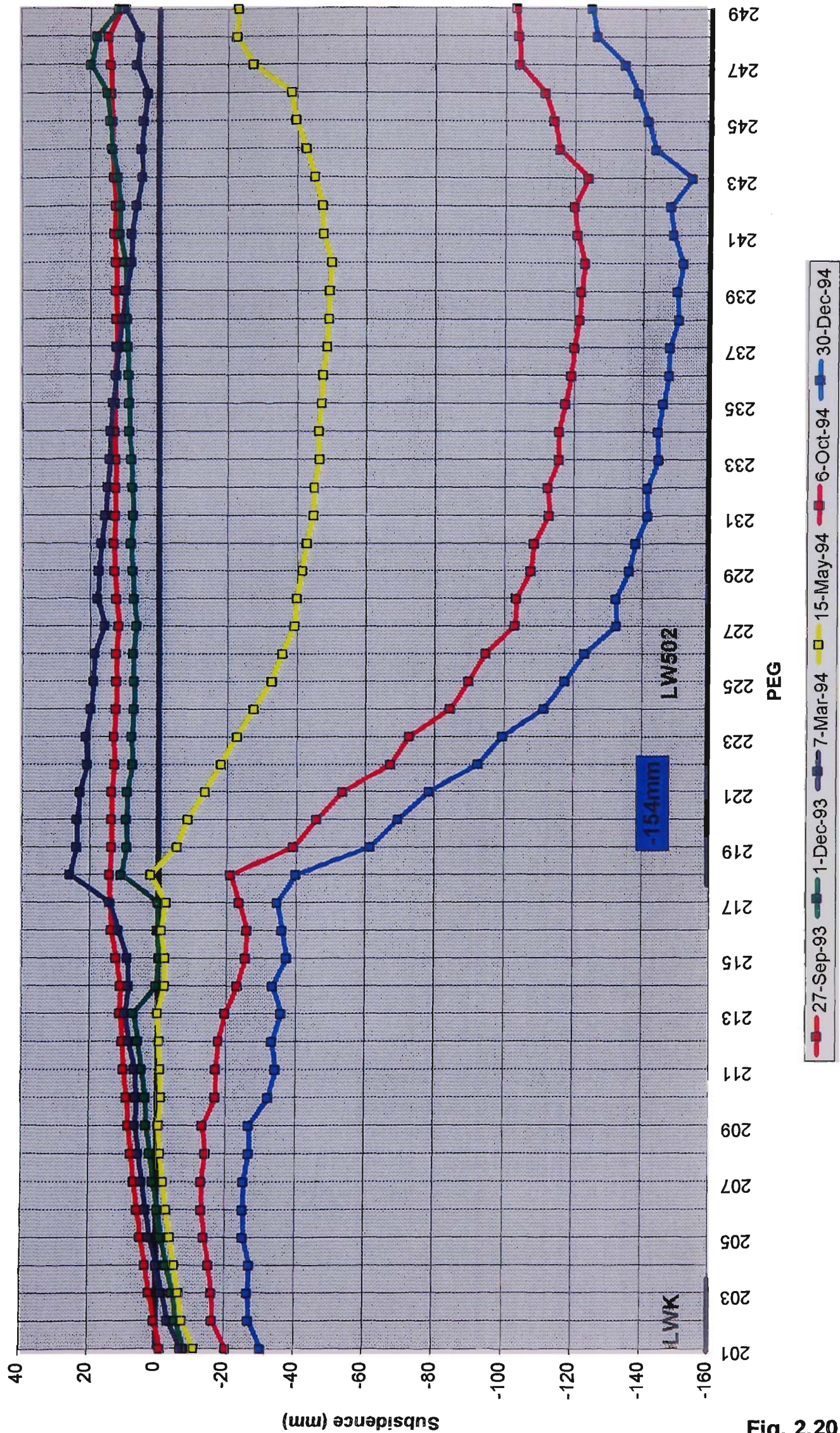


Fig. 2.20

(d) Survey at the Completion of Longwall 503 (September 1994)

The trend of the subsidence is similar to that at the completion of Longwall 501, the difference being the higher maximum subsidence of 124 mm. The maximum strains were 0.25 mm/m tensile and 0.47 mm/m compressive.

(e) Survey at the Completion of Longwall 504 (December 1994)

An increase of subsidence of 27 mm was due to a combination of the impact of Longwall 504 (300 m away) and the influence of residual subsidence.

The location of maximum subsidence is closer to that on Line A-A', compared to that on Line B-B'. This suggests that the maximum subsidence of the Line A-A is quite close to the absolute maximum subsidence of the basin provided the maximum subsidence occurs on this line.

High strains of 0.8 mm/m (tensile) and 0.4 mm/m (compressive) respectively were only recorded close to a steep slope segment of two bays which had an original level difference of 20 m.

2.7.5 General Comments on Subsidence Pattern Along Line D-D'

Figure 2.22 shows that the survey results show extreme variability with ranges of 20 mm being recorded when no mining activity is present. The purple line indicates the uplift expected as the subsidence trough approaches line D-D'.

Figure 2.23 shows that the same influences starting to occur between May 1994 and October '94. These don't appear to be significant as there is no difference in strains measured between October 1994 and December 1995.

(a) Survey at the Completion of Longwall 502 (May 1994)

The original survey of this line was carried out in October 1993. At the completion of Longwall 502 the southern pegs on the line, located at approximately 400 m from the 502 goaf showed a subsidence of 7 mm.

(b) Survey at the Completion of Longwall 503 (September 1994)

The subsidence profile along this line shows extreme variability, within a range of 20 mm from the initial survey values. To date it has not been possible to correlate this movement with mining activity. This confirms that the "rule-of-thumb" 20 mm cut-off value for mining related subsidence is appropriate.

Strains are still low during this survey.

Line D-D' Subsidence - All Mining Surveys

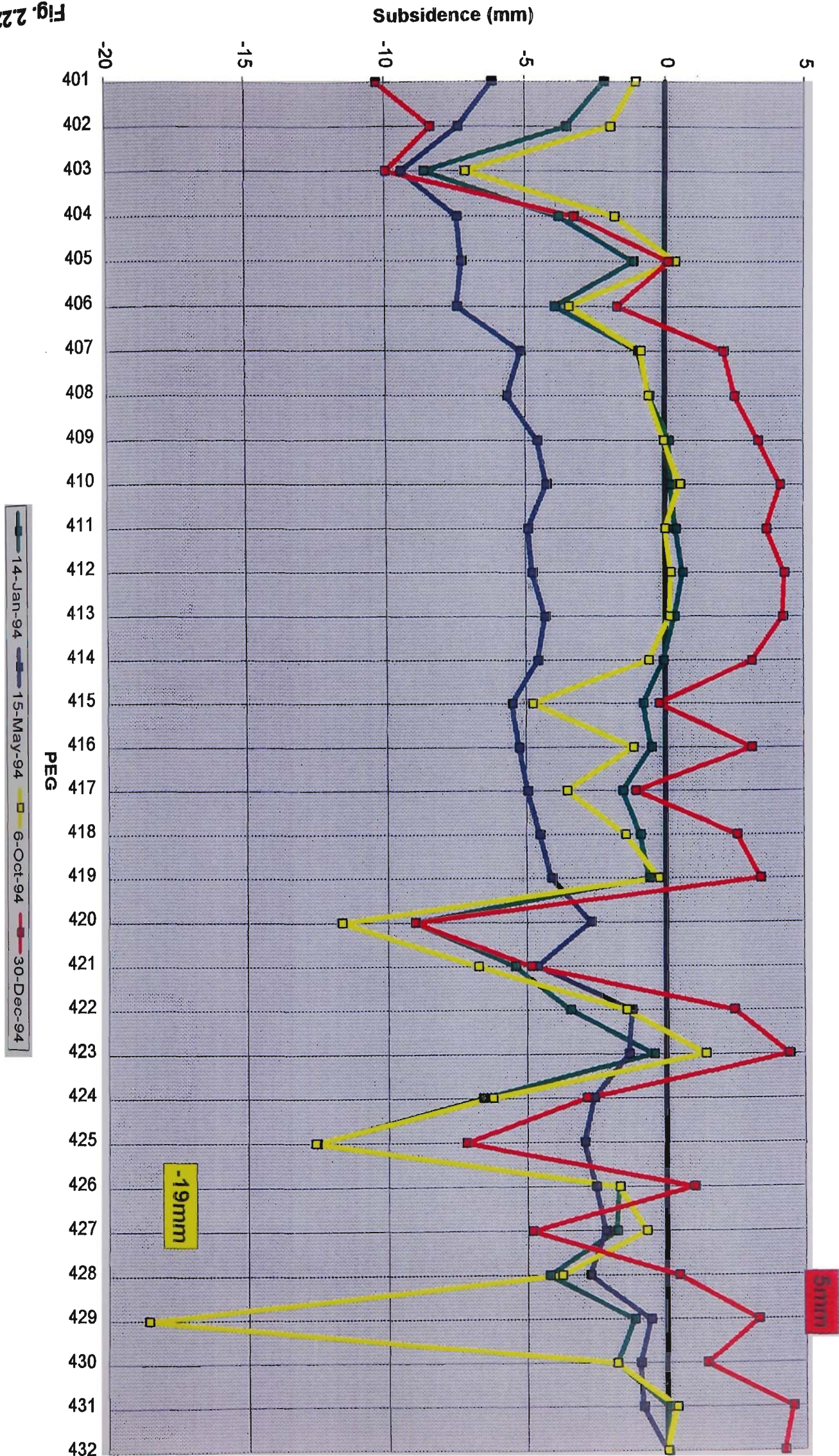


Fig. 2.22

Line D-D' Strain - All Mining Surveys

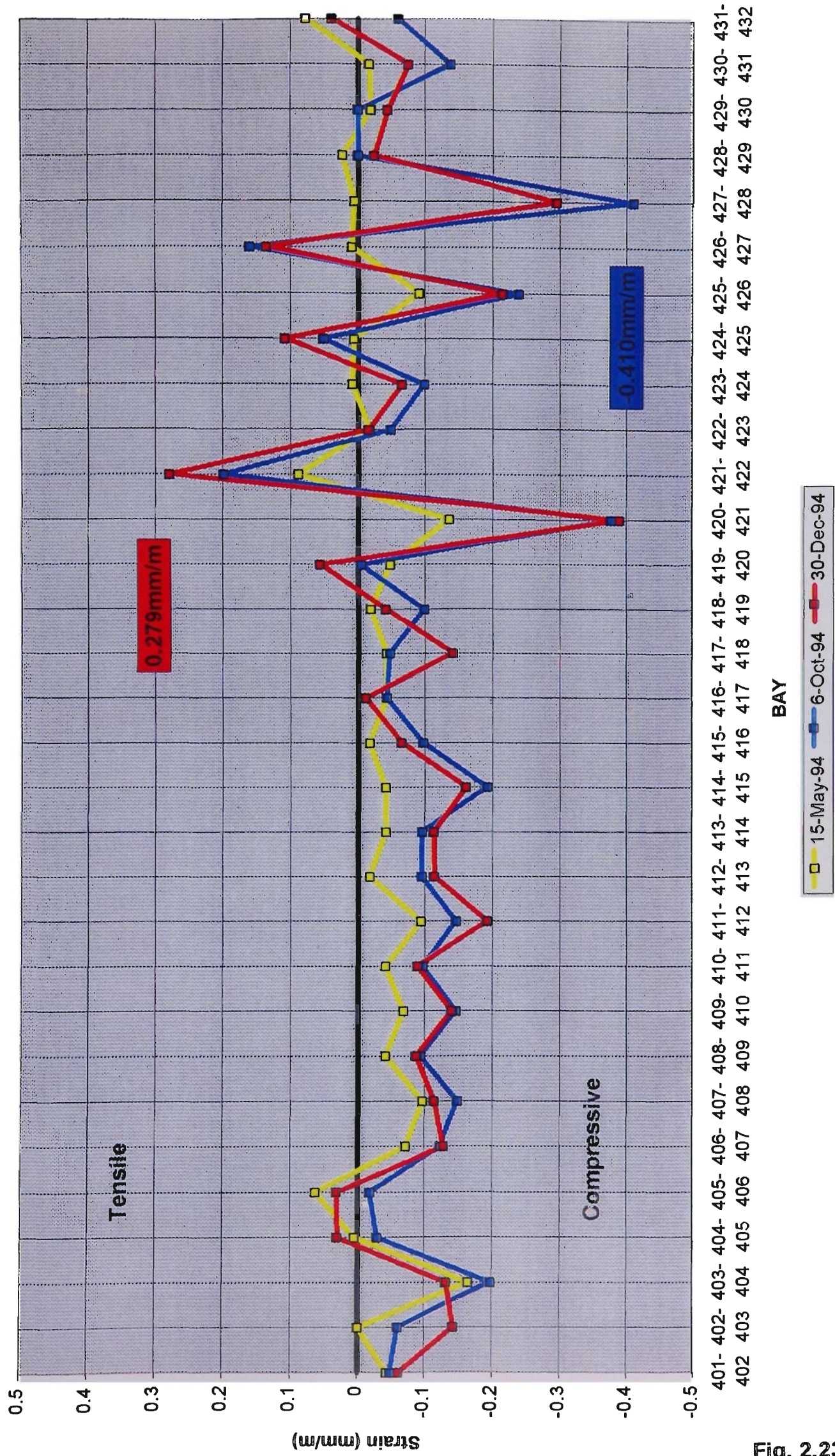


Fig. 2.23

South Bulli Safety Performance

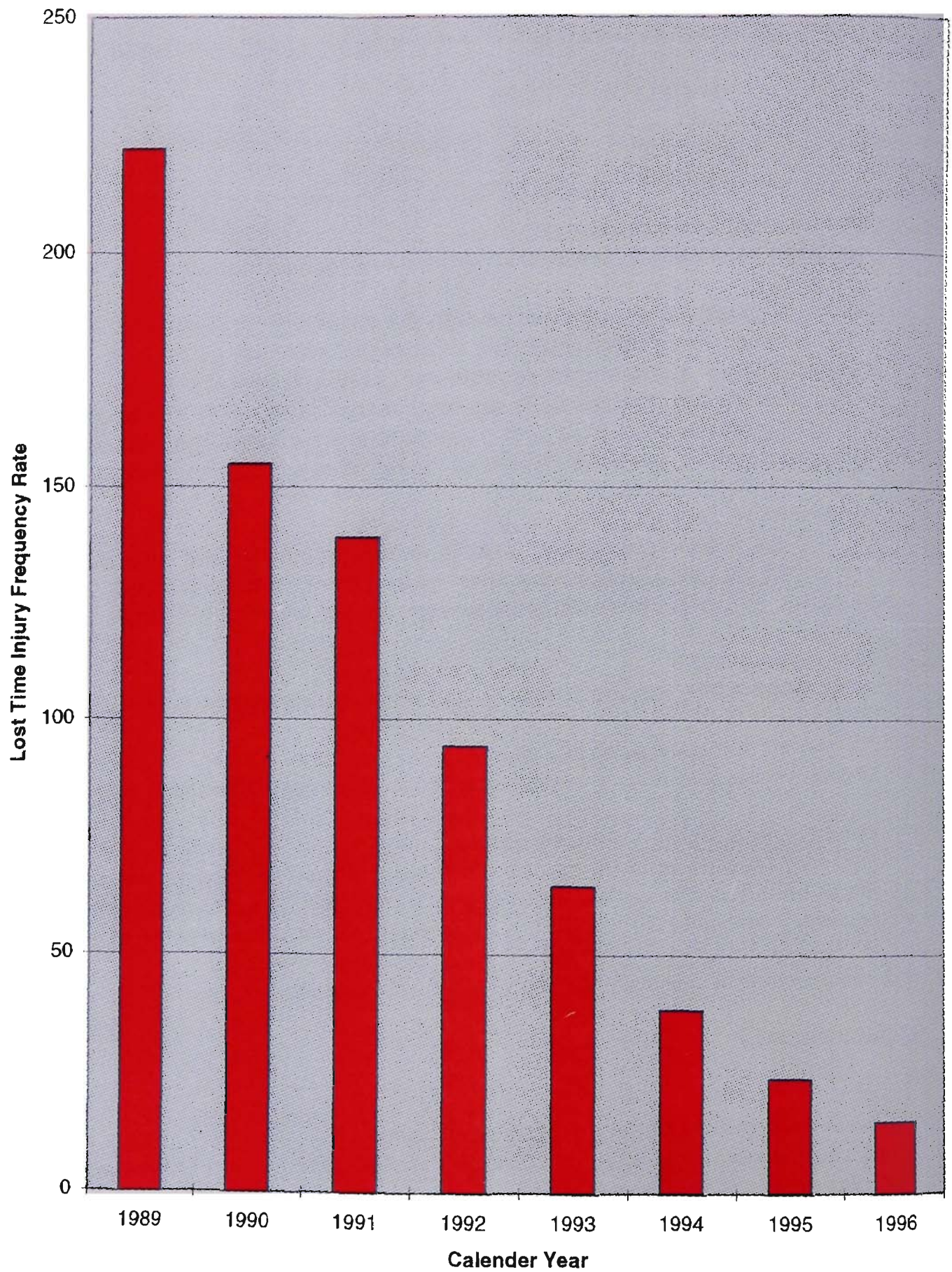


Fig. 1.11

(c) Survey at the Completion of Longwall 504 (December 1994)

The southernmost peg of this line underwent further subsidence of up to 10 mm, and to the north ground uplift of 4 mm occurred. Strains along this line ranged from 0.4 mm/m compressive strain to 0.3 mm/m tensile strain.

2.8 Conclusions

The conclusions after analysis of the first 11 surveys are as follows:-

- "Climatic" conditions do not have a significant effect on the movement of the survey pegs, provided that their construction is adequate. In the Cataract area a "climatic" variation of up to 20 mm is considered appropriate, and in line with general limits of mining induced subsidence.
- Accuracy limitations in level measurement due to bench mark movements used in the Cataract area could be up to 5 mm.
- Strain measurement errors as a result of the steel band measurement are estimated to be 0.05-0.1 mm/m.
- Electronic Distance Measuring measurements are not sufficiently accurate for determining very small ground movements. In the case of the above mentioned 11 surveys, the accuracy of reduced levels is thought to be ± 10 mm, with strain accuracy of ± 0.3 mm/m.
- The extraction of Cordeaux Longwalls 17-20 re-activated subsidence over Longwall K (and probably L, M, N & O Panels) up to a distance of 600 m from the active longwall and contributed to the uplift of the strata above the unmined Cataract panels. The extraction of Longwalls 501 & 502 also induced uplift of strata but with limited effect. This uplift was relatively small and for the most part within the 20 mm tolerance defining the edge of a mining induced subsidence basin.
- The initial prediction for maximum subsidence was 200 mm, which is still higher than the actual measured value for:

Line A-A	-	173 mm
Line B-B	-	156 mm
Line C-C	-	158 mm
Line D-D	-	18 mm

This shows that except for one reading on line A-A of 173 mm all other results were 80% of the predicted theoretical maximum.

Average for	Line A-A	-	0.3 mm compressive	0.5 mm/m tensile
	Line B-B	-	0.2 mm	< 0.1
	Line C-C	-	0.2 mm	< 0.1
	Line D-D	-	0.2 mm	< 0.1

- In this dynamic period of extraction of the first four panels, both maximum strains (tensile and compressive) recorded over all surveyed lines have not exceeded 0.8 mm/m, as isolated figures. These figures (which have decreased during later extractions) may be regarded as including some influence from measurement errors, impact of relief particularities and local small structures, which cannot be evaluated by any prediction method. The prediction methods allow the estimation of the maximum strains for normal conditions, free of anomalies. These isolated strain anomalies reduce with subsequent surveys, and are well below the much higher value of the tensile failure of the surface rocks.
- If the isolated high strain figures (possibly associated with one or more of the suppositions above) are disregarded, the consistent recorded values of the compression strains are less than the predicted values.

CHAPTER 3 - STRATA MONITORING, INVESTIGATIONS & RESULTS STAGE I

3.1 Introduction

This program was proposed by the Water Board to allow strain monitoring to be correlated with the Board's seismic network monitoring system. Additionally, the Water Board desired a monitoring system which would cover pre-mining, mining and a long period of post-mining. (Sydney Water Board Report, 1992.) The program was designed to try and determine if there was any effect of mining the strata above the extraction which could lead to a widespread build up strain and tectonic movement.

To measure the in-situ strain a high-resolution and complex instrument designed and manufactured by the Queensland University was selected. Instrumentation of this type had been previously used to monitor earthquakes in the San Andreas Valley in California, and also in Canberra.

3.2 In-Situ Strain

The program involved the installation of the instruments in three separate boreholes, with solar-powered data collection at desired intervals stored in a computer in an enclosure at the top of each borehole. Battery back up of the solar cells allows the system to work on cloudy days and during the night. The stored data is sent automatically by radio to a central station based in the Cataract Dam Administration camp and stored in a desk top computer. A modem allowed this data to be remotely retrieved for analysis and processing by the CSIRO.

The construction of the holes required special care, as the actual strain instruments had to be installed in borehole sections free of fissures. Borecores from these sections were geomechanically tested for calibration of the instruments.

During 1995 the maintenance of the system, archiving of data and processing, strain computation, event identification and software development has been contracted to the CSIRO, which took over the project and personnel from Queensland University.

The results from the vertical strain monitoring are presented in Appendix A, and suggest that the vertical strain in the Hawkesbury Sandstone at the base of the reservoir is extremely low in engineering terms. This is as expected, with the Hawkesbury deforming elastically in response to undermining.

SOUTH BULLI COLLIERY

LOCATION OF IN-SITU STRAIN INSTRUMENTS

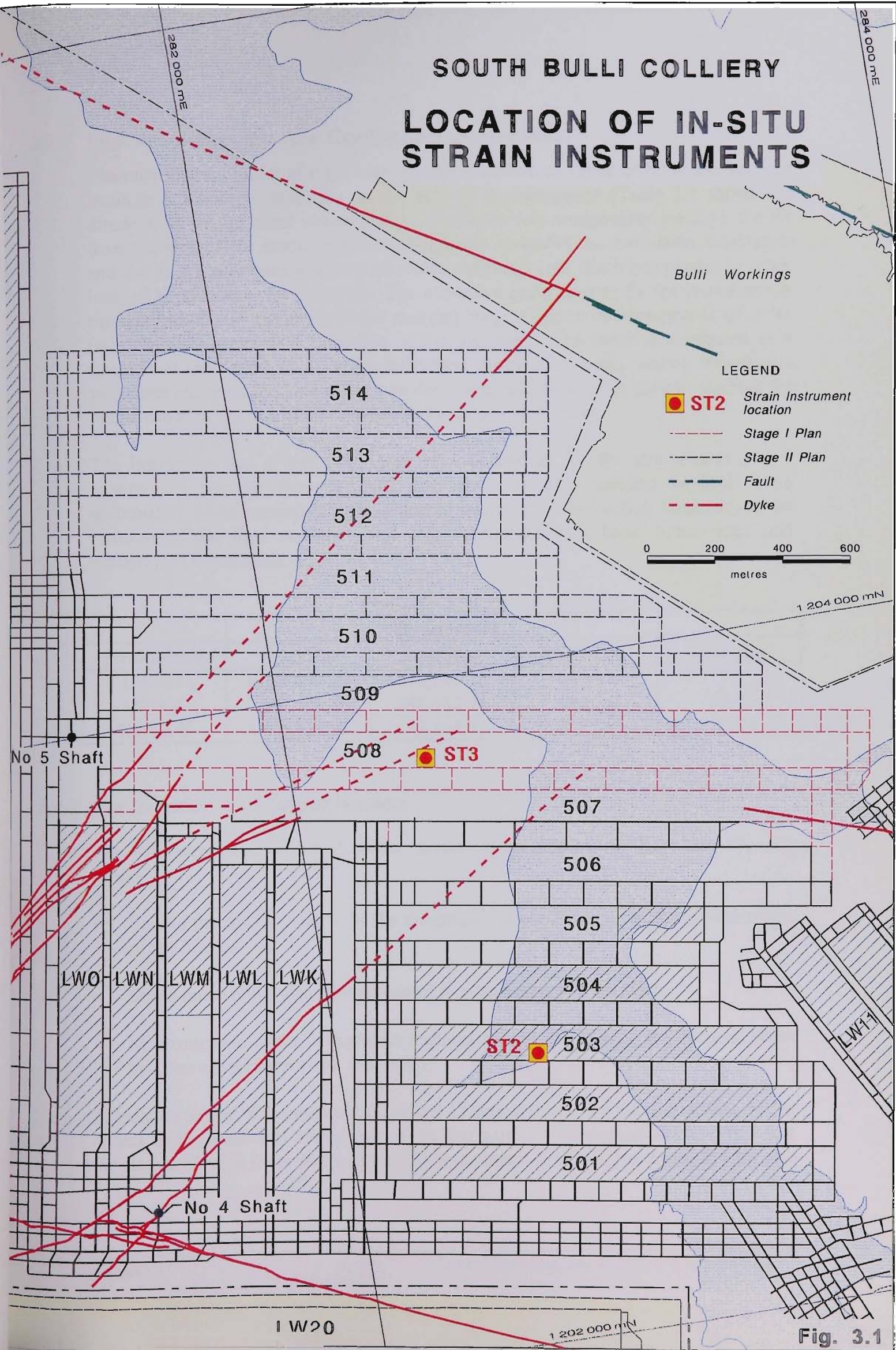


Fig. 3.1

3.2.1 High Resolution Multiple Component Instruments

The instruments consist of eight independent components. Four of these measure the strain in a plane perpendicular to the axis of the instrument (Table 3.1 shows the direction of the installed strainmeters). A further two components measure the tilt from the axis of the instrument, one component measures the instrument orientation and the final component is a non-deforming reference cell. Each component is strain isolated in an independent module. The expansive grout used to fix the instrument in the hole pre-loaded the strainmeters ensuring they remain in compression at all times (tension is measured as a reduction of the pre-load). The strain is monitored as a function of the deformation of the instrument diameter by using sensing transducers with three element capacitors. The non deforming reference cell is used to monitor the performance of the instrument cable and the surface electronics.

The instrument has a high resolution of 1 nanostrain for the strainmeters and 1 nanoradians for the tiltmeters and long term stability, enabling far-field strata deformation measurements of mining-related events. Due to the high sensitivity of the instrument, the data requires earth tide calibration with basic ocean load and topographic corrections.

Table 3.1 - Strainmeter Locations

Strainmeter	Co-ordinates			Depth (m)
	Easting	Northing	A.H.D. (m)	
LW503	1,202,854.23	282,593.26	295.11	51
LW508	1,203,770.67	282,412.44	328.71	93.3
Station Y	1,206,853.81	281,358.92	339.86	110

3.2.2 Site Location and Target Horizon

The sites were selected based on the terrain topography and to meet the following goals:-

- Record the strains induced by the maximum subsidence produced by the extraction of the first panels.
- Strain monitoring with mining located at a minimum of 1 km away.
- Measurements of the background strain in the area (tectonic strain, induced strain by other extractions in the area, etc.).

A location in the 503 peninsula (Figure 3.1) was selected for the monitoring of the effects of the maximum subsidence of the first panels. The second site for recording the strains 1 km in front of the extraction was chosen over 508 panel, and the last site

was located near the dam structure (at "Y" Site- 4 km away from Longwall 501) to measure initially the strain background in this area, and eventually any mining-induced strains as the extraction approached the dam structure.

The horizon for the strain measurements was established near to the Reservoir floor, which corresponds approximately to the base of the Hawkesbury Sandstone.

3.2.3 Vertical Strains

Vertical extensometers were installed in the 503 and 508 In-Situ Strain boreholes. In each borehole five anchors were bonded between the In-Situ Strainmeter instrument and the surface (Table 3.2). The vertical displacements are measured by Linear Variable Differential Transformers (LVDT) and the data is stored in the uphole computer, and transmitted and stored in the central station computer as in the case of the In-situ Strain monitoring.

Table 3.2 Anchor - Displacements		
Anchor No	LW503 Anchor Depths (m)	W508 Anchor Depths (m)
1	20	33
2	28	49
3	36	65
4	44	81
5	52	93

The results from the vertical strain monitoring are presented in Appendix B, and suggest that the vertical strain in the Hawkesbury Sandstone at the base of the reservoir is extremely low in engineering terms. This is as expected, with the Hawkesbury deforming elastically in response to undermining.

3.2.4 Results and Correlation With Mining Events

Initial results, which have been calibrated to within 20% of the real values, indicate that the system is operational and working well. The instruments indicate that the strains developed are much lower than might have been expected. The results, which include the extraction of the first four and a half longwalls, are presented in Appendix 4.

3.3 Numerical Modelling

A Water Board study was organised and undertaken at the end of 1991 using SUBSOL, a three-dimensional displacement discontinuity modelling program which has been developed from MINLAY (MINing of LAYered systems) by MinCad Systems Pty.

MinCad claim its computer program is capable of modelling the surface/seam topography, stress changes, isotropic and anisotropic material properties, unlimited material layers, goaf types, and different mining layouts. Additionally, it offers the possibility of calibrating the material properties using previously obtained monitoring data.

Modelling includes the deformation mechanism of the three induced zones (the goaf zone, the zone of induced fractures and bed separation, and intact strata up to the surface) which depend on the extraction parameters and overburden properties. A novel joint element is used to model the three-dimensional stability of a geological discontinuity such as a dyke or fault.

To determine realistic material properties the study started with a review of influential subsidence factors in the Southern District, and a back-analysis of the subsidence data from the most relevant panels (Bulli Colliery South West panels and 300 series South Bulli panels). The selection of the material properties by this method is claimed to be of vital importance because laboratory test results have under-predicted actual subsidence values.

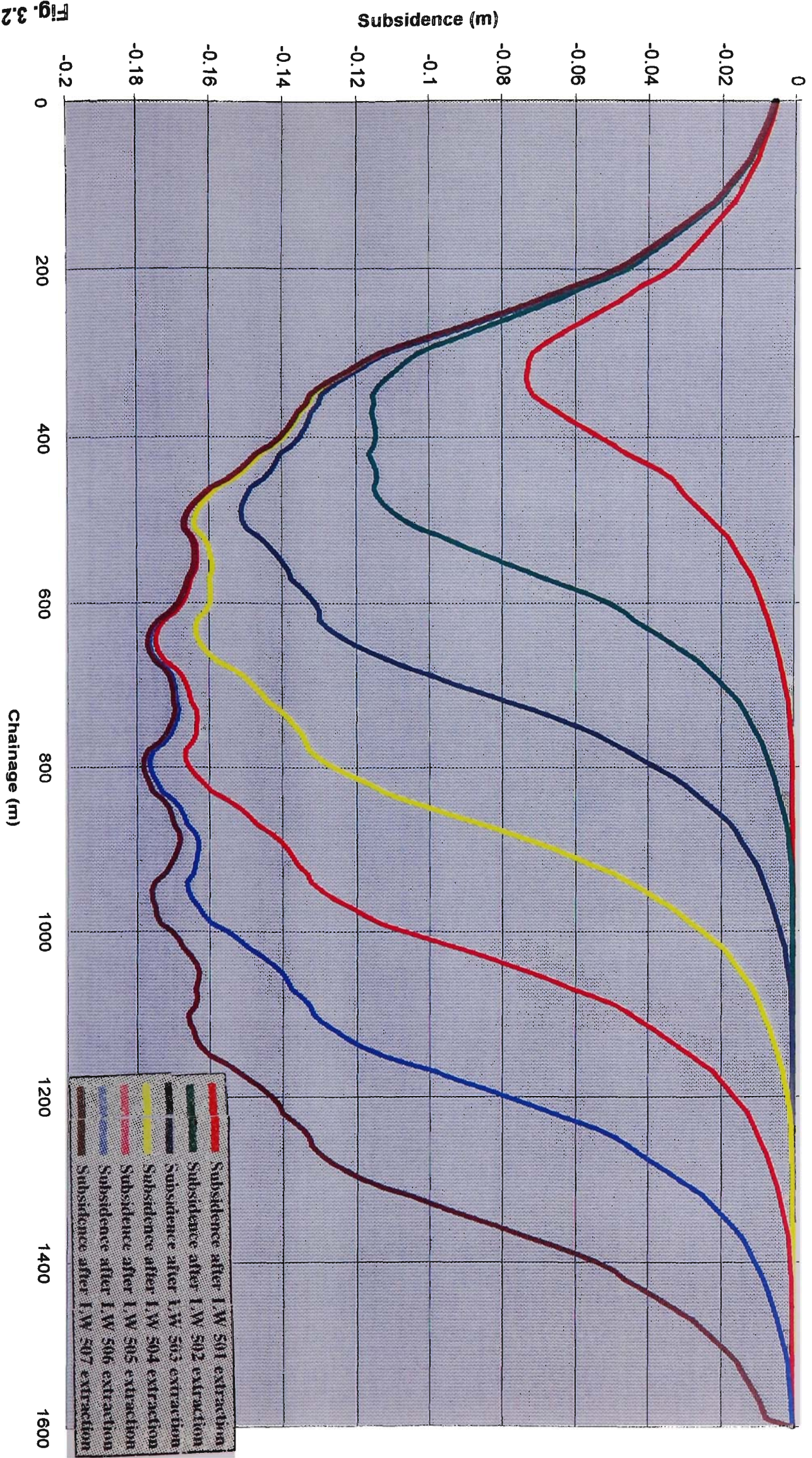
The anisotropic material properties and scaling of elastic module, appropriate goaf properties and appropriate modelling of parting planes mechanics were obtained after a calibration programme involving 25 runs of the program using the observed subsidence data of the South West and 300 panels.

A Cataract layout having 100m panel widths and 60m pillar widths was numerically modelled using the calibration data and some specific parameters such as a cover depth of 330m and stratigraphy from the boreholes surrounding the Reservoir.

The most important conclusions from the exercise are the following:-

- "Maximum" subsidence of 180 mm is reached after the extraction of Longwall 505 (Actual maximum subsidence is predicted after Longwall 507, however Figure 3.2 indicates that there is no significant increase in the magnitude of subsidence after Longwall 505 is complete) and the maximum strains are 0.4 mm/m for tension and 0.9 mm/m for compression.
- Pillar loading is quite uniform from the first to the last extracted panel, with an average pillar stress of 18.4 MPa (Figure 3.3). The vertical stress variation over the pillar is from 15.5 to 23 MPa and in the middle of the goaf is only 1 MPa. These stresses are low in comparison with virgin vertical stress of 8.25 MPa.
- Critical loading of the hypothetical fault with an adjacent failed pillar occurs during the 504 panel extraction. The zone for which inelastic behaviour exists extends from the surface to a depth of 140m, which is similar to the scenario of no inter-panel failure.

Stage I MinCad Subsidence Predictions



South Bull Colliery - 500 Panels
Predicted Vertical Stresses

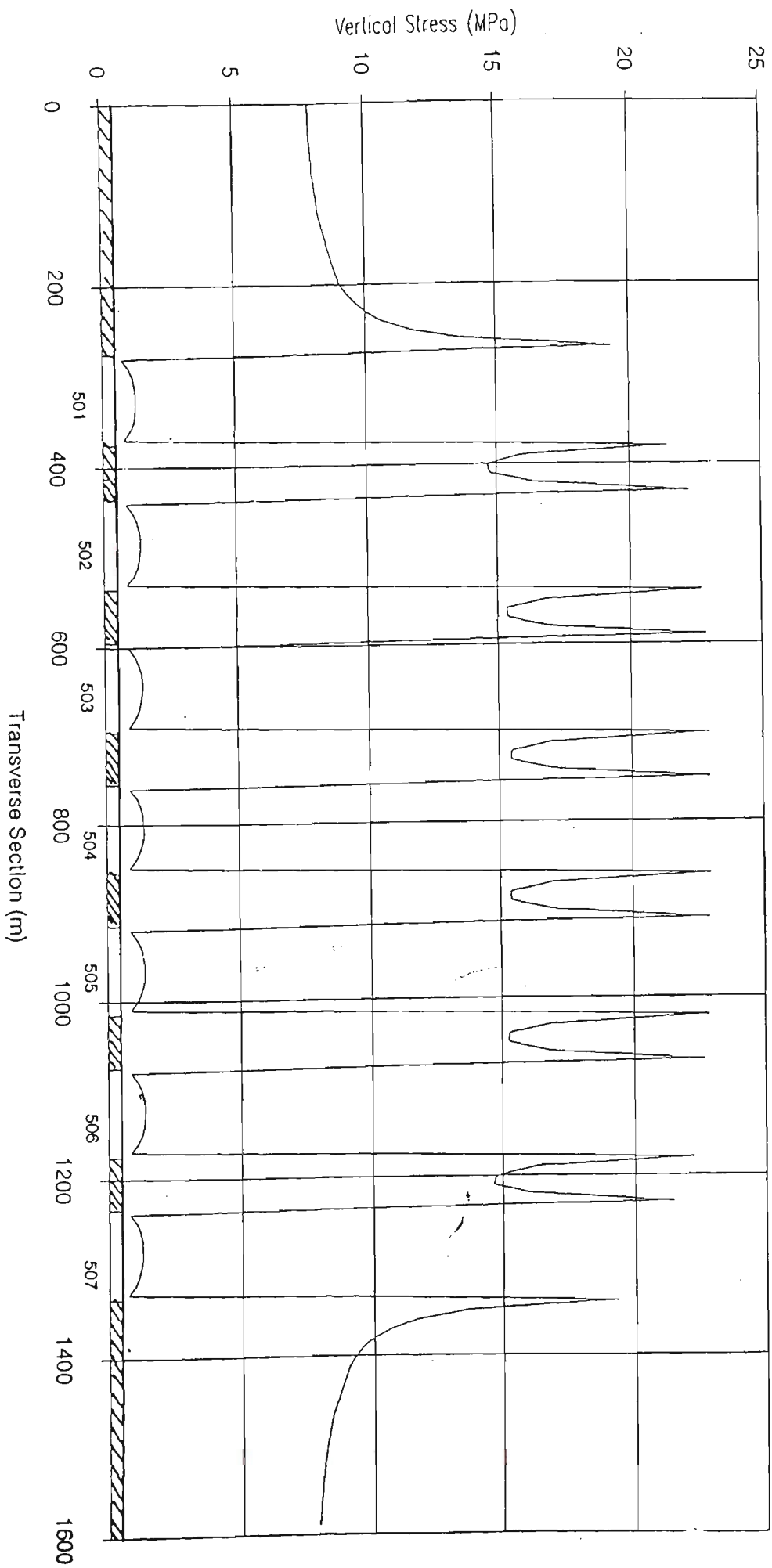


Fig. 3.3

500 series panels:

To date the most important parameters (subsidence and strain) are thought to be in reasonable agreement with the observations along line A-A', given that Cordeaux's

Longwalls 17 to 20 were not modelled, the modelled extraction geometry was slightly different to the actual layout and the depth of cover in the model was less than that of Line A-A' where the actual results were obtained.

Figure 3.4 shows that predicted subsidence versus actual Line A-A'.

The actual strains are within the envelope of the predicted strains and suggest that the empirical predictions using the Southern Coalfields guidelines are suitably accurate.

As a result MinCad were commissioned to re-run the model using a variation on the Stage II layout which is sought. This will be described more fully later on in this thesis.

The vertical stress predicted after the extraction of Longwall 507 was 23 MPa near the edge of the pillar and 15 MPa in the middle of the pillar.

The study also investigated two "what if?" scenarios to determine their impact on the subsidence and pillar loading. The first scenario supposed a fault parallel with the panels was modelled in the pillar between Longwall's 503 and 504 with a dip of 82.5 degrees with reference to a Fault Stability Index (ratio of mobilised shear strength to the shear loading). The results showed an increase in subsidence after the extraction of Longwall 504 from 165 mm for "expected pillar behaviour" to 380 mm after pillar failure and with a maximum of 0.5 mm/m tensile strain and 0.8 mm/m maximum compressive strain. These are both far below the laboratory-determined failure values for the Hawkesbury Sandstone. Average loading of the adjacent pillar increases marginally to 22.1 MPa, below the failure criteria for the pillar.

The second scenario consisted of the change of the layout by increasing the panel width to 200m and reducing the pillar width to 40m. The predicted subsidence for this scenario increases significantly to 950 mm while the maximum strains change very little (to 0.5 mm/m for tensile strain and 0.9 mm/m for compressive strains). The maximum predicted pillar loading increased to 34 MPa, close to the pillar strength predicted by MinCad (Although pillar strength studies reported later in this thesis infer a much higher strength than the MinCad-assumed strength). The conclusion of the study was that such a layout does not appear to greatly increase the risk to the reservoir, compared to the approved layout, provided the inter-panel pillars remain stable.

To date the comparison between the MinCad predictions and the observed data suggest that this mathematical modelling is a more complete prediction tool than the

Stage I Subsidence Results - MinCad Vs. Actuals

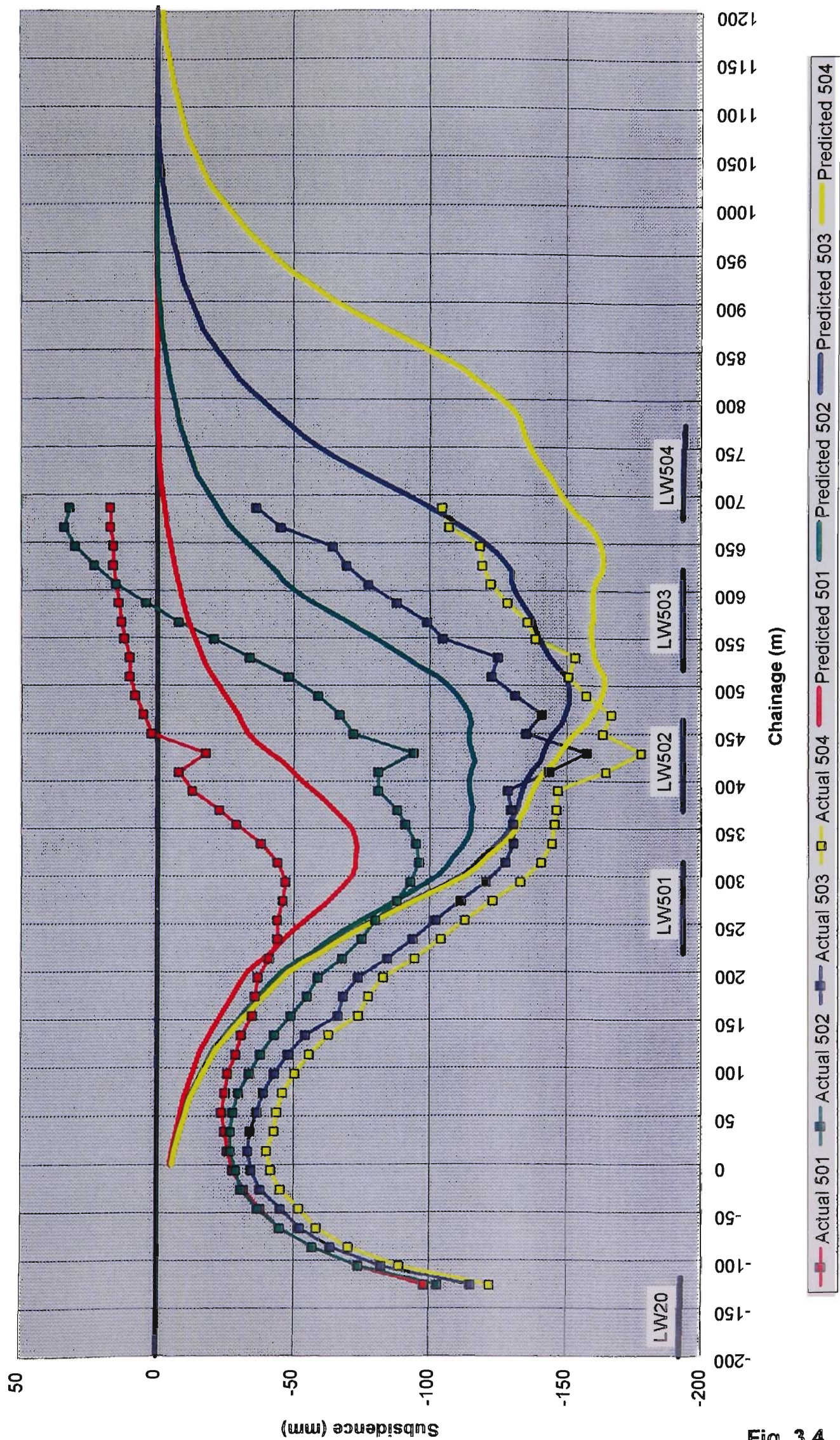


Fig 3.4

empirical method used in the Stage I Application, giving subsidence profiles for every panel. In addition, it gives an idea about the distribution of stress on the chain pillars. Prediction of the strata behaviour in the vicinity of a geological defect can not yet be quantified due to a lack of field data; and as such it is not yet clear if the defined parameter, Fault Stability Index is a relevant way of assessing such behaviour.

3.4 Chain Pillar Stability Monitoring

Stress monitoring of chain pillars beneath the Cataract Reservoir has been undertaken at four sites between LW501 and LW504.

The monitoring has been conducted using hydraulic borehole platened flatjacks and vibrating wire rigid inclusion stressmeters. The stressmeters are installed approximately mid-seam in the longwall chain pillars. They have been installed from cut-throughs into pillars to a depth of approximately 10m, which is beyond the initial localised roadway stress concentration zone.

3.4.1 Stressmeter Selection

The selection of stressmeters was based on a requirement to monitor (potentially) high pillar loads for an extended time period (years). The only type of stressmeter design that is potentially capable of meeting both these requirements is the hydraulic borehole form of stressmeter.

Hydraulic cells have been installed at all four sites. A number of reliability and performance problems have been encountered with these prototype cells. These problems are primarily a result of a forced change of design due to availability and cost of connecting hydraulic tubing from the initially specified stainless steel to copper tube. Consequently, a back-up "duplicate" installation of vibrating wire rigid inclusion stressmeters were installed in the latest pillar monitoring site in G504.

The main limitations of these rigid inclusion cells is a maximum stress change of between 20 and 25 MPa, and an incapability of reading high stresses due to localised borehole yield prior to surrounding coal failure.

A number of hydraulic cells have, however produced reliable data which has subsequently been verified by the alternative vibrating wire rigid inclusion stressmeters.

With regard to all in-situ monitoring programs, all stressmeters show localised deviation due to variation in cell construction, installation and local geological conditions. Ideally, a large number of stress monitoring readings should be combined before conclusions are drawn on the in-situ stress field. Typically, stressmeter readings are considered to have an inherent inaccuracy of about 15%.

3.4.2 Site Selection and Description

The first monitoring site was located in Longwall 501 maingate (Figure 3.5), and included a hydraulic cell and a rib extensometer. This instrumentation was installed as part of another investigation, not related to pillar stability, and the instruments mentioned were used for test purposes prior to a full instrumentation of a chain pillar. One cell and extensometer were monitored until the Longwall 501 passed the site. The results from this site were encouraging enough to warrant the use of the instrumentation at the second site in G502.

The second site was installed in 6C/T in G502, to be sufficiently far from the panel start and stop positions to pick up the maximum loading on these chain pillars. The instrumentation consisted of six hydraulic cells installed in such a configuration as to give a representative pillar loading profile. Extensometers were installed in the Longwall 503 tailgate and the cut-through to provide information on lateral pillar deformation. These were not of a type which could be read remotely. The cells and cables were protected by steel pipes to protect them from the goaf behind the longwall. The passage of Longwall 502 was monitored with some success, however due to a long delay in approving a transducer for underground use, the cells could not be read from when Longwall 503 passed the site until after Longwall 503 had finished. Readings taken at this time indicated that somewhere in Longwall 503 tailgate, the cable had been severed during the goaf formation.

Three cells were installed in G503 at 3 C/T during the period when the G502 cells could not be read. These were installed close to the Longwall 503 side of the chain pillar, to provide additional data at a distance into the pillar where there was insufficient data from the G502 site. The cells at this site were protected using electrical conduit, laid along the floor of the tailgate. It was hoped that the coal routinely ploughed into the tailgate by the shearer on each cut would blanket the cables from the goaf, while reducing the likelihood of damage from shearing at steel pipe joints. This did not work, and the connection to the cells was lost.

Due to reliability problems with some hydraulic cells, it was decided to install vibrating wire solid inclusion cells in addition to the hydraulic cells. Initially 8 hydraulic cells and 8 solid inclusion cells were installed in 5C/T, along with two 15 metre extensometers, of a type which could be read remotely. Over time a number of cells failed, however the data obtained from this site confirmed the results from earlier sites.

3.5 Results

Figure 3.6 shows a compilation plot of three hydraulic (H) cells and 6 solid inclusion (I) stressmeters, as well as their distance into the pillar, relative to the pillar side closest to the extraction. The instrumented pillars were between 300 and 400m from the face finish line, except for the G503 installation, which was only 100m from the face stop line.

SOUTH BULLI COLLIERY PILLAR MONITORING SITES

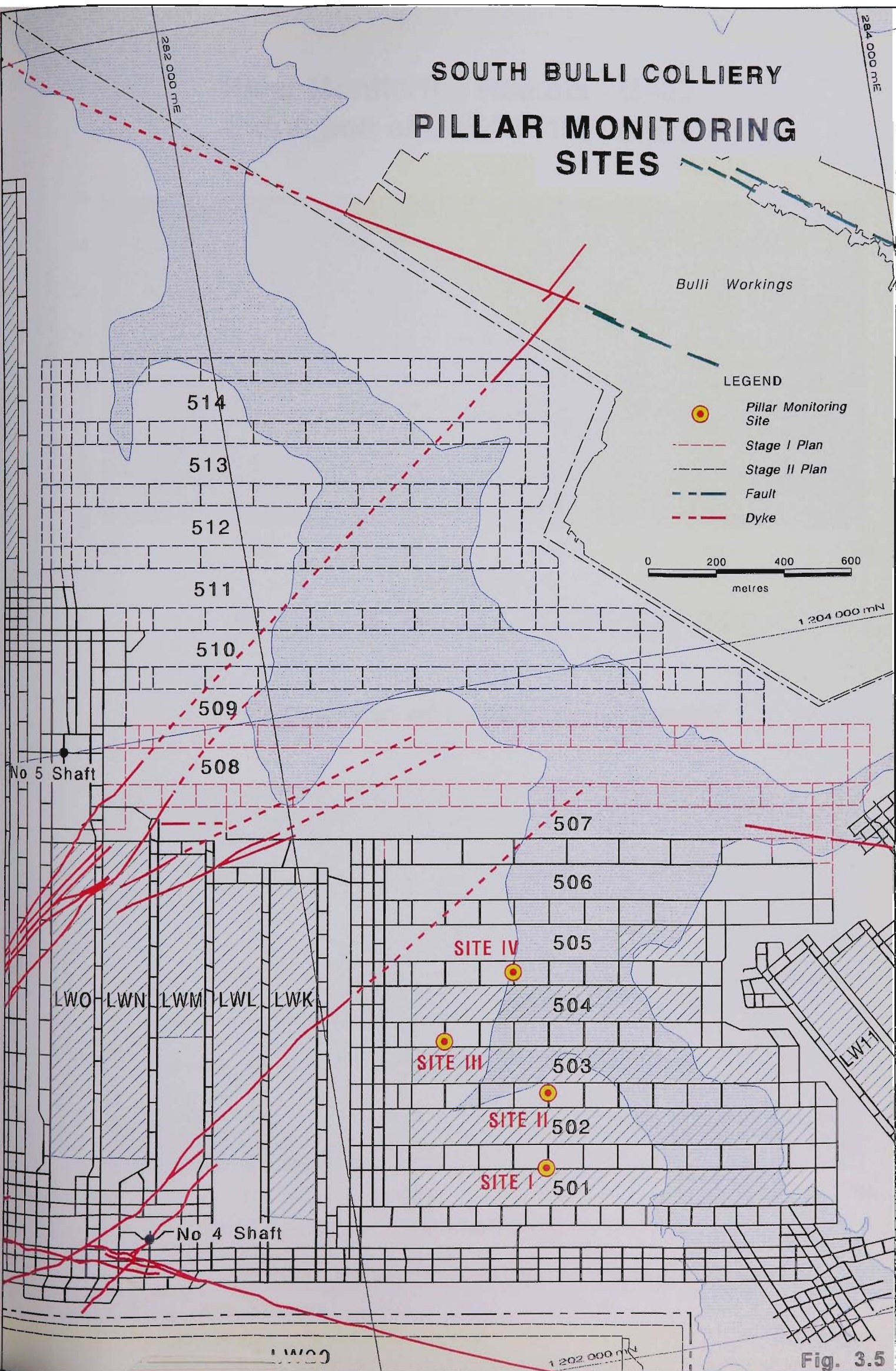
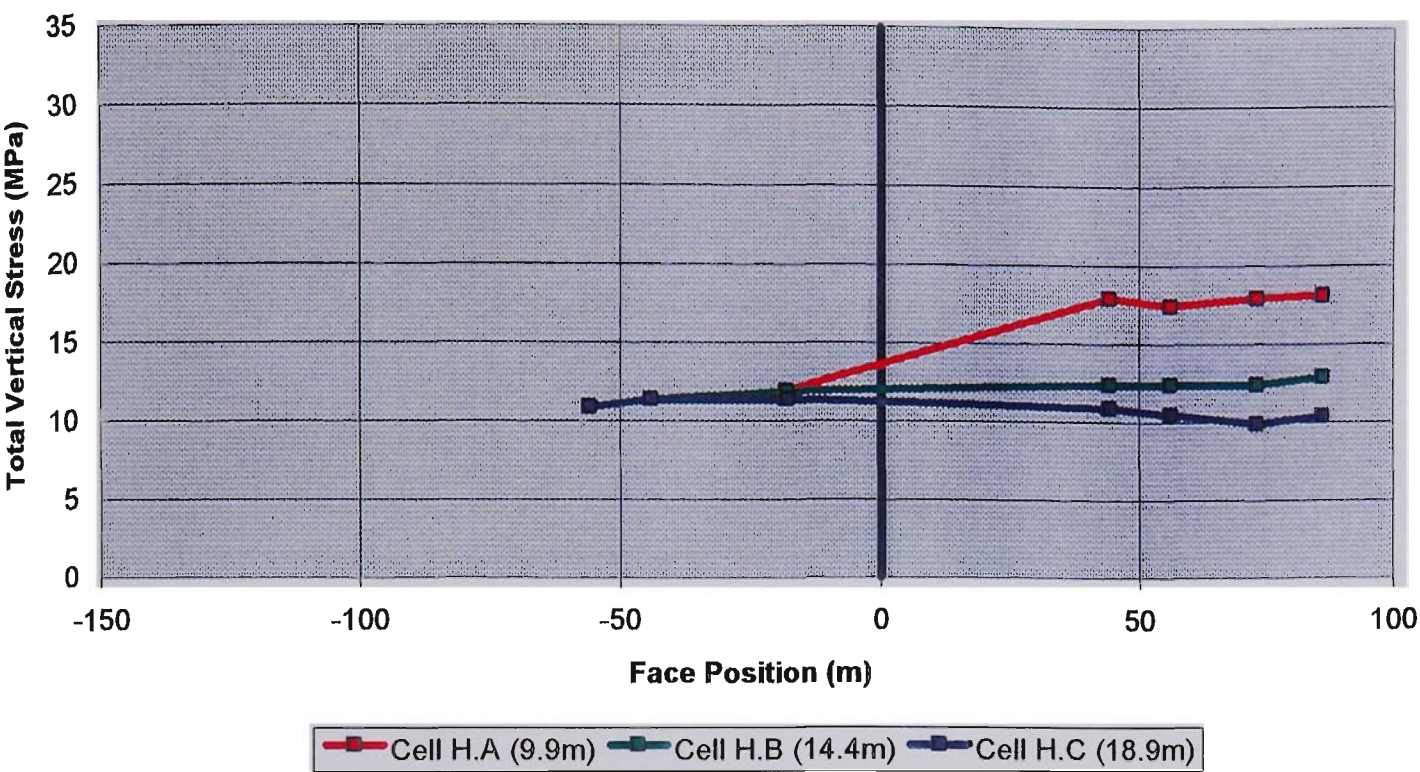


Fig. 3.5

Pillar Monitoring Results - G503

Extraction of LW503 (1st Panel)



Extraction of LW504 (2nd Panel)

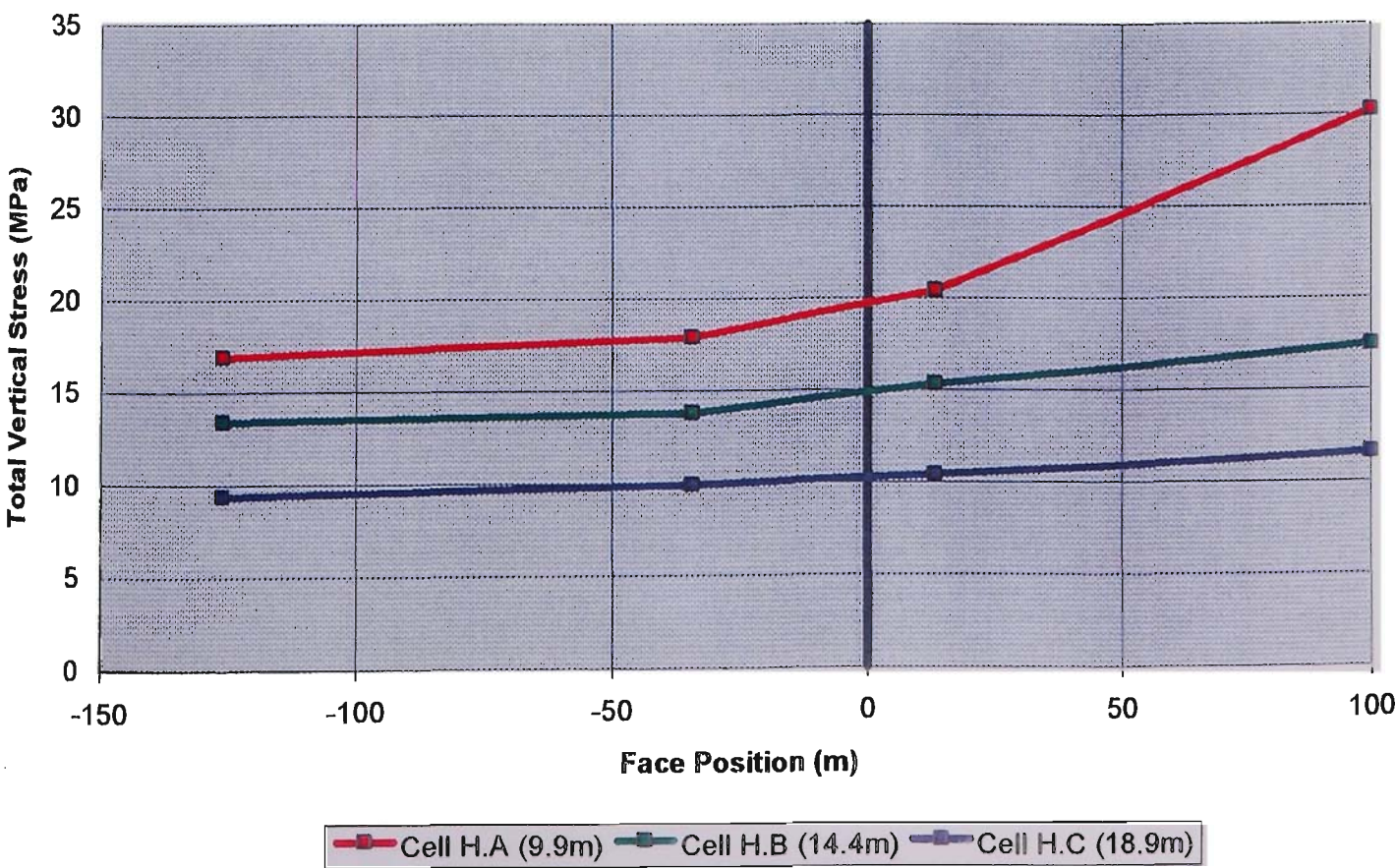


Fig. 3.6

The data represents the stress change produced in a chain pillar by extraction of a longwall on one side of the pillar. The Figure 3.6 shows that the approaching face was detected about 40 m inbye. The majority of the stress increase had occurred by the time the longwall was 100m past the monitoring cut-through.

Cell G501 H1 located 1.5 m into the chain pillar rib, showed that the coal at this depth continued to take load up to when the longwall face was adjacent, at which point monitoring ceased as the cell meter passed into the goaf.

Figure 3.7 shows the vertical stress change versus face position during the extraction of Longwalls 503 and 504. The results include the initial stress increase from a 'second' panel for the G503 and G504 monitoring sites. Some data was lost for the G503 site during the transfer from manual readings at the cut-through, to remote monitoring outbye. This time period is shown as the assumed stress increase between the -30m and +10m face position (light dashed lines). The indicated increases are simply meant to show the overall stress change trends.

Readings were obtained until the second face was about 100 m outbye and the goaf severed the remote monitoring cable. The cell located 9.9 m into the rib continued to carry load, implying that the yield zone was less than this distance.

Figure 3.6 shows only the vertical stress change versus face position for the G503 chain pillar during the extraction of Longwalls 503 and 504. The results shows that the far pillar side, next to the 'first' extracted panel, increased in stress during extraction of the second panel. It also showed that the second face was detected again about 40 m inbye.

The monitored stress increases indicate that the yield zone had not progressed into the pillar past the stressmeter located 9.9 m from the rib at this stage of mining. Earlier results indicate that with the face 100 m past the instrument site, the majority of the increase in stress has occurred. This last conclusion assumes that the stresses are continuing to increase and that the peak stress had not been reached.

Figure 3.6 shows the vertical stress change versus time for the G504 chain pillar during the extraction of Longwall 504. The results show that two of the hydraulic stressmeters, H1 and H5, began to show an apparent drop in stress in comparison to stable readings from equivalent positioned Solid Inclusion cells I2 and I5. The results show that there is little overall change in stress with time once the longwall has passed the monitoring site by more than 100m. Stressmeters located towards the pillar rib showed a 1 MPa (approximately) increase over the 2 month period following the completion of the panel.

Figure 3.8 shows the vertical stress profile for the 'first' panel extracted case. The plot uses the maximum monitored stress value for each stress meter. The plot includes a

Pillar Monitoring Results Composite Loading Profile (G503/504)

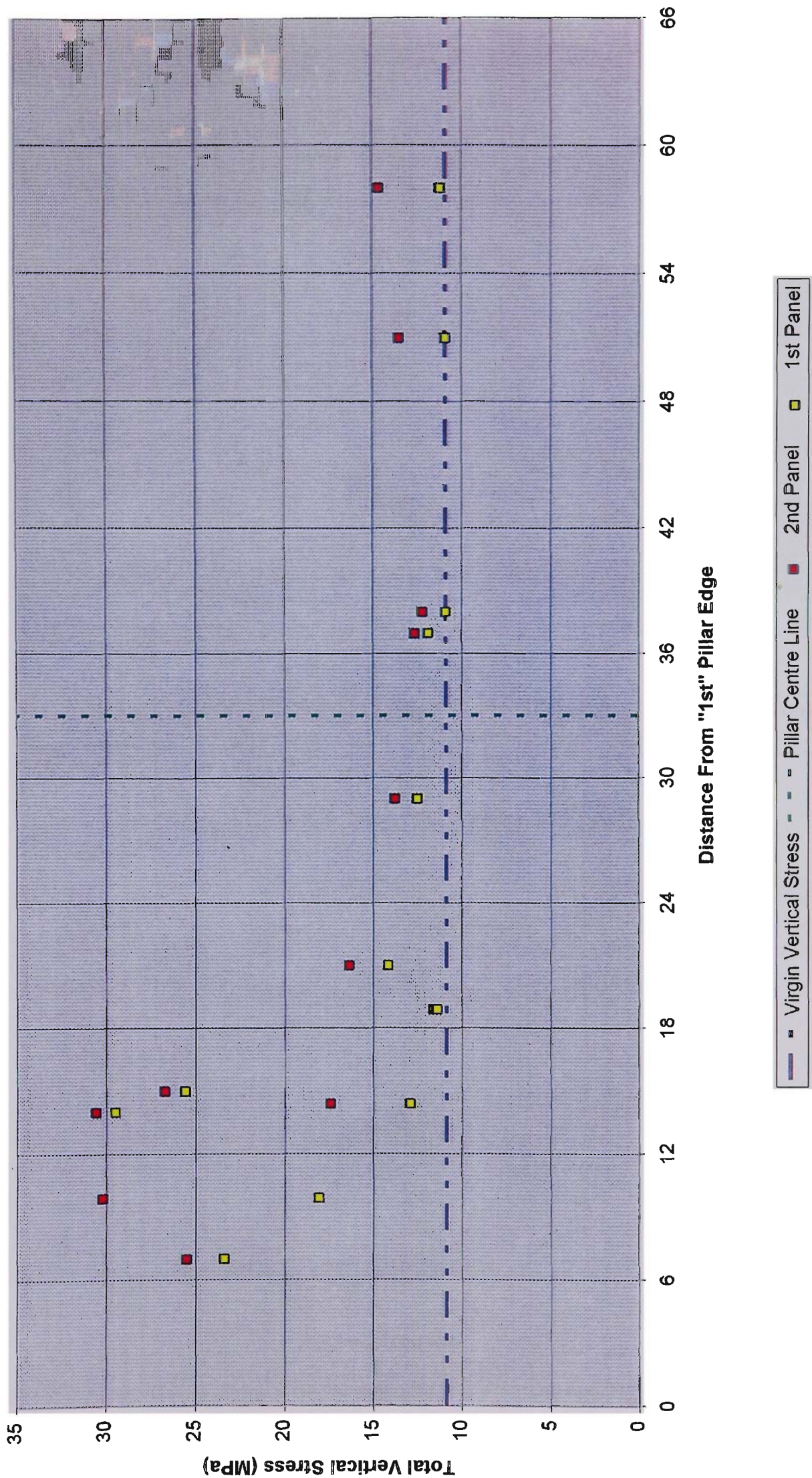
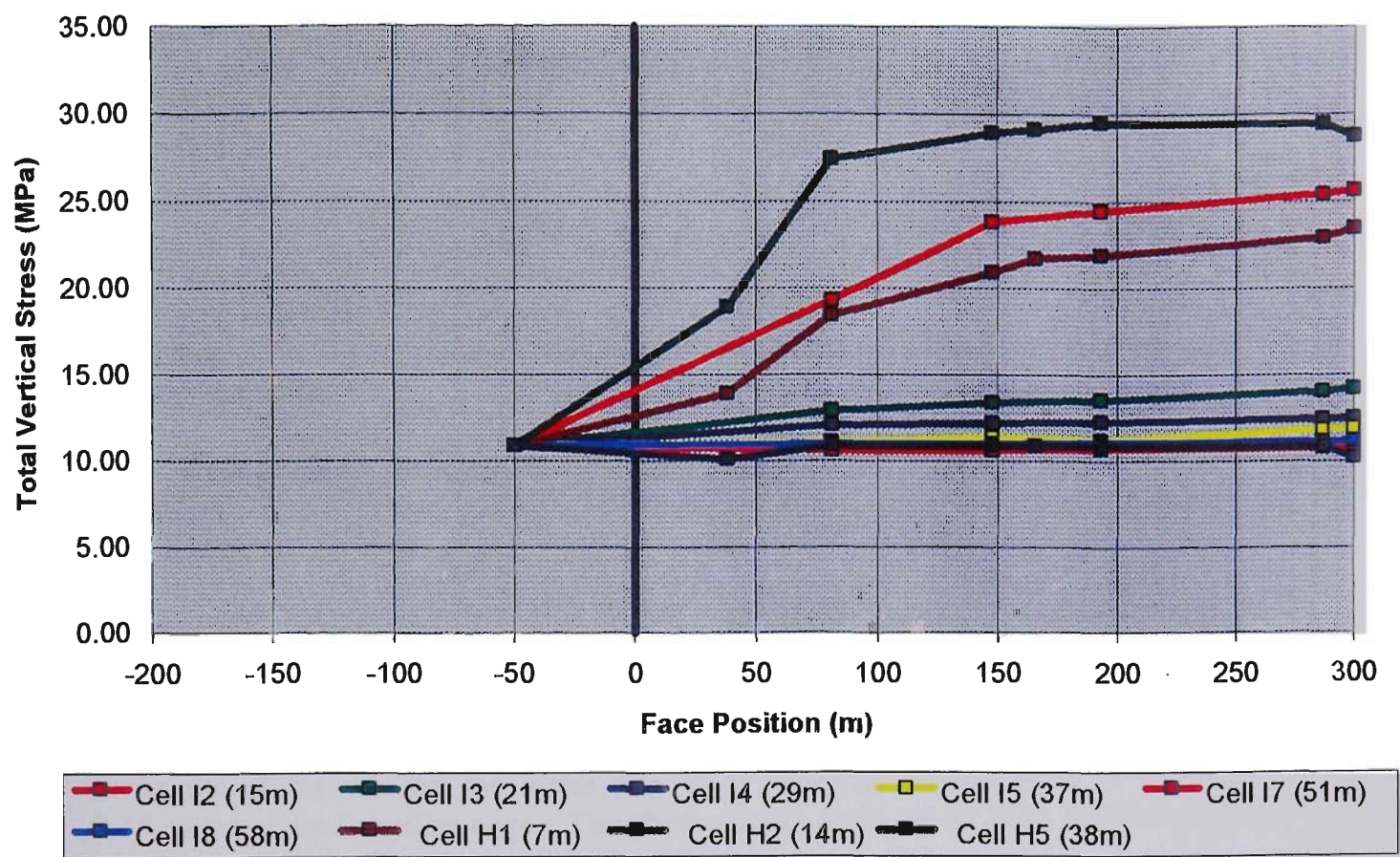


Fig. 3.8

Pillar Monitoring Results - G504

Extraction of LW504 (1st Panel)



Extraction of LW505 (2nd Panel)

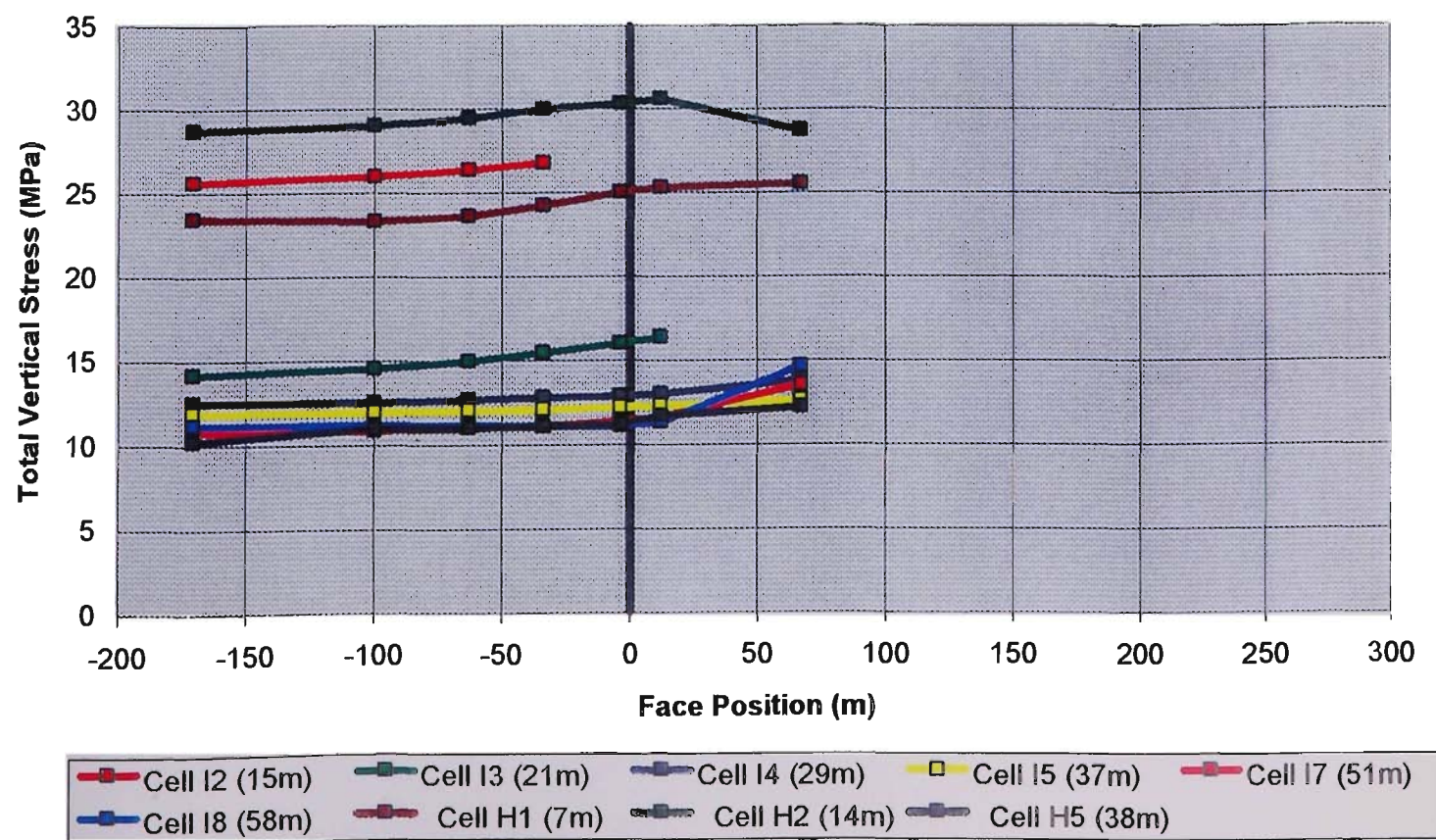


Fig. 3.7

constant vertical "initial stress" datum equivalent to 360 m cover depth to indicate approximate total pillar stress values. The plot shows that the major stress increase occurs within the first 20 m of the pillar with the core experiencing a small increase of about 1 MPa. The plot infers that a wide elastic pillar core should exist following extraction of the second longwall.

3.6 Conclusions

Background stress levels for this depth of cover are about 12 MPa and consistent with what was expected.

Stress levels in the pillar generally start increasing as the longwall abutment core approaches. This distance is about 30-40 metres and consistent with our research found in other mines in this region.

Maximum pillar stress levels are reached when the second abutment zone comes from the next longwall. This reaches a level of 30-32 MPa and appears to remain consistent after the longwall has passed the site by more than 100 m.

Across the pillars we see the stress rise to a maximum of 32 MPa in a zone 10-15 metres from the pillar edge. This then quickly drops to 16 MPa at 20 metres and 12 MPa at 33 metres which is the pillar centre.

This confirms that the layout is conservative and the pillar has a 35- 40 m core which is unloaded.

CHAPTER 4 - HYDROLOGY

4.1 Introduction

An extensive program was developed to quantify the effects on hydrology and the pressure of fracture zones caused by mining subsidences.

The programs were designed to look at two major areas:

- 1) the chemical analysis of water to determine its source location, and
- 2) the ground water pressure at different depths prior to and during the process of mining to determine the maximum height effects of subsidence and zone of crack propagation due to caving.

4.2 Mine Water

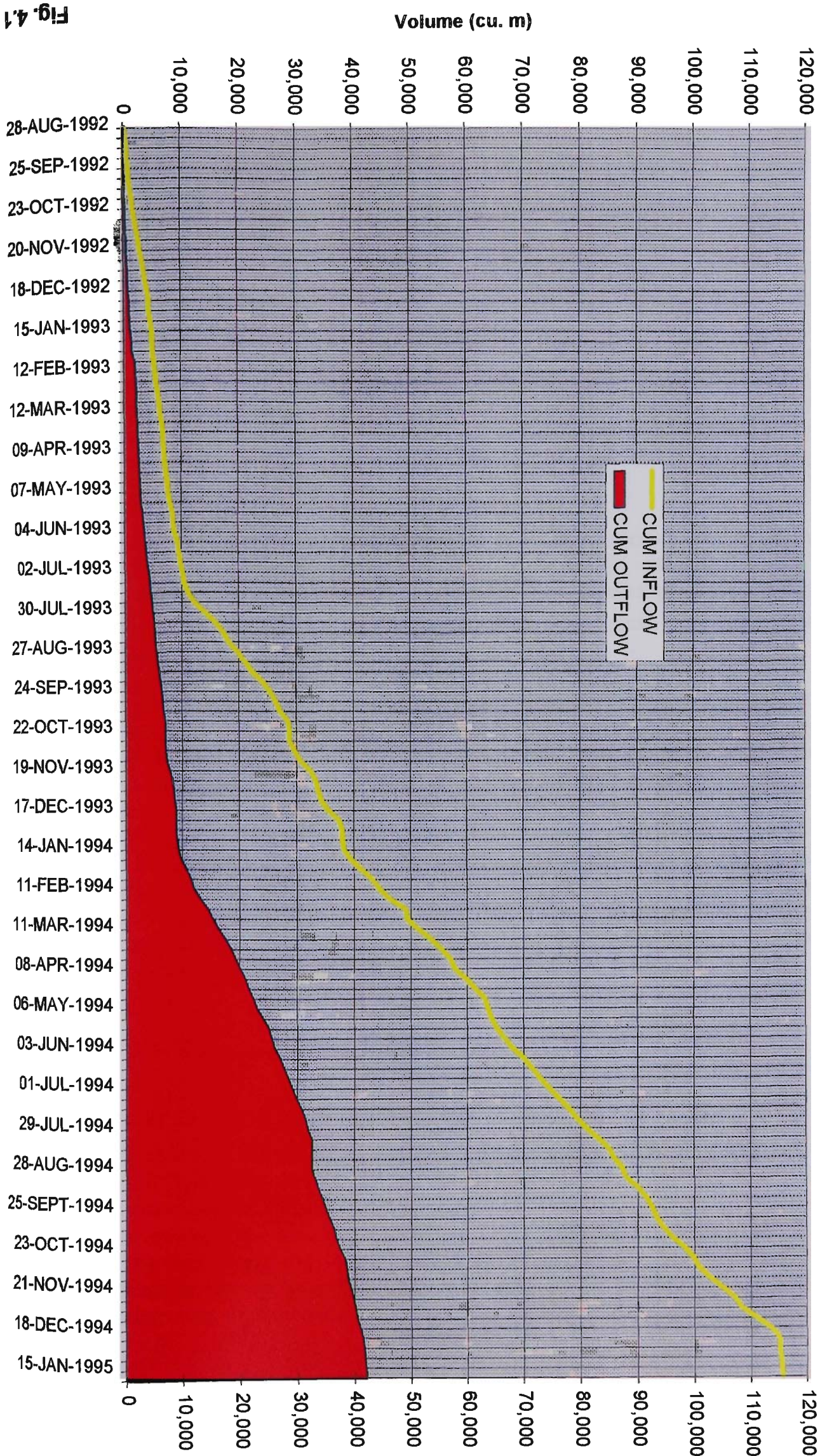
An automatic system to measure all water pumped into and out of the Cataract area was implemented for the water balance study. This system transmits the data to the surface and stores the data in a computer based in the Colliery's Control Room. The water flowrates (both in and out) are also continuously indicated on a screen in the Control Room, which is always manned while men are working underground.

Currently the quantity of water pumped out of the Cataract is approximately 38% of the water which is pumped in. The outflow consists mainly of water which has been pumped into the mine for dust suppression and other operational reasons. Water drippers in the roof, usually at longwall take-offs do contribute, but this is a negligible amount.

The difference between water inflow and water outflow can be accounted for by the escape of water from the area through other means, including an increase in the moisture of coal (from 1% to 8%) via picking up dust suppression water; an increase in the humidity of the mine atmosphere and percolation through the floor, etc.

Figure 4.1 shows the current status of cumulative water inflows and outflows. These clearly show an increase in water usage when Longwall 501 commenced in June 1993, although an increase in water pumped out from the Cataract did not occur until January 1994. This delay is thought to be due to waste water from Longwall 501 leaving the Cataract area via the O4 roadways during June to December 1993. This was not picked up by the monitoring system due to practical difficulties, however all waste water (except water leaving via the ventilation and conveyor belt systems) from Longwall 502 onwards. This implies that the rate of water leaving the Cataract area has been reasonably consistent since longwalling commenced in this area, and confirms the statement that any water coming from drippers or through the goaf is too small to measure. Water balance have been reported monthly to Dam Safety Committee.

UNDERGROUND WATER MONITORING



4.3 Ground Water

In December 1992 a ground-water programme, previously approved by the Dam Safety Committee was implemented. This consisted of a 200 mm diameter hole near the Reservoir over Longwall 501 and the installation of ten piezometers to measure the water pressure at five levels (one in the Hawkesbury Sandstone, three in the Bulgo Sandstone and one in the Scarborough Sandstone - Figure 4.3). The location of the hole is shown in Figure 4.2, and a illustrative section through the strata is shown in Figure 4.4. At the surface a datalogger was installed to record the data from the piezometers at desired time intervals. This data was periodically down-loaded onto a portable computer for later analysis.

Prior to piezometer installation, packer tests were carried out to measure the permeability of certain stratigraphic units. The results were in line with similar formations from elsewhere in the Southern Coalfield. The range of permeability values varied from 9.1×10^{-5} to 1.5×10^{-4} m/day. Both these figures were obtained from the Bulgo Sandstone.

Shortly after installation, seven of the ten piezometers monitoring at four of the levels failed. The cause of this failure is still not known for certain, but is apparently partly due to water penetrating inside the piezometers. The failure of these piezometers reduced the monitoring programme to two piezometers at the level of the Scarborough Sandstone, and one piezometer in the middle of the Bulgo Sandstone.

A complementary programme was carried out consisting of three holes over Longwall 502 in which piezometers (from a different manufacturer) were embedded in sand filters and suspended in stand-pipes (Figure 4.5). This programme was completed in mid-August 1993 after the extraction of Longwall 501 had commenced, but before the face was within 500m of the site.

4.4 Water Source Analysis and Testing

4.4.1 Water Source Analysis and Testing

The collection and testing of water entering the workings under the Cataract Dam at South Bulli Mine was carried out to ascertain the origin of this water. Through chemical analysis it was hoped to determine the source of the water and determine if it was leaking from the surface. Identifying water entering the pit was not difficult due to the dry nature of the pit as any inflow was easily noticed. This did however present difficulties because very little water was found to be entering the workings while mining under the Cataract Dam.

SOUTH BULLI COLLIERY

LOCATION OF PIEZOMETER BOREHOLES

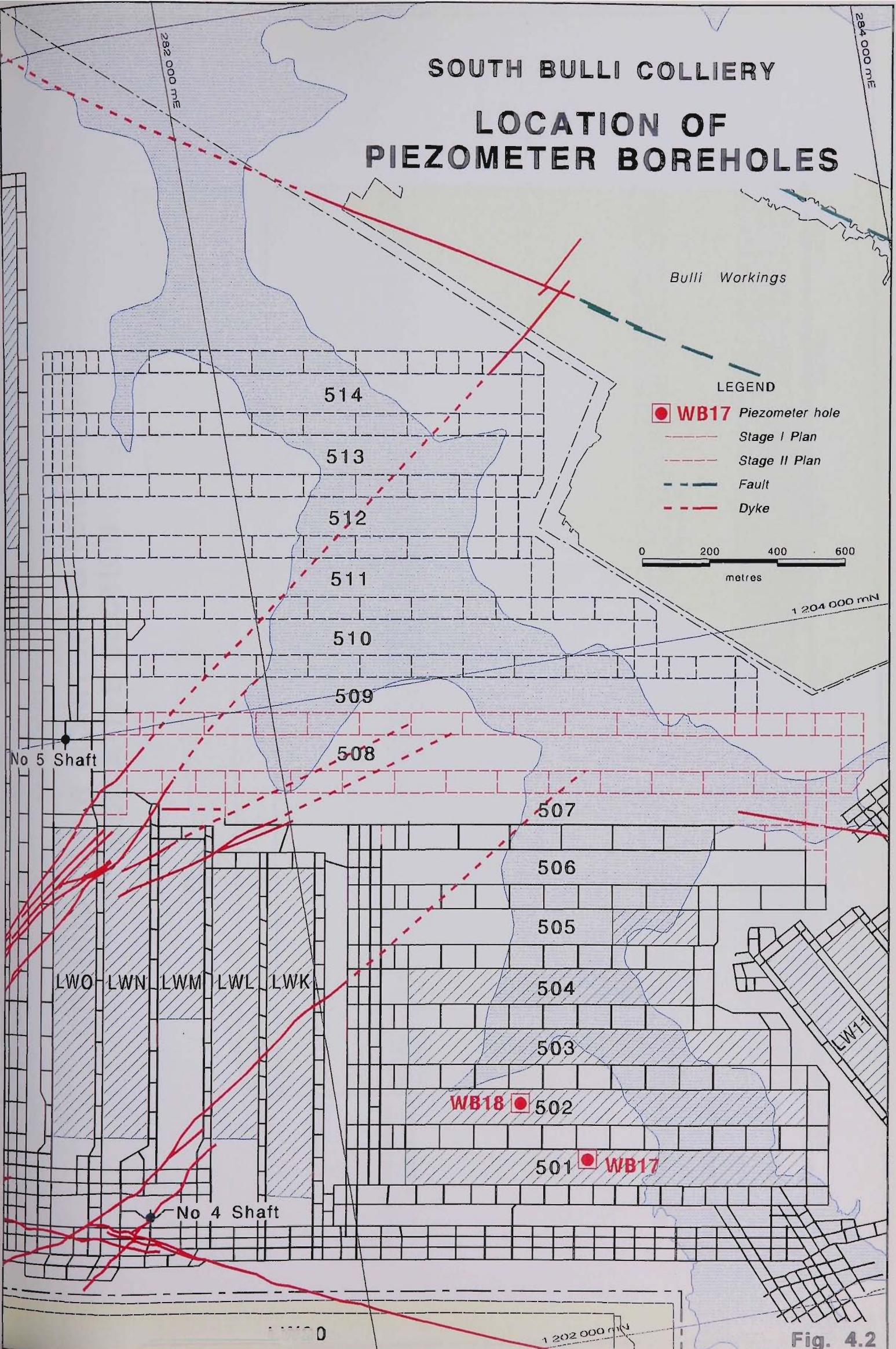


Fig. 4.2

GROUNDWATER MONITORING PROGRAMME INDICATIVE SECTION

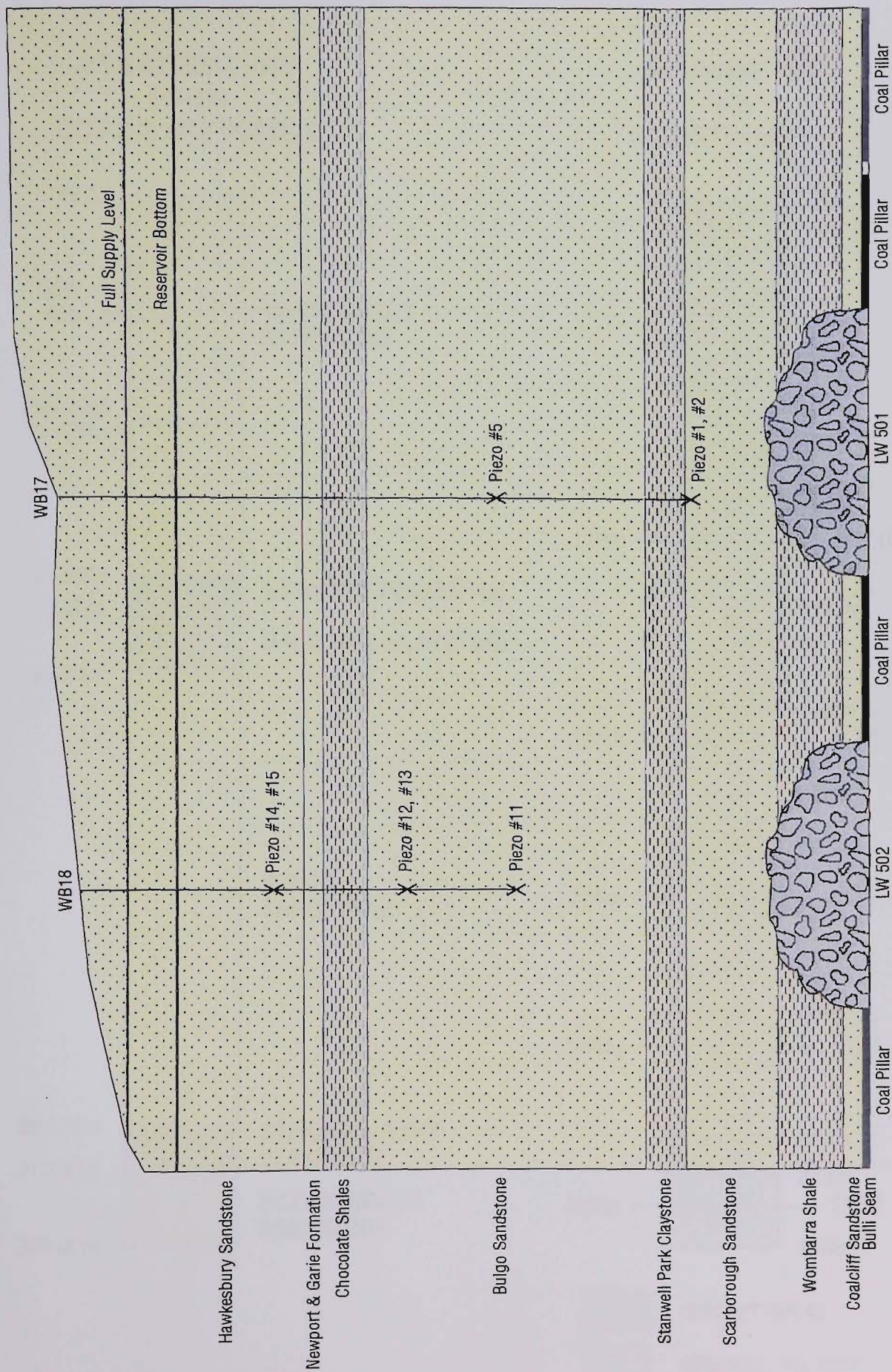


Fig. 4.3

LW501 PIEZOMETER BOREHOLE CONSTRUCTION

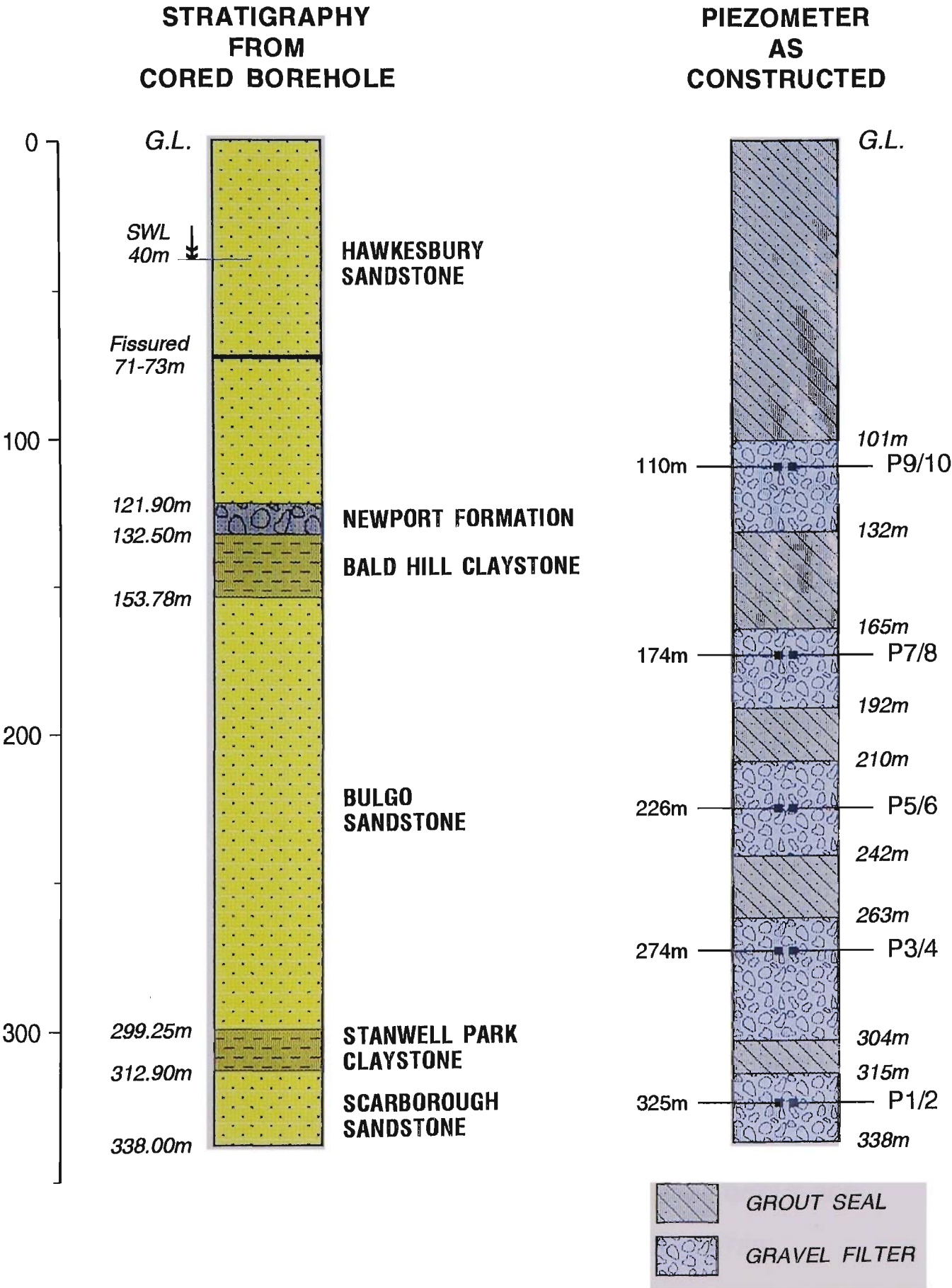


Fig. 4.4

LW502 PIEZOMETER BOREHOLE CONSTRUCTION

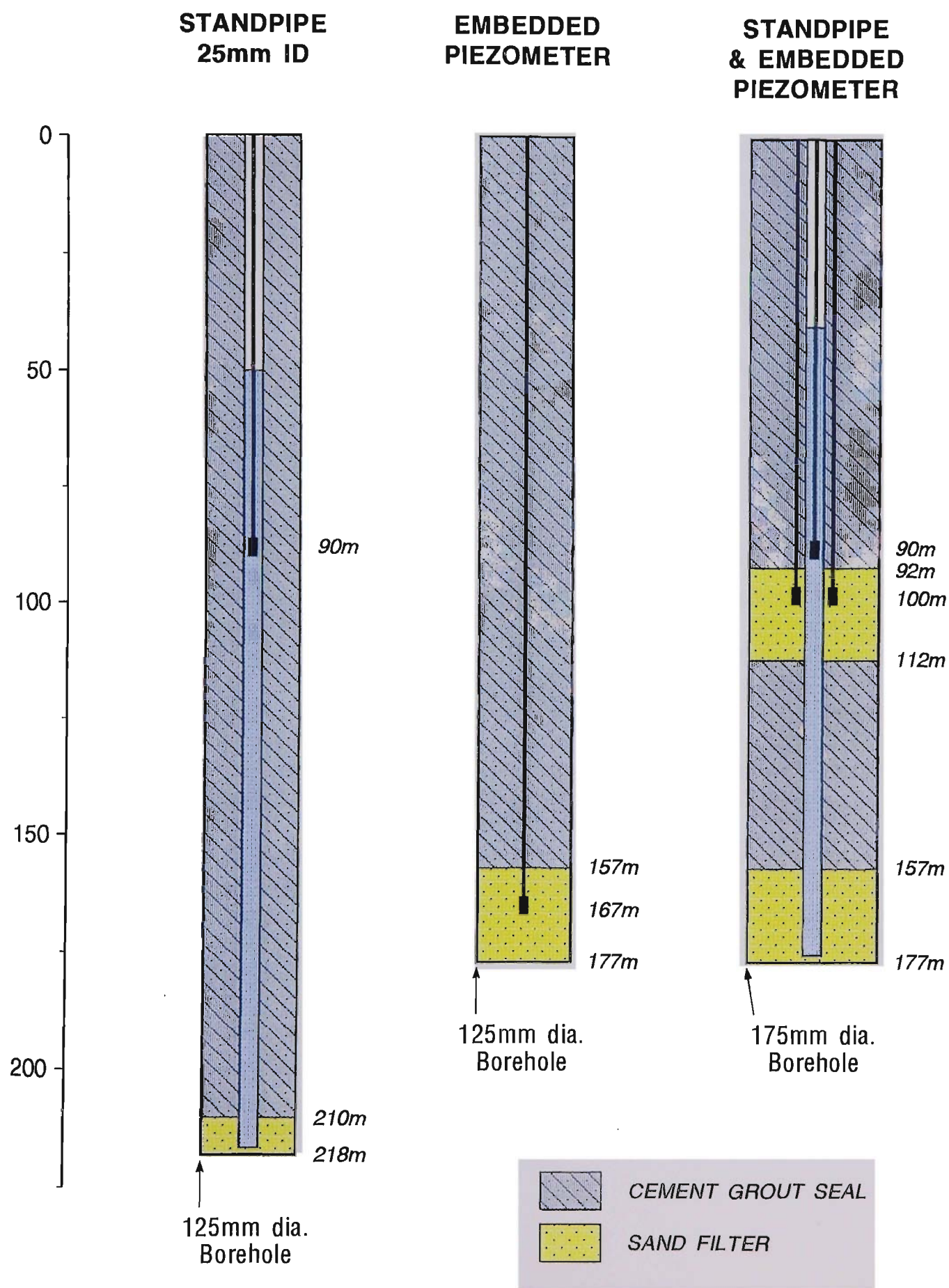


Fig. 4.5

4.4.2 Water Collection Sites

The location of water collection was in the workings under the Cataract Dam which is the current workings of South Bulli. The roof of the development headings and recently driven cut-throughs were the major sites of water collection. The collection of water usually occurred near sites of geological features such as the dykes that are present in the Cataract North district. Water collection sites at the longwall face (maingate) were also utilised when water was noticed leaking from the roof. Figure 4.6 shows the sites of water collection.

Difficulty was encountered in establishing sites for water collection as very little water was able to be found. Deputies were consulted regularly as to whether water was present in their district, but in most cases they reported that no water was seen leaking from the roof.

Other areas of the mine under the Cataract Dam were also inspected as potential sites of water collection. These areas included the roadways in R Main and Cataract North including the sites of completed longwalls. However no water was found in any of these locations. This has resulted in limited numbers of water samples available for analysis.

4.4.3 Method of Water Collection

Once a water collection site was established, a person was sent underground with one litre CASCO sample containers. Depending on the rate at which the water was dripping from the roof, the person collecting the water would either stand beneath the site and 'catch' the drips in the container or have the container tied to structure on the roof and left to collect the water. When the latter method was used, adequate protection was placed around the container to ensure that dust and dirt did not enter the container and contaminate the sample. The sample would be set up in the day and left overnight to collect the water and brought up with the shift the next day.

Once the water had been collected, the collection site and the date were recorded. The samples were then sent to CASCO in Wollongong where the composition of the water was analysed for specific constituents. The water samples were refrigerated and transported as soon as possible to CASCO to ensure that the water was not contaminated and the composition not effected.

4.4.4 Analysis of Water Samples

There was an instance where the water samples collected underground were analysed but the analysis did not include testing for carbonates. It was later established that the composition of carbonates in the water was necessary and so these results are incomplete and unable to be used in the final analysis.

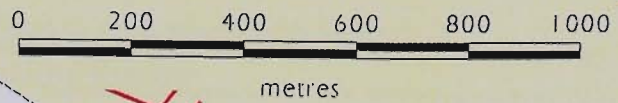


bellambi

BELLAMBI COLLIERIES PTY. LTD.

SOUTH BULLI COLLIERY UNDERGROUND WATER CHARACTERISATION PROGRAM

Scale 1 : 15 000



WATER SAMPLING SITES

● Sample points

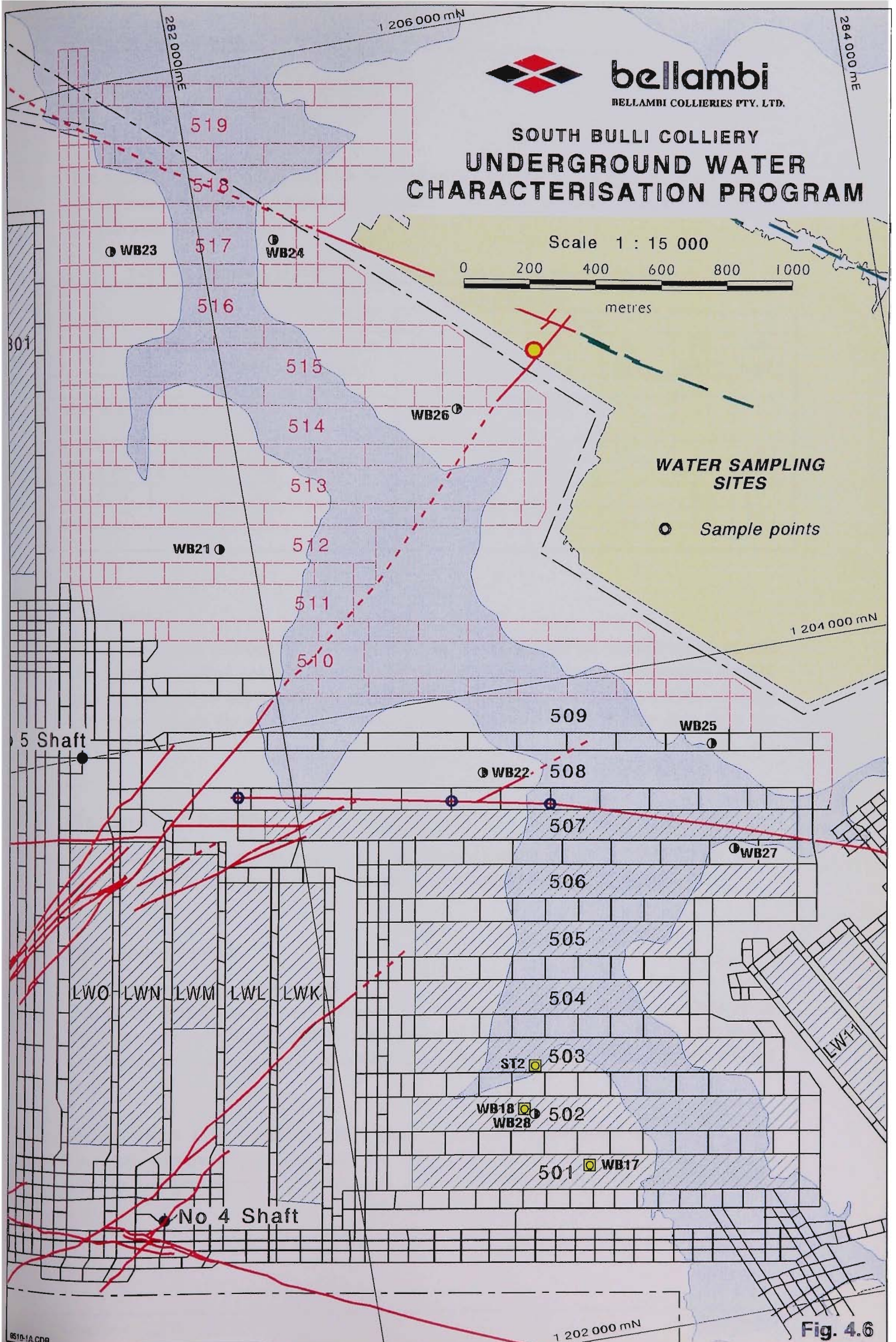


Fig. 4.6

The samples that were analysed are detailed in the Table 4.1. Analysis involved testing for various non-metal and metal components. The location and chemical composition of each sample is provided.

Table 4.1 - Analysis of Underground Water Sample from South Bulli Colliery

Location	Date Sampled	Analysis Results							
				Metals					
		Chloride (mg/L)	Sulphate (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)
G507 7CT Dyke	12.9.95	58	6	9	6	1700	10	< 0.1	< 0.1
G507 3 CT	6.10.95	60	4	8	7	1640	8	0.1	< 0.1
G507 3 CT	6.10.95	65	4	10	7	1580	7	< 0.1	< 0.1
G507 9 CT	7.10.95	69	245	6	7	1370	9	0.3	< 0.1
G507 9 CT	7.10.95	65	233	6	7	1320	8	0.2	< 0.1

4.4.5 Conclusion

As no consistent sources of roof water can be found around the extraction areas, the conclusions reached are that the method of operation and design parameters are not causing damage to any overlying aquifer which expresses itself into the mine. Taking the water balance figures as well, there is no evidence of major aquifer entry into the caved areas.

4.5 Piezometer Results

The results from the pre-mining period and during the extraction of the first four panels are shown in Figures 4.7 - 4.10 and are described below:

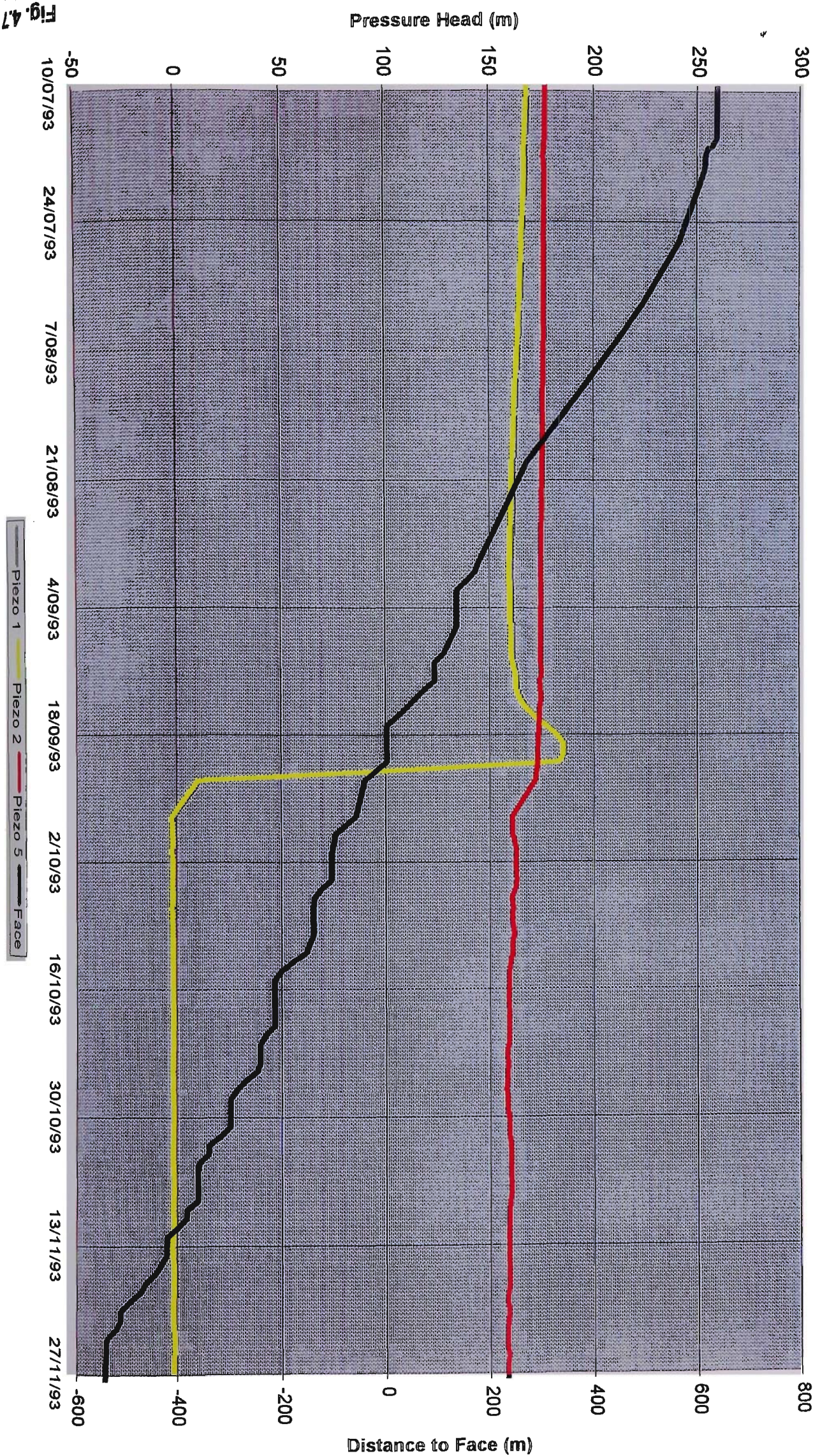
4.5.1 Pre-mining Period

(a) Longwall 501 Piezometers

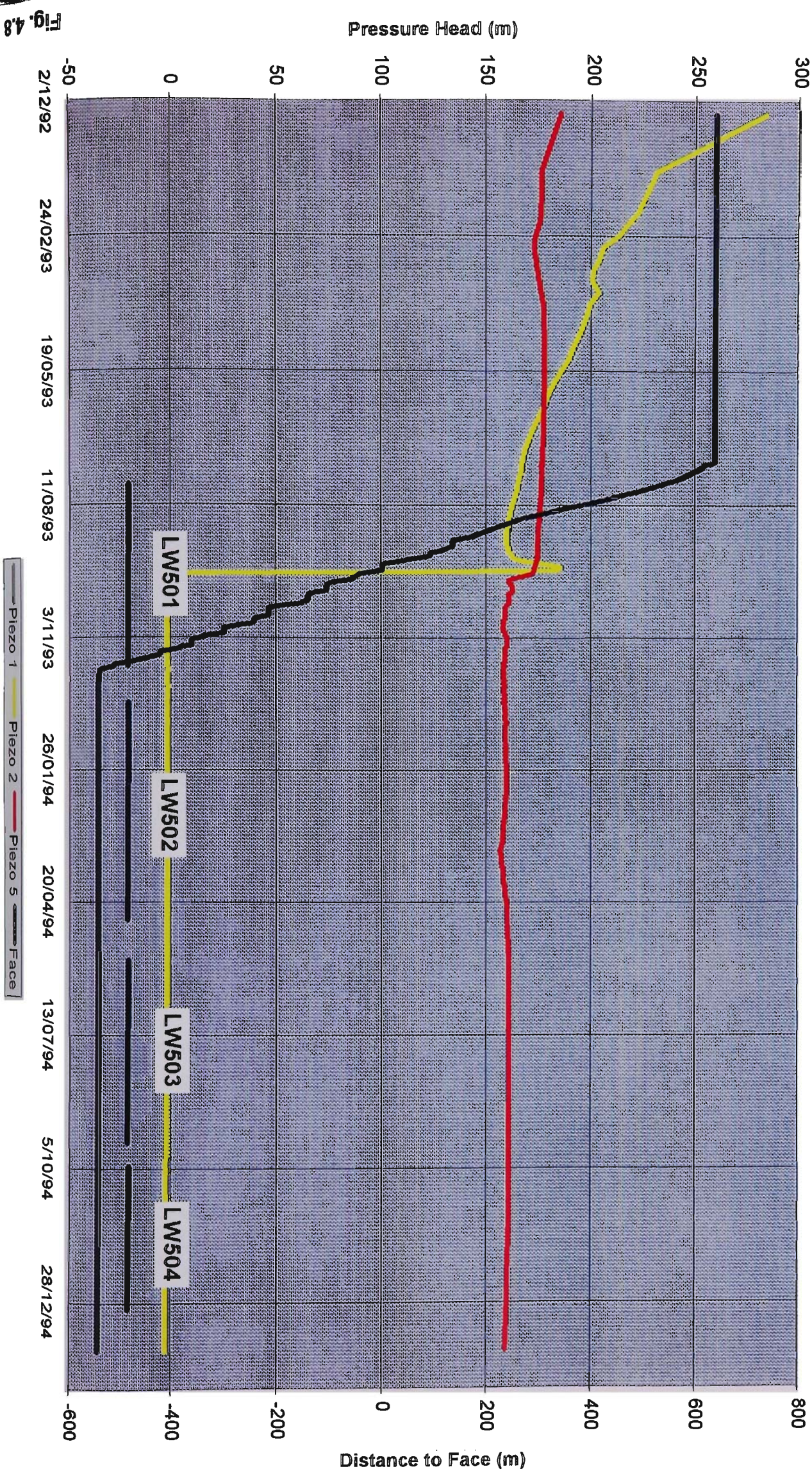
During the installation process a higher than typical hydraulic pressure was induced in the borehole environment, due to the density of the grout used to seal the borehole. This period was therefore a time during which the local pressure régime re-established itself.

The pressures at the piezometers located 185m above the seam (mid-Bulgo unit) stabilised quickly, suggesting that the difference between the installation hydraulic pressure and groundwater pressure was very small. Stabilisation for the piezometers

LW501 Groundwater Monitoring : During LW501 Extraction



LW501 Groundwater Monitoring : During LW501-504 Extraction



85 m above the Bulli Seam (Scarborough Sandstone) took almost the entire period from installation until Longwall 501 undermined the area. In addition the pressure at the Scarborough level was significantly lower than the mid-Bulgo level. This is likely to be due to one or a combination of:-

- The Stanwell Park Claystone (between the Scarborough and Bulgo Sandstones) having a very low vertical permeability.
- The disturbance of Scarborough Sandstone by earlier mining in the Bulli Seam operations.
- Different recharge areas at the surface outcrops.
- The existence of the anticline/syncline system.

4.5.2 During Longwall 501 Extraction

(a) Longwall 501 Piezometers

Just prior to undermining the borehole/piezometer nest, the Scarborough piezometer indicated a rapid increase in the pressure head of up to 30 m. This rapid rise in pressure is attributed to the compression of the strata immediately ahead of the longwall face. After the passage of the longwall the pressure of both piezometers dropped to zero and has remained at this value ever since, continuing to give a signal when interrogated by the readout box. This behaviour suggests the propagation of the vertical fractures occurred rapidly up to or some distance above this level (85 m above the seam floor). In addition, the differential bed separation above this level has been insufficient to damage the electrical connection.

The water pressure in the middle of the Bulgo Sandstone remained stable until the face undermined the borehole after which a slight drop (11m) in water pressure head was recorded. This implies that at 185 m above seam a relaxation of confining/pore pressure occurred.

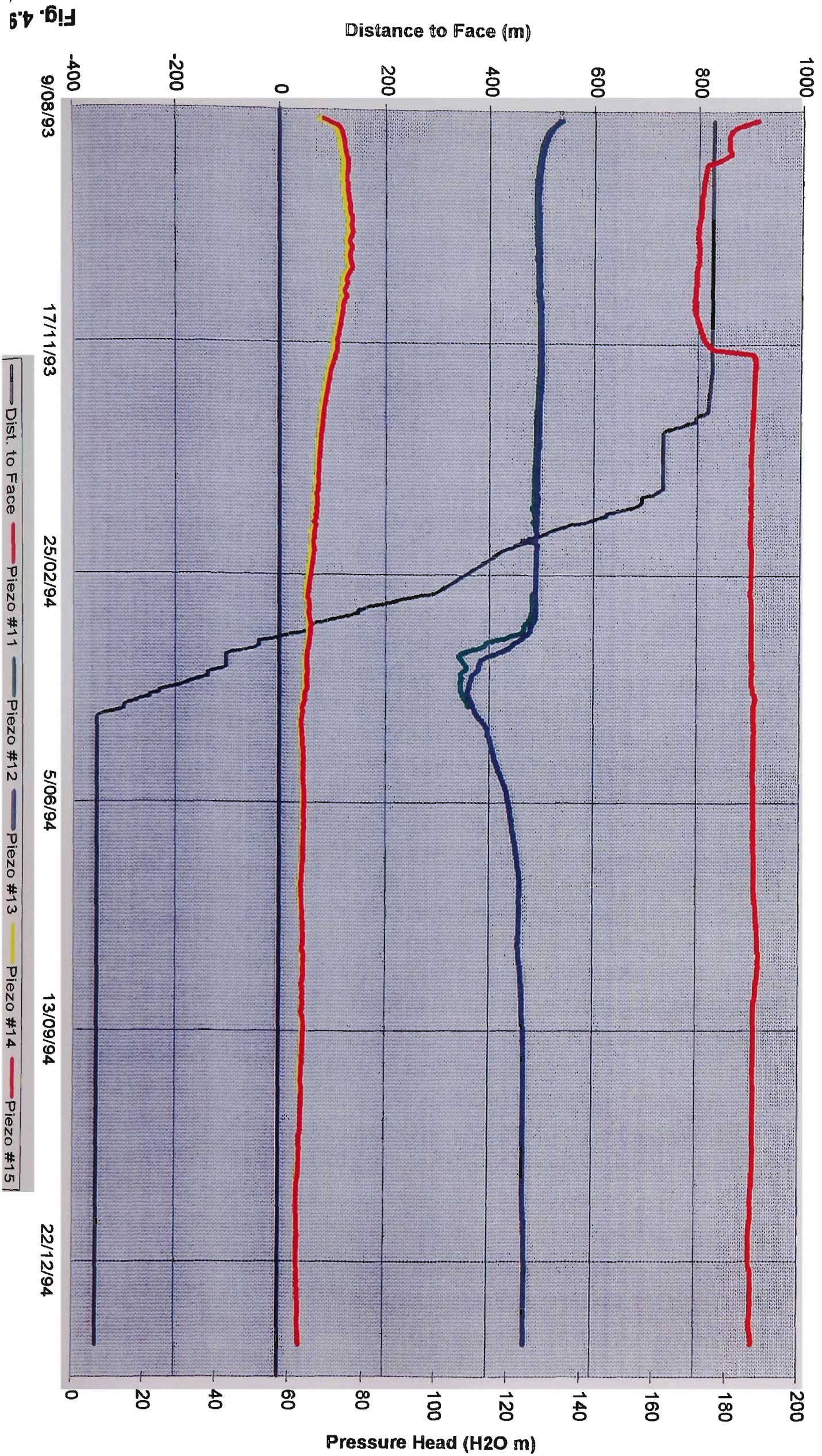
(b) Longwall 502 Piezometers

(Refer to Figure 4.9)

The piezometer located 185 m above the seam in a standpipe experienced a small pressure reduction when the Longwall 501 faceline was at its closest to the 502 borehole, while the other piezometers showed no clear link with the mining operations. There was a slight rise and subsequent gradual drop in pressure in the Hawkesbury Sandstone, however this cannot be attributed to the mining operation, but rather to climatic changes.

The piezometers in the Upper Bulgo Sandstone (240 m above the base of the seam), one embedded and one in a standpipe, did not record any measurable pressure change.

LW502 Groundwater Monitoring - During LW502 Extraction



LW502 Groundwater Monitoring : During LW501-504 Extraction

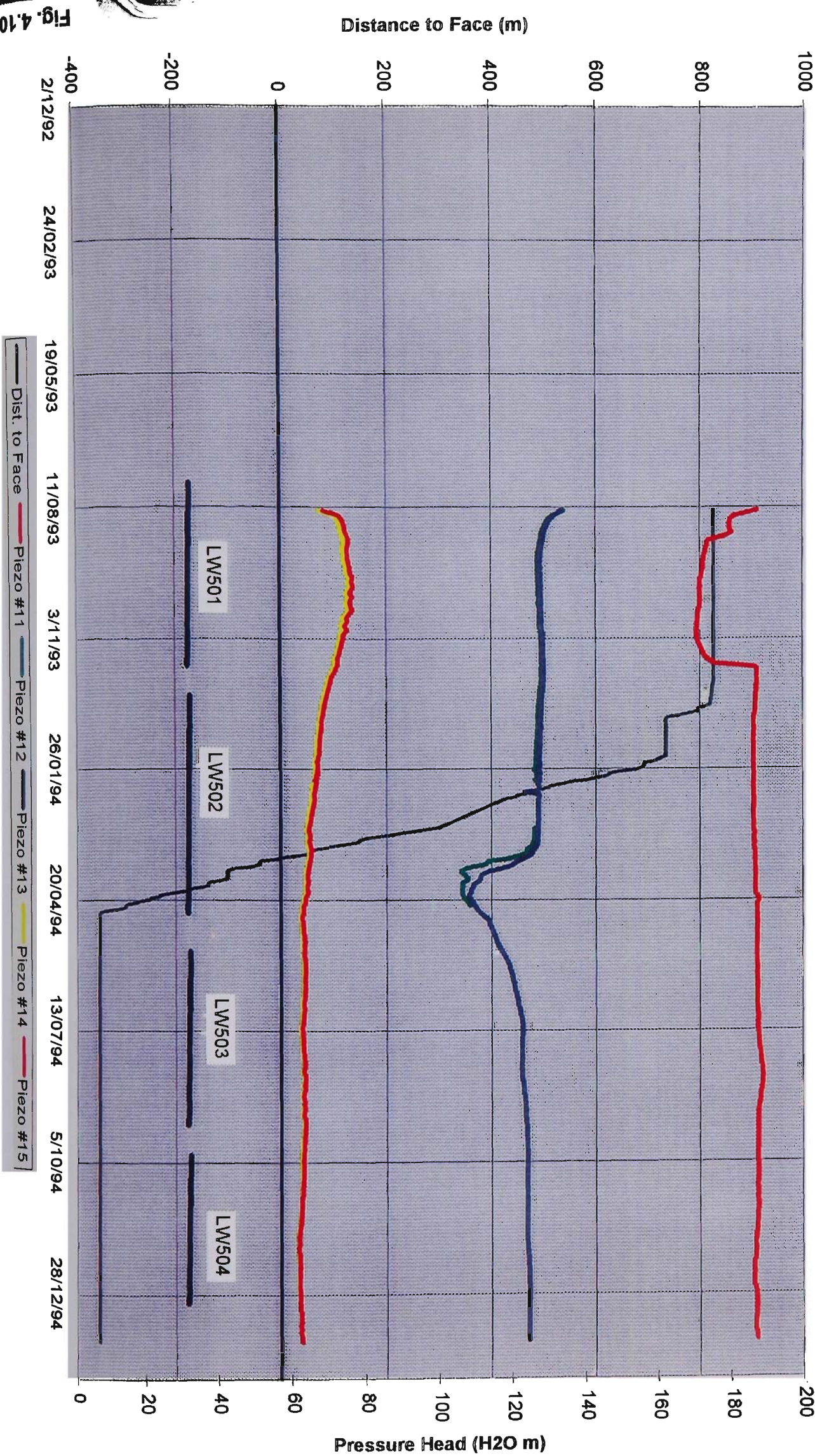


Fig. 4.10

4.5.3 During the Extraction of Longwall 502

(a) Longwall 501 Piezometers

The mid Bulgo piezometer indicated a very slight pressure increase between the end of Longwall 501 and first part of Longwall 502's extraction. As Longwall 502 faceline reached it's closest point to the 501 borehole a small decrease in pressure occurred, however this reversed as the longwall passed, and the pressure was reestablished at its "pre 502" value before Longwall 502 was complete.

(b) Longwall 502 Piezometers

The piezometer 185 m did react to the passage of Longwall 501, however the undermining of the borehole by Longwall 502 produced only a very slight, and temporary change in pressure. The difference in pressure (27 m) between this piezometer and the corresponding piezometer of Longwall 501 is due partially to the strata inclination between the boreholes, construction type (one in a standpipe compared with an embedded piezometer) and calibration of the piezometers by the manufacturer (Sinco vs. GSA).

The piezometers which are 240 m above the seam showed a 20 m pressure drop during Longwall 502 extraction. The embedded piezometer appeared to respond to strata movement more rapidly than the standpipe piezometer, however the standpipe did respond quite rapidly. Shortly after undermining, the pressure was observed to recover in both piezometers, to a level equal to its pre-undermining value. The embedded piezometer ceased to function after the recovery of the pressure head, however its intermittent operation prior to undermining indicates that the failure was not due to being undermined.

The piezometers in the Hawkesbury indicated a stabilisation of the pressure at this horizon.

4.5.4 During the Longwall 503 Extraction

(a) Longwall 501 Piezometers

There was a negligible response at the 185 m level piezometer to the passage of Longwall 503. The piezometers located 85 m above seam continued to record zero pressure.

(b) Longwall 502 Piezometers

The piezometer monitoring the 185 m level showed a small pressure drop (1.4 m) and a subsequent recovery which correlated well with the passage of Longwall 503. The Upper Bulgo piezometer (240m level) continued its trend of pressure head recovery, which commenced after Longwall 502, with no real reaction to the extraction of Longwall 503.

The Hawkesbury Sandstone piezometers did not show a noticeable change in pressure.

4.5.5 During the Longwall 504 Extraction

(a) Longwall 501 Piezometers

There was no discernible response at the 185m level piezometer to the passage of Longwall 504. The piezometers located 85m above seam continued to record zero pressure.

(b) Longwall 502 Piezometers

During the extraction of Longwall 504 all piezometer pressures varied by about 1m of head. While these variations consisted of either a slight, slow drop followed by a slight, slow rise, or vice-versa, because of the low magnitudes of the changes, it is not possible to definitely attribute them to the underground operations.

4.6 Conclusions

The result of the water monitoring programme to date confirms the assumptions about the existence of three zones between the seam and the surface. The first zone is that of caving and linked fractures. The actual caving horizon is thought to extend up to 40m or so above the seam, however this becomes a zone with a number of linked fractures, and in terms of the groundwater régime are similar. This zone extends at least 85m above the seam in the Cataract area, but does not extend up to the mid Bulgo sandstone level. It is considered that this zone of linked fractures may not extend into the Bulgo Sandstone at all.

It is not known whether the linked vertical fractures propagated through the Stanwell Park Claystone and further up into the Bulgo Sandstone. If this occurred, it would be expected that the water pressure in the Bulgo Sandstone would diminish slowly, but steadily with time. This area of the groundwater regime is of interest, and will be investigated further in the future.

The second level is that of non-linked fractures and bed separation. This covers from the mid Bulgo level (and possibly lower) up to the Upper Bulgo (and possibly higher).

In this zone there are definite changes in the groundwater pressure as a result of the strata being disturbed by mining, however there appears to be no loss of water from the strata. Differential vertical displacement is low at this level, as evidenced by the continuing electrical connection to the Scarborough piezometers.

The third level is that of flexed strata without bed separation or linked fractures, and this level has very little response to undermining. This level is thought to correspond to the monitored level in the Hawkesbury sandstone.

The confirmation of the existence of the first three zones, and an estimate of their extents suggests that strata is behaving as expected and that disturbance of the strata above the Stanwell Park Claystone is of a minor nature.

CHAPTER 5 - MINE DESIGN STAGE II EXTRACTION

5.1 Introduction

The results from the various monitoring programs and the investigations undertaken in the area of panels 509 to 514 gave confidence to propose a new panel layout which increased recovery of coal without threatening the water storage.

The proposed layout is supported by a geological appraisal of the future extraction area and a new evaluation of the predictions for the surface subsidence and system stability.

5.2 Geological Appraisal

5.2.1. Surface Geology

Elevations close to the Stage II extraction area vary between 270 m (the lowest point covered by the stored waters) and 355 m (all levels are relative to Australian Height Datum), with the full supply water level of Lake Cataract at 290 m (Figure 5.1). The thickness of the Bulli Seam overburden thus varies between 305m under the lake, and 450 m, along the western edges of development headings. The occurrence of the 300 m (approximately) depth of cover contour is restricted to the very eastern end of the Longwall 507 panel. The minimum depth of cover over the Stage II area is closer to 313 m, and this occurs slightly further from the longwall start line. This excludes a spot area over Longwall 508 which has 305 m cover depth (Figure 5.2).

Surface geological mapping has been completed and plotted on a scale of 1:2,000. The map extends beyond the 35° Angle of Draw Marginal Zone on both shores of the Cataract Reservoir, and covers the area between R Main panel in the south and the northern boundary of the South Bulli Colliery Holding along the western shore line. Along the eastern shore the study ended in the vicinity of the projected Longwall 519 panel. At this location, and in some further remote and inaccessible spots on the eastern shoreline, air photographs had to be relied on for the position of cliffs and steps.

In an area where the "exposed" cover is exclusively Hawkesbury Sandstone, surface mapping was concentrated on the morphological configuration of the terrain. Alluvium, colluvium, major joint zones and directions, continuity and physical dimensions of cliff/step lines were mapped together with available survey points (subsidence survey lines, survey triangulation points, peg numbers), surface features (eg. roads, borehole sites, mine shafts). Major lineaments picked on air photographs have also been transferred to the map, with variable degrees of accuracy (Figure 5.3 and 5.4).



BELLAMBI COLLIERIES PTY. LTD.

SOUTH BULLI COLLIERY - CATARACT DISTRICT
STRUCTURE CONTOURS OF BASE OF BULLI SEAM

-METRES BELOW SEA LEVEL-
(CONTOUR INTERVAL 10 M)

DRAWN : B. AGARWAL

SCALE : 1 : 10000

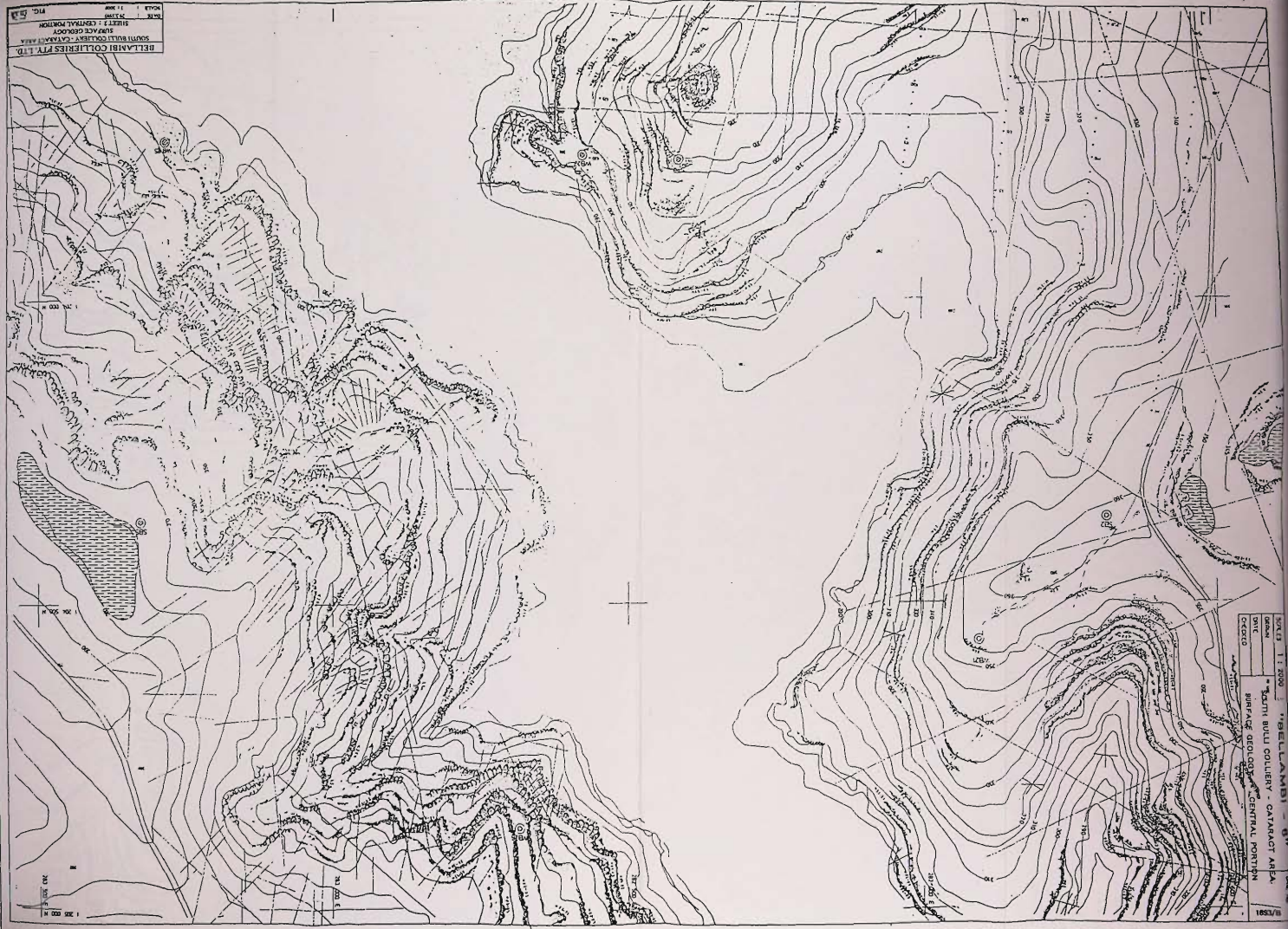
DATE : 25-Jun-1996

REVISED :

CHECKED :

PLAN No. Pg. 15

SCALE 1:500
 "BELLAMBI" - 3"
 SOUTH BULL COLLIERY - CATACT AREA
 BRITAIN GEOLOGICAL SURVEY
 SHEET 2 - CENTRAL PORTION
 1855/1

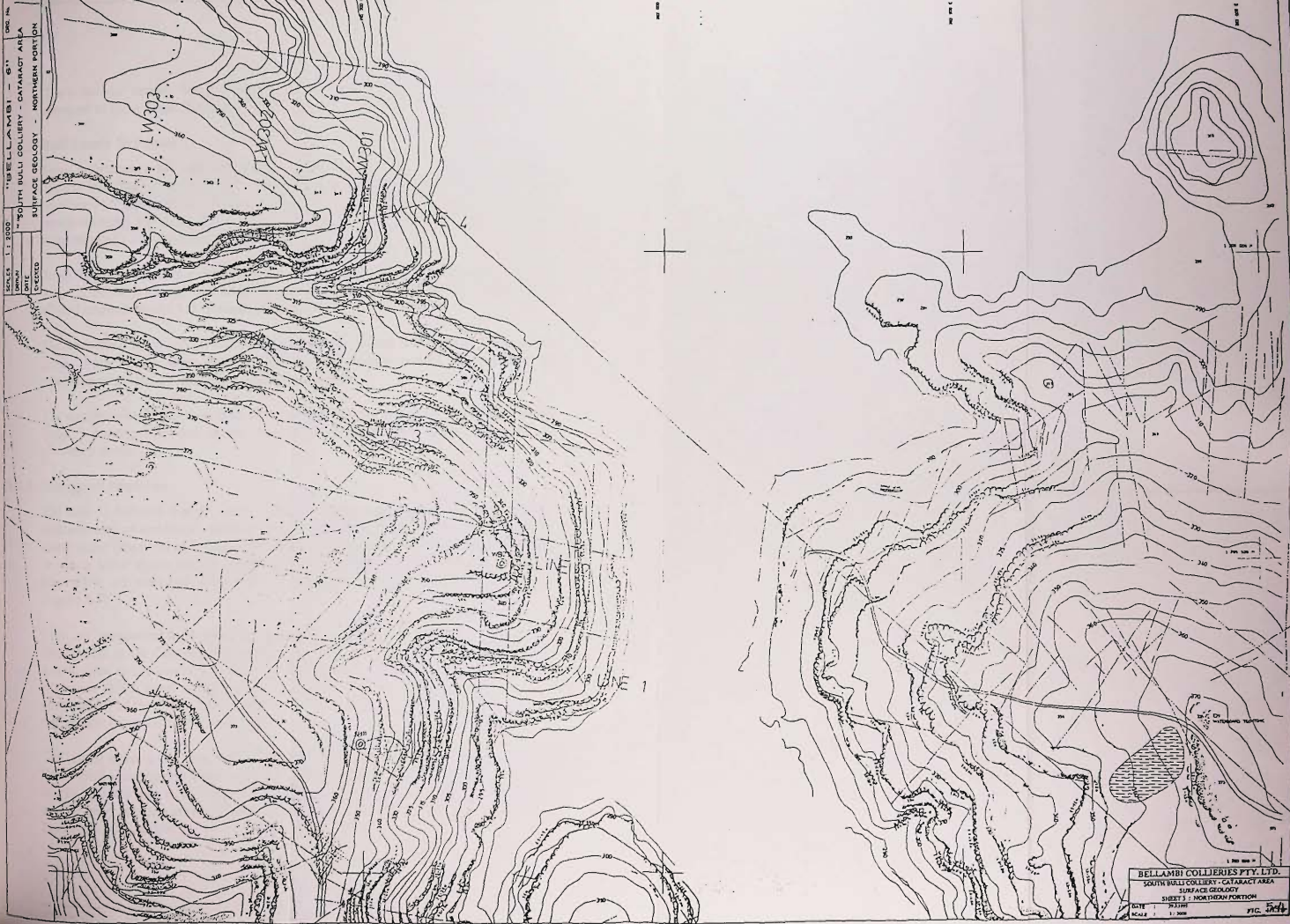


SCALE 1:500
 "BELLAMBI" - 3"
 SOUTH BULL COLLIERY - CATACT AREA
 BRITAIN GEOLOGICAL SURVEY
 SHEET 2 - CENTRAL PORTION
 1855/1

SCALE 1:5000
DATE
CHECKED
BY

BELLAMBI - 6"
SOUTH BULLI COLLIERY - CATARACT AREA
SURFACE GEOLOGY - NORTHERN PORTION

0/181



BELLAMBI COLLIERIES PTY. LTD.
SOUTH BULLI COLLIERY - CATARACT AREA
SURFACE GEOLOGY
SHEET 1 - NORTHERN PORTION
DATE 1/1/1966
SCALE 1:5000
PTC 54/6

There are no known faults in the extracted South Bulli/Bulli workings that are expected to cross Stage II Cataract panels.

5.2.2 Bulli Seam Structure

Seam inclination, previously thought to be fairly regular, with an average gradient of slightly less than 3° towards the southwest, appears to have some relatively steep portions (4.5°) interrupted by flatter areas (1.5°), as seam levels in recently drilled boreholes along the shore line were up to 9 m from their predicted positions, with no suggestion of a discontinuity (Figure 5.5).

Seam thickness is likely to vary between 2.45 m and 2.65 m in the southern part of Stage II extraction area, with some thicker or thinner patches. Further thinning will affect Longwall blocks 515 onwards (Figure 5.6).

The immediate seam roof is expected to be similar to that in the Stage I Extraction Area, being mainly shale with laminite patches, locally eroded and replaced by sandstone channels representing a palaeo river system.

The composition of the seam floor is better known now than prior to the start of the Stage I development, due to the data obtained by the floor drilling program, as presented above.

5.2.3 Structural Features

The area is believed free of major faulting. Small-scale faulting (ie. with vertical displacements of less than 1 metre) is considered likely to exist only for short distances, along major stone-roll axes (these are compaction features rather than tectonic faults) or along some dykes (minor secondary displacements). Such features, randomly reported in old workings, are usually discontinuous, both horizontally and vertically (Figure 5.7).

Only one unexpected dyke made an appearance in the Stage I extraction area, a 0.1m thick feeder in the Cataract West heading, running close to a known dyke. Another known dyke in Longwalls K and L was intersected in Cataract North panels, but did not reach G505 panel where a strong joint system lines up with the anticipated continuation of the dyke. Only faint joints were observed in G506, and identified as the easterly extension of the same feature.

The largest dyke in the area, with a thickness of 0.9m in coal at the edge of the old South Bulli workings (Q Main panel), and expected to cut across the future longwall blocks 507-509 was recognised by the most recent in-seam seismic survey, together with an array of other dykes, all within an area situated at the western-most portion of Longwalls 507 and 508.



BELLAMBI COLLIERIES PTY. LTD.

SOUTH BULLI COLLIERY - CATARACT DISTRICT
STRUCTURE CONTOURS OF BASE OF BULLI SEAM

--METRES BELOW SEA LEVEL--
(CONTOUR INTERVAL 10 M)

DRAWN : B. AGRAH

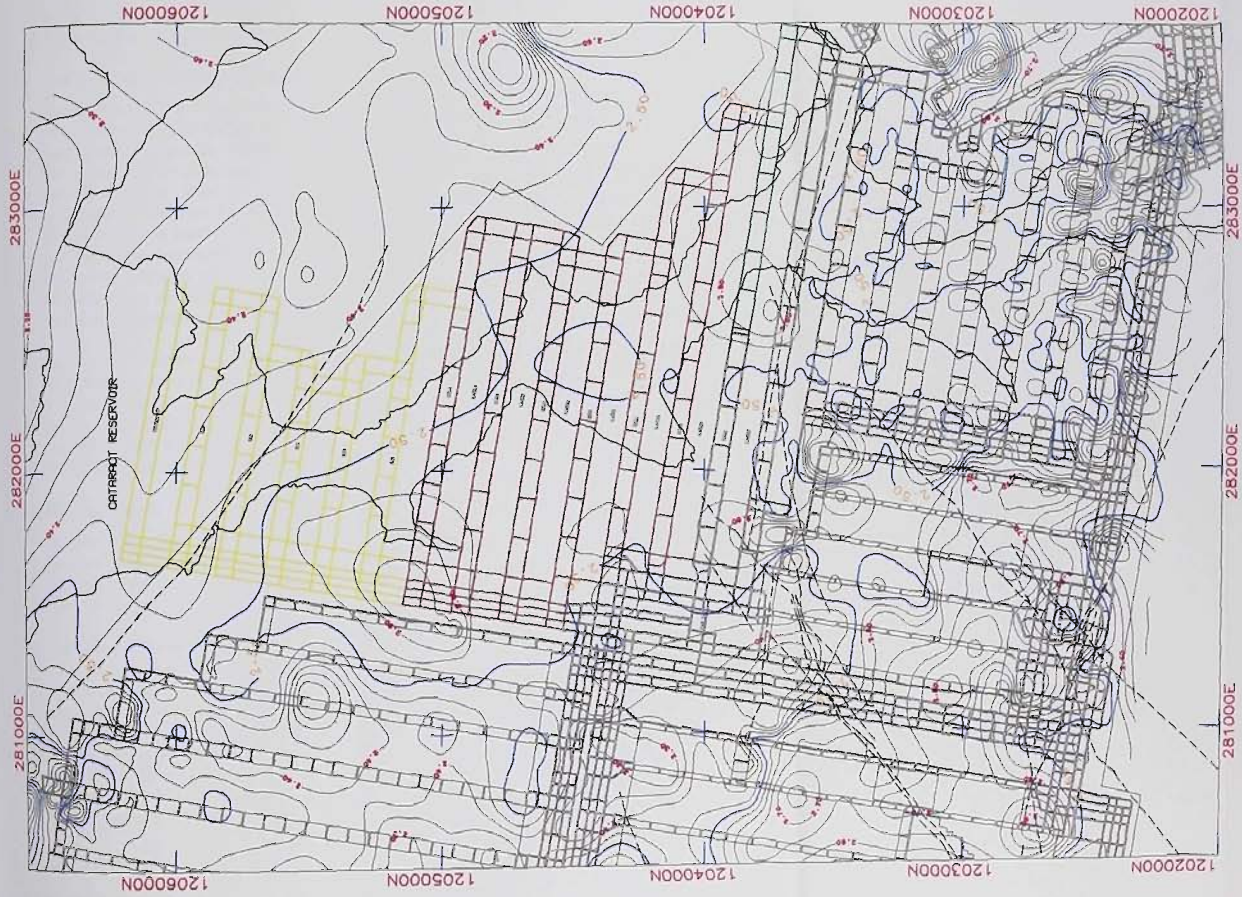
SCALE : 1 : 10000

DATE : 25-Jun-1996

REVISED :

CHECKED :

PLAN No. Pg. 15



BELLAMBI COLLIERIES PTY. LTD.

SOUTH BULLI COLLIERY - CATARACT DISTRICT

BULL SEAM ISOPACHS

-WORKING SECTION-

(CONTOUR INTERVAL 0.05 M)

DRAWER : : BAGRAU

SCALE : 1:10000

DATE : 28-JUN-1998

REVISÉ :

CHECKED : _____

PLAN No. 5.0

Major roof jointing was absent away from known dykes, and it is anticipated this will be the same in the Stage II Extraction Area.

5.2.4 Surface Expressions of Underground Features

The presence of intrusive, near vertical dykes in Bulli seam workings, likely to extend in areas underlying the Cataract Reservoir, always brings about the apprehension about their possible upward continuity which might, following longwall extraction and ensuing surface subsidence, cause a direct link between the base of the reservoir and the workings. Thus the detection of surface lineaments lining up, even broadly, with known underground features was always considered as a high priority objective. Only a very small number of such surface lineaments were positively identified in the past, and the corresponding features underground were visited by Dam Safety Committee members prior to the start of Stage I mining. All places along these features, under the lake, were found to be totally dry, but this observation could not lead to a generalisation as longwall mining had not taken place in those areas.

Field work involved in surface mapping permitted a close study of one surface lineament presumed to be the surface expression of a dyke expected to enter the lake area starting at the southeast corner of the Longwall 507. Details of observations at this site were given earlier in this report. It is the intention that whether this joint zone actually contains a dyke coming near the surface, or not, it was investigated by drilling an angled hole from a point on the shoreline.

5.2.5 Drilling Results

In order to investigate a potential feature running from the seam level to the surface in Longwall 507, an angled bore hole was drilled from the surface to intersect such a feature, if present, below the Bald Hill Claystone. Figure 5.8 shows the setout of the bore hole.

The bore hole failed to intersect any feature. It was drilled to a total depth of 310 m, with the central interval being cored for 70 m, which corresponded to approximately 20 m either side of the inferred position of the feature in a horizontal direction. Inspection of the core revealed that there were no igneous features or fracture/joint zones present in the cored interval. The hole was continued to an angled depth of 310 m but did not intersect any igneous material. Inspection of sonic logs did not indicate a fracture zone present in the hole. The hole was packer tested to determine Lugeon permeabilities, and results are shown in Figure 5.9. These did not show any high permeability zones within the tested intervals.

5.3 Mine Design

5.3.1 Extraction Method

The substantial fixed costs and overheads associated with an old mine such as South Bulli require high volume production achieved with low variable costs in a safe

manner. This can only be achieved by the extraction of the Cataract reserves utilising longwall technology.

5.3.2 Cataract Layout

The mine layout remains broadly the same for Stage I concerning the panel orientation and extraction sequence, location and number of pillars between the main headings, barrier pillar between the panels and the main headings, and pillars between the panels and old workings.

Minor alterations have been included in the Stage II mine design, and the principals behind these have already been approved as minor variations to the existing Bellambi-6 Approval. These refer to the length of the longwall chain pillars, bleeder pillar widths, splitting of the main heading barrier pillar, etc.

The proposed Stage II mining plan is shown in Figure 5.2. Important features of this plan are:-

- Longwalls extracting from east to west.
- Main headings running south-north to the west of the reservoir.
- Chain pillar widths of 60m (solid)
- Longwall goaf widths of 111.1 m and 120 m (cf current width of 110 m).

The mine plan is therefore very similar, the main difference being a slight increase in goaf width.

Table 5.1 below summarises the main features of the individual panels:-

Table 5.1 - Panel Parameters Longwalls 508 - 514

	508	509	510	511	512	513	514
Seam Thickness (m)	2.67	2.67	2.64	2.65	2.63	2.63	2.63
Minimum Cover Depth (m)	305	315	320	320	315	315	310
Maximum Cover Depth [Plateau](m)	440	450	445	445	430	410	390
Maximum Cover Depth [Reservoir](m)	385	385	380	370	360	360	360
Panel Width (m)	111.1	111.1	111.1	120	120	120	120
Pillar Width (m)	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Panel Width: Min. Cover Depth (%)	36.4	35.2	34.7	37.5	38.1	38.1	38.7
Pillar Width: Min. Cover Depth (%)	19.7	19.0	18.8	18.8	19.0	19.0	19.5

The proposed alterations, which refer only to increased panel width (the pillar widths remain the same are justified below).

Since the increase in panel width changes the subsidence factors, and to a lesser extent the pillar loading, the following justification involves new predictions for subsidence (with emphasis on tensile strain magnitudes) and the evaluation of pillar stability.

5.4 Surface Subsidence Prediction

The proposed new layout is a variation on the dimensions currently mined under the Bellambi-6 Approval and as such a different subsidence and strain profile would be expected.

The edge of the last panel of the proposed Stage II extraction (Longwall 514) is 1.8 km south of the dam wall. The prediction of surface subsidence characteristics is therefore related only to the integrity of the Reservoir. In this case the most important subsidence factor is the induced tensile strain. A sufficient increase in tensile strain can be responsible, in certain circumstances, for inducing fractures and opening pre-existing joints. The existence/formation of cracks at the surface (where the strata is unconfined in one plane) does not necessarily imply the existence of a conduit between the surface and the underground workings; the continuity of such a feature being subject to the nature of the rock layers and their position within the overburden.

All prediction methods assume that the overburden is free from structural defects. It is likely that the Stage II layout will involve mining in areas which are not free from structures. There is no accepted method of predicting subsidence affected by structures. As will be demonstrated later however, the majority of the reservoir is predicted to be in a permanent compressive strain zone, once extraction is complete, which will minimise any risk.

There are a number of prediction methods used worldwide, but those which have some potential for application are empirically derived relationships, the graphical method, numerical modelling and influence functions. Prior to 1993, only two methods of subsidence prediction had been used for the Stage I Layout :-

- The empirical method derived for the Southern Coalfield
- "MinCad" Numerical Modelling

The present design layout has applied the following four methods to calculate surface subsidence :-

- The empirical method derived for the Southern Coalfield
- "MinCad" Numerical Modelling
- CISPM (Influence Function)
- Incremental Profile Method

The Cataract extraction layout consists of narrow panels and wide chain pillars. Both of these parameters have a strong influence on the subsidence characteristics therefore the prediction methods will concentrate on these parameters for the proposed layout.

The width of the panels and pillars and other parameters, such as cover depth, extraction height and ratios are shown in Table 5.2.

Table 5.2 Panel Pillar Extraction Parameters 508 - 514

	508	509	510	511	512	513	514
Extracted Height (m)	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Minimum Cover Depth (m)	305	315	320	320	315	315	310
Average Cover Depth (m)	363	363	378	375	368	383	349
Panel Width (m)	111.1	111.1	111.1	120	120	120	120
Pillar Width (m)	60	60	60	60	60	60	60
Panel Width/Min. Cover Depth (%)	36.4	35.2	34.7	37.5	38.1	38.1	38.7
Pillar Width: Min. Cover Depth (%)	19.7	19.0	18.8	18.8	19.0	19.0	19.4
Panel Width: Average Cover Depth (%)	30.6	30.6	29.4	32.0	32.6	31.3	34.4
Pillar Width: Average Cover Depth (%)	16.5	16.5	15.9	16.0	16.3	15.7	17.2

Note: The seam thickness/cover depths above result from interpretation of the most recent drilling data (December 1994).

5.4.1 Empirical Method-Subsidence Curves for the Southern Coalfield

The present subsidence predictions are based on the 1985 guidelines for Surface Subsidence Prediction in the Southern Coalfield (Holla, 1985), which were extended in 1988 to include layout ratios similar to the Cataract. In 1988 the author examined the predictions versus actual data and concluded the discrepancy in all cases was around or within $\pm 10\%$. Subsidence results made available between 1988-1993 (Table 5.3) were examined and obtained a similar range of accuracy, except for one isolated case of $+13\%$.

Table 5.3 - Subsidence Results from South Coast Mines

Mine	Average Panel Width/ Cover Ratio (%)	Average Pillar Width/ Cover Ratio (%)	Actual Subsidence/ Mining Height (%)	Predicted Subsidence (%)	Discrepancy %
A	36	6.7	37.6	34.5	-8.2
B	44	8	34.4	34.5	0.3
C	56	9.3	34.5	39	13
D	48.9	9.6	30.9	34	10
E	48.5	9.5	31.9	33.8	6
F	42.5	8	33.4	33.5	0.3
G	43.5	7.3	39.6	36.5	-7.8

The confirmation of the empirical curves created by Holla for subsidence data since 1985, combined with interim subsidence results from Longwalls 501-504 confirm that the empirical method is a valid prediction tool for estimation of maximum subsidence.

a) Maximum Subsidence

For the prediction of maximum subsidence the graph showing subsidence as a function of the panel width to cover depth and pillar width to cover depth for critical extraction conditions is used (Figure 5.7). The pillar ratios of Stage II are different than those of the original graph (which displayed only the 4%, 8% and 16% pillar width ratios), and to overcome this careful interpolation/extrapolation was carried out.

Normal use of the prediction method uses average cover depth. The analysis performed for this Application uses the minimum cover depth, which is a conservative approach, and overestimates subsidence.

Taking into account the characteristics of the panels related to the minimum cover depth, and the empirical graph, the predictions for the subsidence are as follows:-

Table 5.4 - Predictions for Subsidence

	508	509	510	511	512	513	514
Subsidence for minimum cover (mm)	215	200	180	260	275	275	280

The above figures represent the subsidence when all panels have the same extraction geometry and depth of cover. In practice the subsidence of a panel is influenced by the subsidence of adjacent panels, and in the cases above the maximum subsidence over panels close to the Stage I panels will be less than that above due to the influence of the narrower panels/wider pillars. In addition, the subsidence along a panel is influenced by the cover depth, which changes along and across the panels.

Southern Coalfield Subsidence (After Holla, 1988)

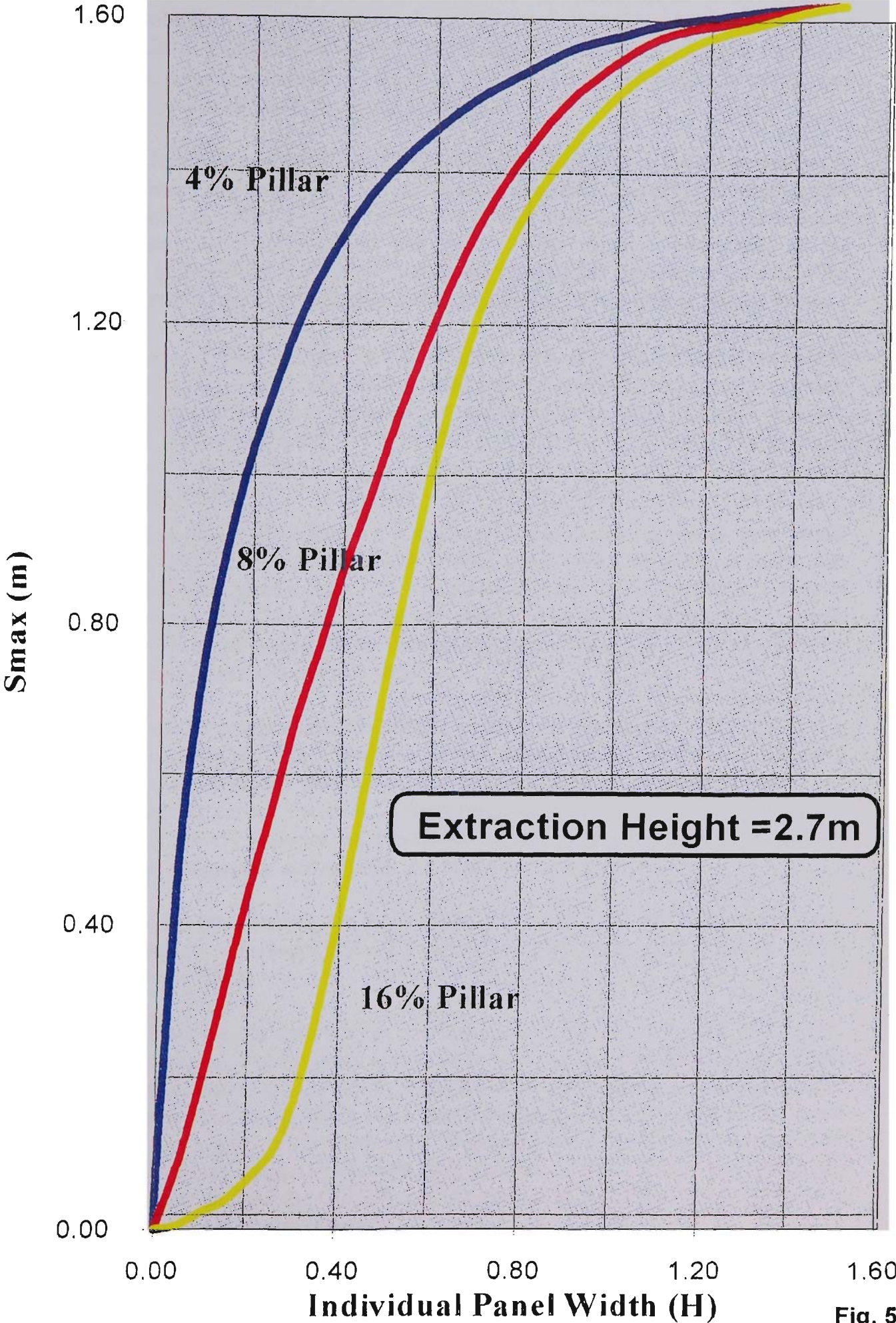


Fig. 5.7

b) Surface Horizontal Strains

The empirical method considers that the strains are proportional to the ratio of maximum subsidence to cover depth, and a factor which varies with the type of the strain (tensile or compressive) as well as the ratio of the panel width to the cover depth. The guidelines contain plots for the average values of maximum tensile and compressive strains for different panel width ratios.

Experience has indicated that it is difficult to obtain consistent strain measurements in the field. Strain is influenced by ground movements such as shrinking or swelling due to climatic effects. Measurement errors also have a large part to play in inconsistent readings, particularly when strains are small. Other factors contributing to the consistency of the results include the orientation, spacing and intensity of jointing. The lower the strain magnitude the higher is the contribution of non-mining related strains.

The conclusion of the Guidelines is that strains in Southern Coalfield are relative low, rarely exceeding 1.5 mm/m for tensile strains and 3.5 mm/m for compressive strains. However much higher values are recorded and these are related to local conditions such as cliffs, joints, faults, etc.

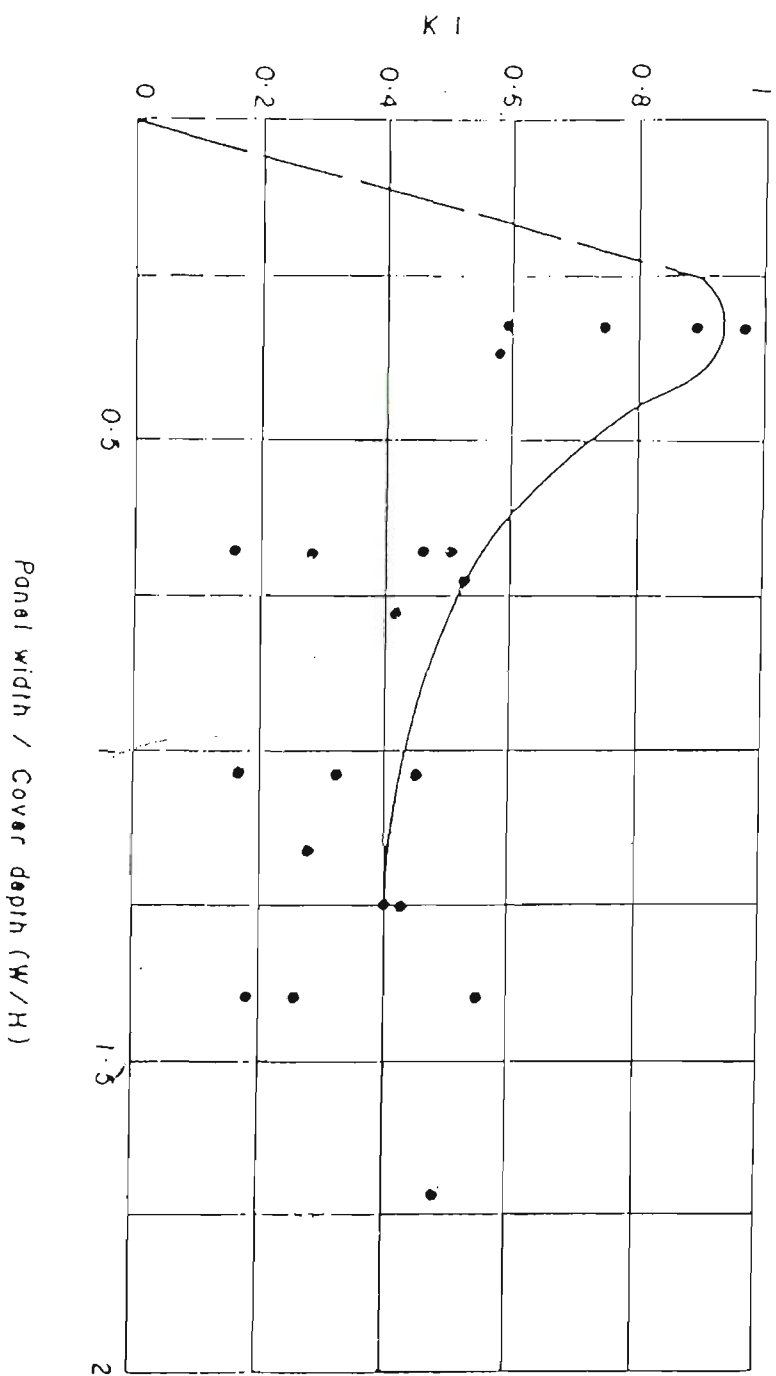
(1) Tensile Strain

The guidelines' Figure 14 (Figure 5.8 in this report) shows that the tensile strain factor is very high (0.95) for extractions with smaller panel width/cover depth ratios, and about 0.4 for ratios greater than 1.25. In practical terms, using the 300 m minimum depth of cover at the Cataract, a longwall panel 375 m wide would induce a tensile strain only 42% of the magnitude of that induced by the Stage I and II panels. Smaller panels therefore increase the tensile strain.

In the area of the graph where the smaller panel/cover depths are located there is a considerable scatter of data. Because of this scatter Bulli Colliery and Longwall 501-503 subsidence results were chosen for their similarity to the Stage II layout and plotted against the curve. The Bulli Colliery results are situated on the curve, however the Longwall 501-503 results are positioned slightly below the curve. It appears therefore that the graph is adequate for the prediction of tensile strain.

Using the curve, the tensile factor for the Stage II layout is 0.9, which in combination with the maximum subsidence defined above, gives a prediction of 0.8 mm/m for the maximum tensile strain.

As Figure 5.9 shows, the maximum tensile factor is very high for low panel width ratio. On the other hand the tensile strain is directly proportional to the maximum subsidence which in turn, at different pillar ratios, is polynomially proportional to the panel width ratio. Therefore the tensile strain has a particular behaviour depending on the panel width ratios, for a given pillar width ratio. Figure 5.10 is the result of the calculation of the tensile strain using the formula, the maximum tensile factor and maximum subsidence factor all from the Guidelines. The particularities of this graph, based on a cover depth of 380 m, are as follows:



Relationship of maximum tensile strain factor KI to W/H ratio.

TENSILE STRAINS For 380m Cover Depth

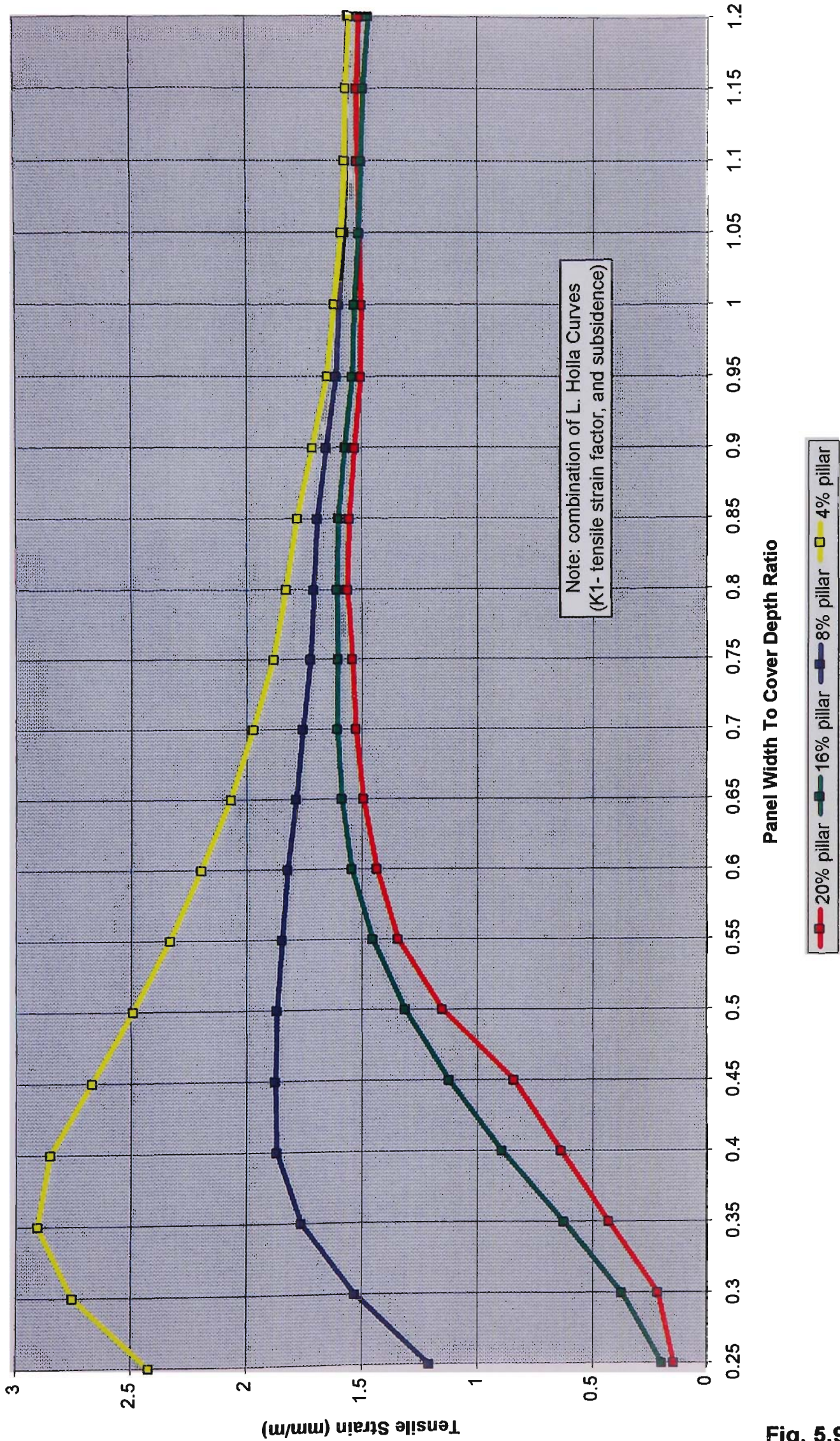


Fig. 5.9

TENSILE STRAINS For 300m Cover Depth

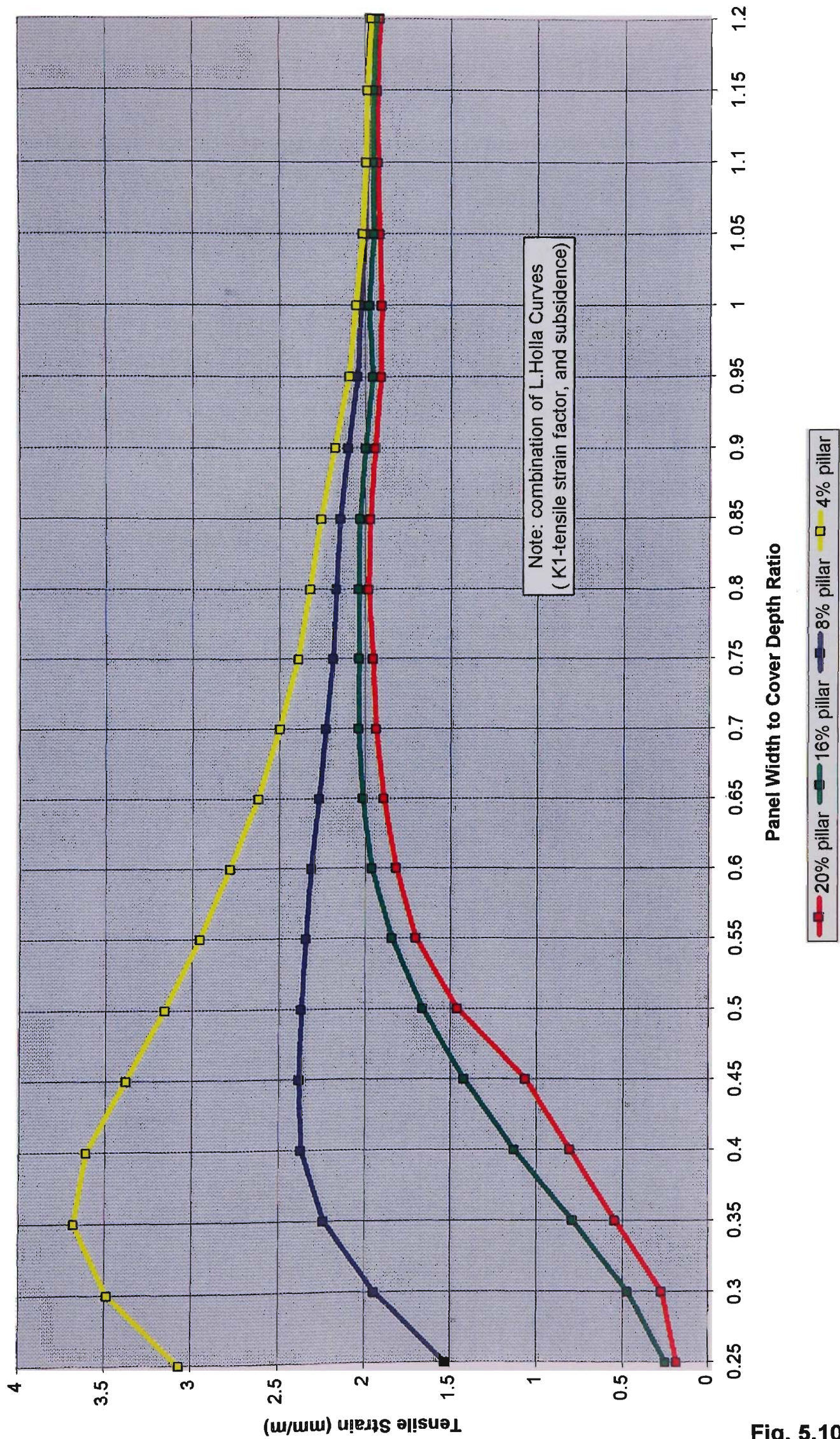


Fig. 5.10

- The tensile strain for the lower panel ratios is higher than that for very large panel ratios provided the pillar ratios are less than 8% of cover depth.
- For panels wider than the cover depth the tensile strain, irrespective of the panel ratios, is approximately 1.5 mm/m, which corresponds to the conclusions of the Guidelines.
- For pillar ratios greater than 16% of cover depth there is no "hump" of tensile strain, as in the smaller panel ratios segment. Because the pillar width-to-height ratio in the Cataract area is approximately 19%, the Cataract extraction lies outside the area of the graph where tensile strain is highly sensitive to small changes in the pillar ratios, which is a positive aspect.

Figure 5.10 presents the same tensile strain variation when the cover depth is close to the minimum cover depth of the Cataract reservoir. The conclusions are the same, except that the tensile strain for the wider panel ratios is around 2 mm/m.

(2) Compressive Strain

The graph for the compressive strain factor presented in Figure 5.11 indicates a smaller relative variation in the strain factor for smaller panel ratios, although again there is a wide scatter in the data presented.

The factor which corresponds to the Stage II layout is 1.4, which through a similar process to that for the tensile strains above, gives a predicted maximum compressive strain of 1.2 mm/m.

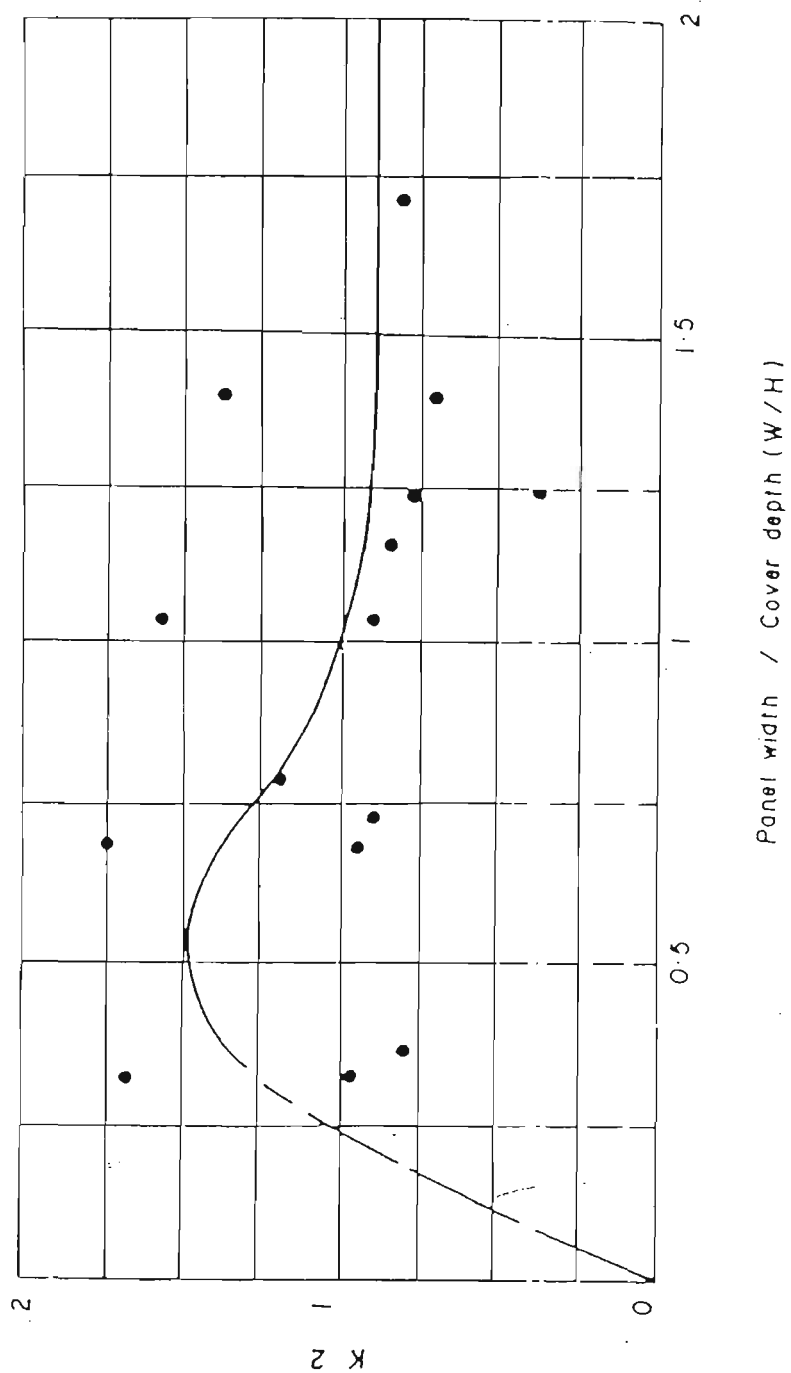
(3) Conclusions

The maximum average of predicted tensile strain induced at the surface is 0.8 mm/m, assuming that the strain is unaffected by the presence of any structures. This is very low in comparison with the tensile failure strain of the Hawkesbury Sandstone, recent geomechanical testing of which suggests a range between 3.0 mm/m and 7.0 mm/m.

The presence of any extensive structural feature may create a higher concentration of horizontal strain. Accordingly, any feature such as a fault or dyke uncovered at the surface or underground will be closely investigated.

5.4.2 Numerical Modelling

After the subsidence results from the Longwall 503 extraction were obtained and compared with the predictions from the MinCad SUBSOL model, higher confidence was given to the method, despite the omissions from the original model (ie Cordeaux longwall extraction).



Relationship of maximum compressive strain factor K_2 to W/H ratio.

It was decided to re-run the model, using a different layout to the initial run of the model. In the re-run, Longwalls 501 to 506 had 110 m goafs (as per actuals), and the chain pillars were 65m wide (compared to 66m actuals). Longwall 507 was modelled at 105m width, with all chain pillars from G507 onwards (except for G510 which was modelled with a 60 m wide pillar) having 50m solid pillars.

This layout of 120 m wide goafs and 50m wide pillars was chosen, as it was hoped that the stability of 50 m pillars would have been satisfactorily demonstrated by the present time.

The scenario is a “what if ?” hypothesis. The actual layout is more conservative than that modelled, and as such the subsidence, strains and pillar loadings are all higher than expected for the Stage II mine plan. Comparison between this models results and those from the 1992 work suggest that the proposed layout would experience subsidence close to the levels predicted by use of the Empirical Method as described above.

In order to facilitate a direct comparison with the previous work, the effects of the Cordeaux Longwalls 17-20 were not modelled. Rock properties were kept the same as in the previous model, and the depth of cover was kept constant at 330 m. Although this is slightly higher than the actual minimum depth of cover, it is believed that this will not result in an unrealistic value for the maximum subsidence.

The following table summarises the results from the three modelled layouts;-

Table 5.5 - Results from Modelled Layouts

Goaf Width (m)	Pillar Width (m)	Max. Subsidence (mm)	Max. Compressive Strain (mm/m)	Max. Tensile Strain (mm/m)
100	60	180	0.900	0.400
200	40	960	0.900	0.500
120	50	393	1.090	0.297

Figure 5.12 shows the surface subsidence along the cross line shown in Figure 5.13. The line has been staggered to accommodate the shape of the Cataract panels.

Figure 5.12 indicates transverse strains along the same line. As in previous model runs, the extracted area is entirely in compressive strain, with tensile strains only developing beyond the extraction.

5.4.3 Influence Functions (Peng., Source for proprietary use of Influence Functions)

This is a different method of modelling to that carried out by MinCad. While the MinCad work is based on the rock properties of the site, the Influence Function

Stage II MinCad Subsidence Prediction

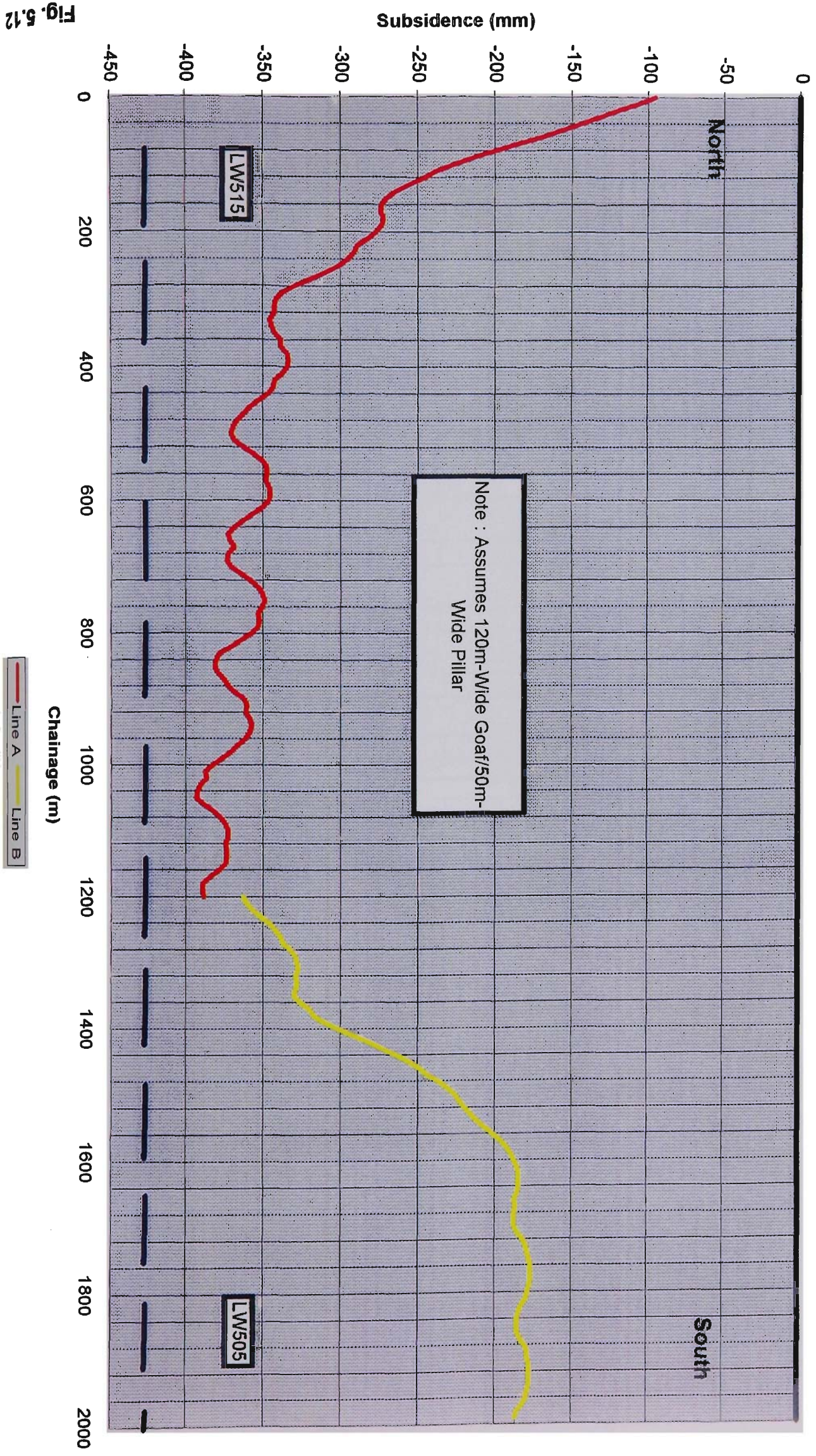


Fig. 5.12

SOUTH BULLI COLLIERY

**LOCATION OF MINCAD
SUBSIDENCE/STRAIN PREDICTION
SECTION LINE**

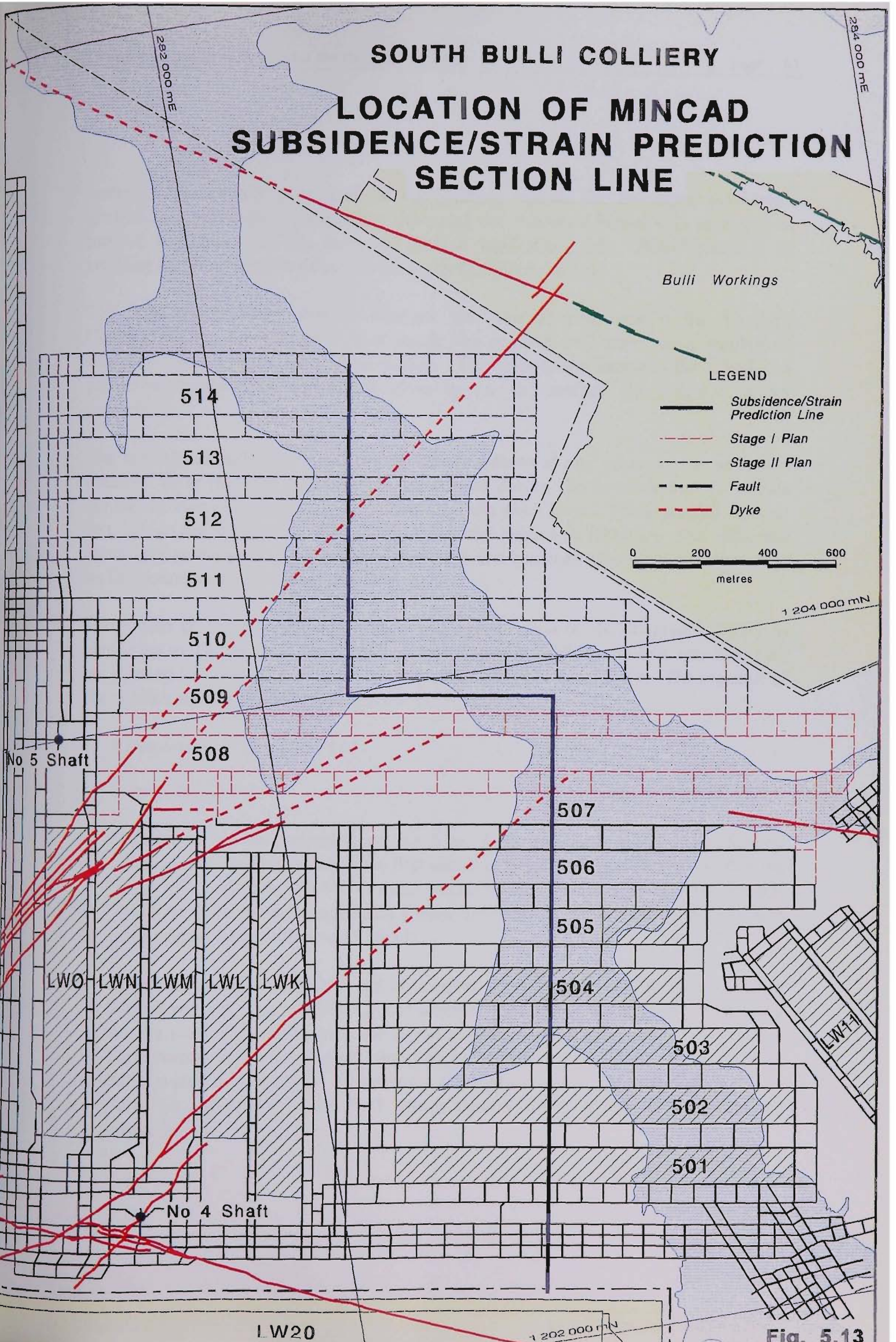


Fig. 5.13

method is essentially a method of curve-fitting against the measured subsidence profiles in a particular mining area. Although the Influence Function is an empirical method it differs from the empirical method used above (the "Holla" method) by enabling the development of curves for every subsidence factor.

The Influence Function method has not yet been demonstrated in the Southern Coalfield to my knowledge. As a result, the method was tested in a number of scenarios, with specific objectives in each. The comparison between the actual and predicted curves were sufficiently close to use the method for Stage II layout predictions.

The concept of Influence Functions is that subsidence at any point on the surface is obtained from the sum of all surface subsidence due to the extraction of an infinite number of elements within a critical radius, at the seam level. The extracted element just below the surface point of interest has the maximum influence; that influence diminishes as the surface point moves outwards and becomes zero when the element is on the boundary of the radius of influence.

The results of the predictions are described below. Due to the program's ability to handle up to 10 panels at once, two scenarios were modelled; the first was the tenth panel being 513, the second with the tenth panel being Longwall 514. The location of the prediction lines is shown in Figure 5.15.

a) Completion of Longwall 513

(1) Crosslines

- Subsidence on the extension of the Line A-A (Figure 5.16) is insignificantly influenced by the extraction of the first panels of Stage II (Figure 5.17). In fact the layout of Longwalls 508-510 is quite similar to the layout of Stage I (Longwalls 501-506), the only difference being a small difference in cover depth (10-25 m) and pillar width (6 m smaller than Stage I).
- Maximum subsidence of 257 mm is observed on the line over Cat. North (180 m West Line). It is noticeable that the southern side of the subsidence profile has a smaller induced slope because the layout in this area (Longwalls 507-510) is more conservative and has a steeper slope on the northern side where the increase in panel width is proposed. Accordingly the maximum average strains (Figure 5.) occur on 180 m West Line (0.35 mm/m [tensile] and 0.46 mm/m [compressive] respectively).

Stage II MinCad Strain Prediction

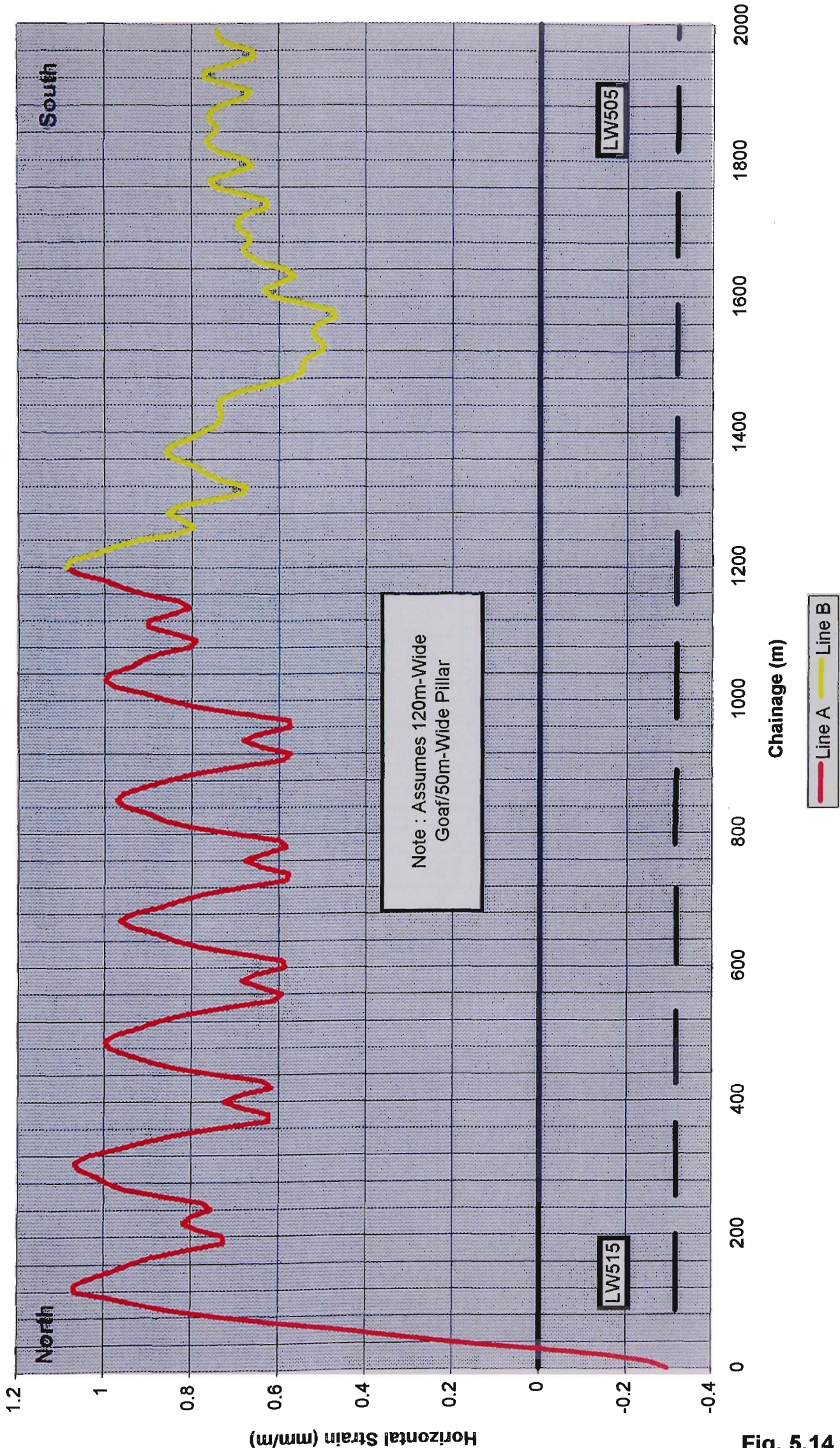


Fig. 5.14

SOUTH BULLI COLLIERY

STAGE II - CISPM SUBSIDENCE PREDICTION LINES

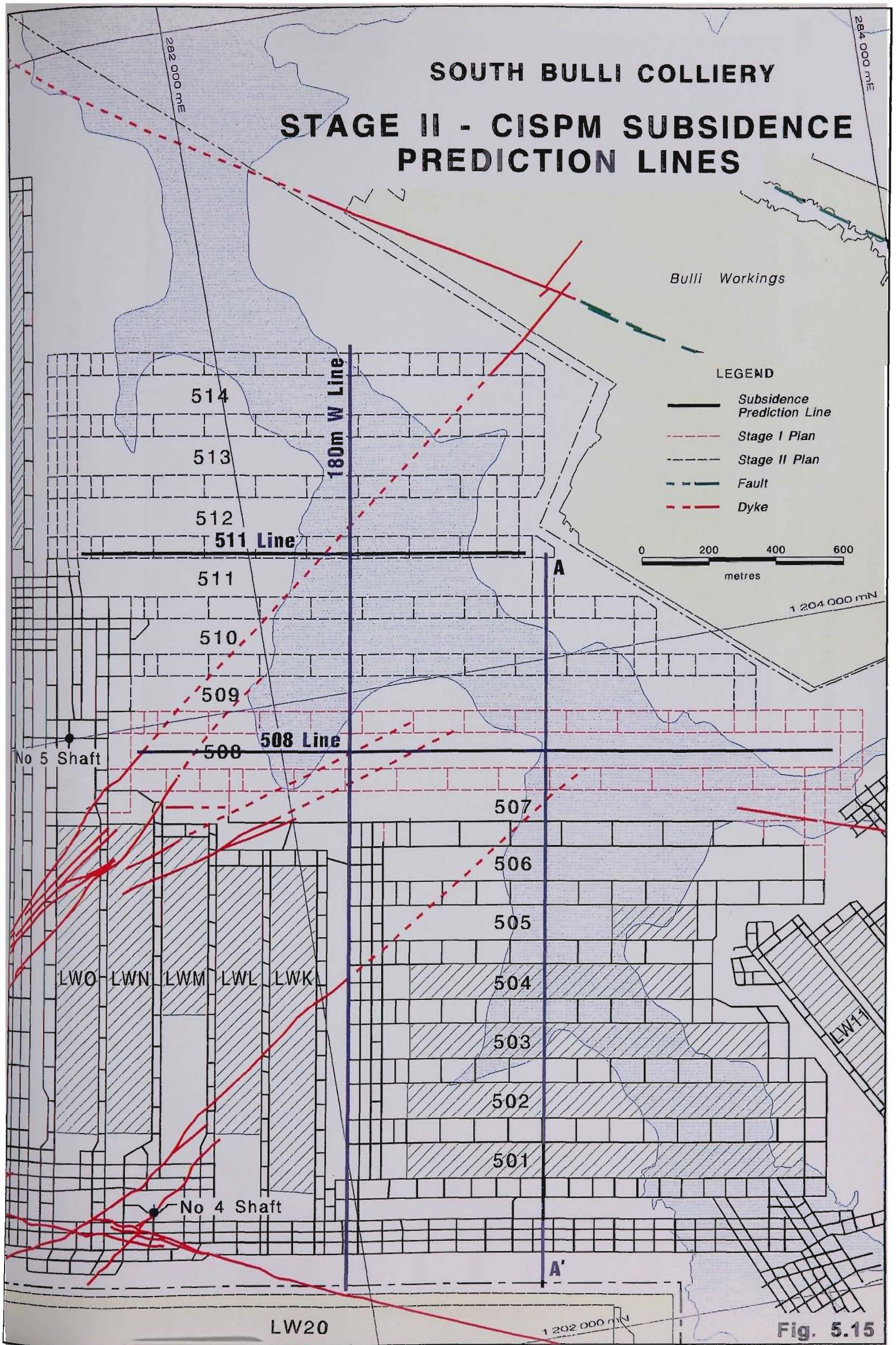


Fig. 5.15

CISPM LW504-513 Crossline Predicted Subsidence

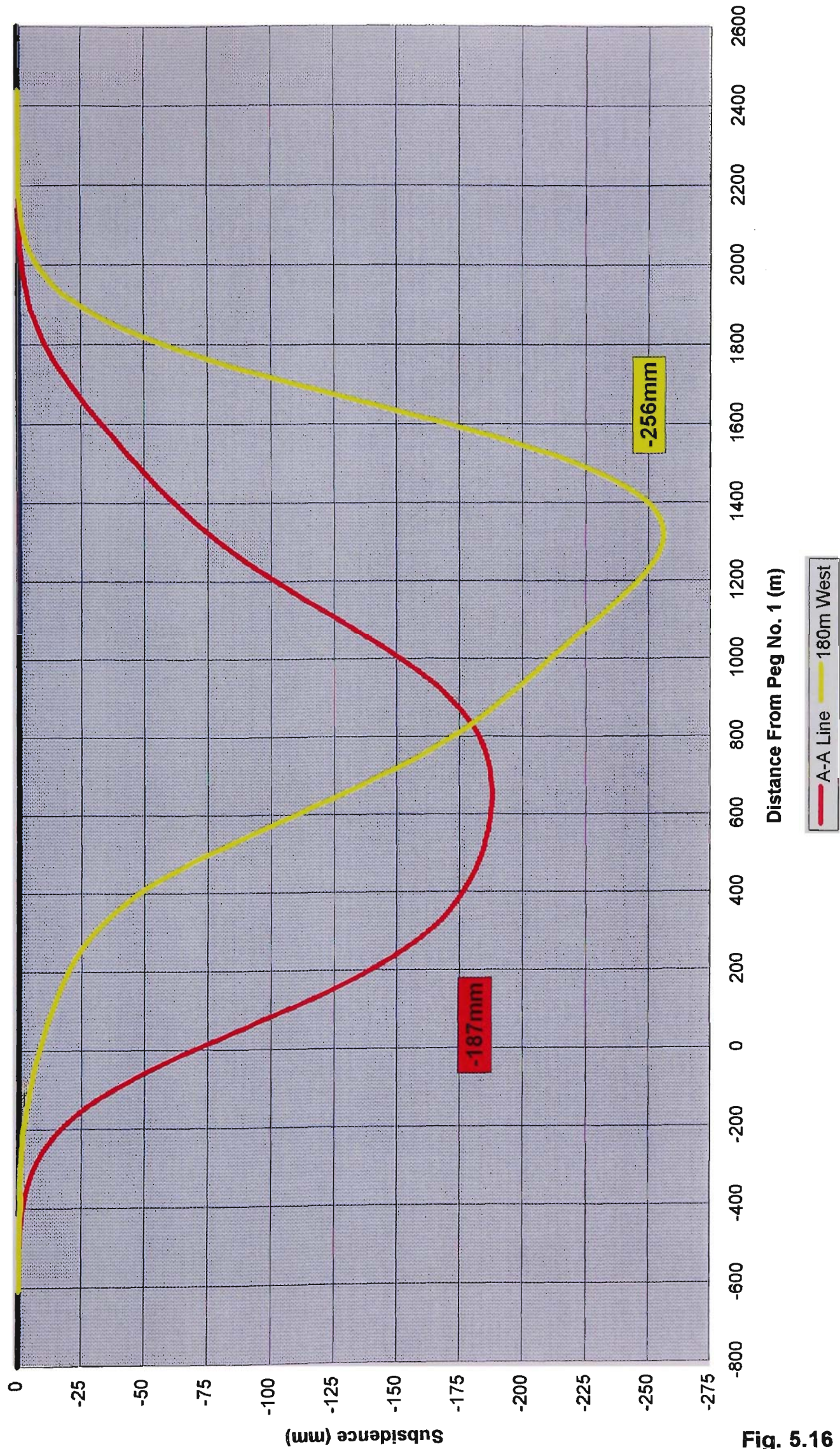


Fig. 5.16

CISPM LW504-513 Crossline Predicted Strain

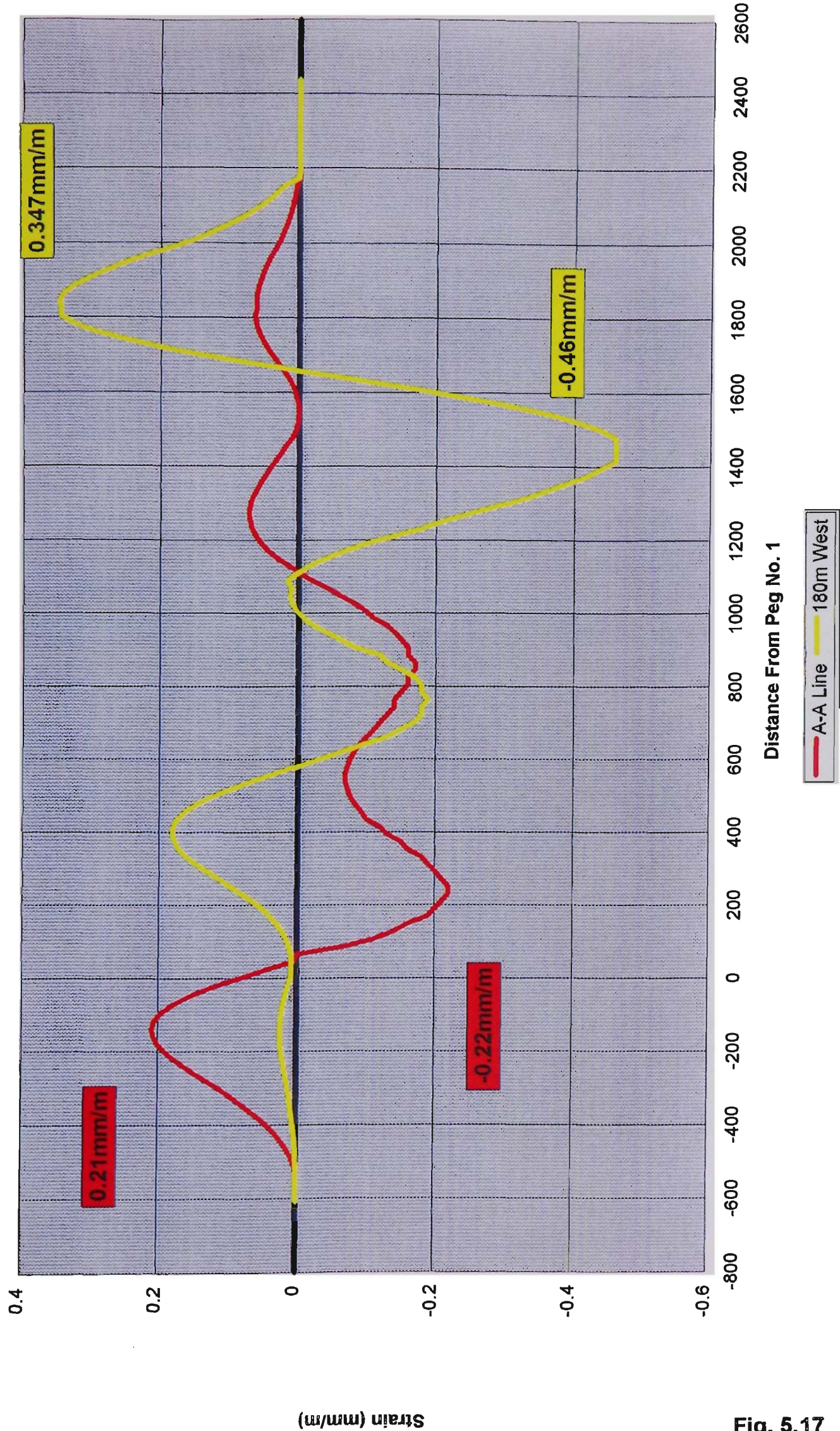


Fig. 5.17

(2) *Longitudinal Lines*

- The predicted subsidence profile of Longwall 508 centre line (Figure 5.19) indicates that the panel length is very large. The western side exhibits a milder slope firstly due to the limited impact of Longwalls 504-506 and secondly to the shorter panel width of Longwall 507 and its finishing line which lags behind Longwall 508 by 100 m. In contrast the eastern side has a higher slope because of the full impact of surrounding panels.
- The maximum subsidence is shown on the north end line of Longwall 511 (257 mm). The maximum average strains of +0.3 mm/m and -0.34 mm/m respectively are shown on this line.

b) Completion of Longwall 514

(1) *Crosslines*

The subsidence influence of the extraction of another wider panel (Longwall 514) on the Line A-A is minimal. However on the 180m West Line the subsidence reaches 272 mm, ie. a 15 mm increase in comparison with the situation at the end of Longwall 513 (Figure 5.20).

- The shape of the northern subsidence profile on Line A-A is peculiar, but understandable because after crossing nothing of eastern end of panels 512-513 it picks up a small part of Longwall 514.
- Maximum average strains (+0.35 mm/m and -0.4 mm/m) are presented on the 180m West Line in the area of the new layout where the maximum subsidence is predicted (Figure 5.21).

(2) *Longitudinal Lines*

- Maximum subsidence on the mid 508 panel line is 199 mm and is located to the west of A-A' Crossline resulting an increase of 11 mm in comparison with the end of 513 panel extraction (Figure 5.22).
- Maximum subsidence on Longwall 511 North End Line is the same as on the 180m West Line.
- Strains are fractionally smaller than those shown on the crosslines (Figure 5.23).

c) Conclusions

To provide the subsidence and strain results from the CISPM model in a format which can be more readily understood, 52 lines (each containing 150 points) running parallel to the gateroads were analysed. The results of the subsidence modelling are shown as a contour diagram (Figure 5.24) and as a three-dimensional isometric view (Figure 5.26). The contoured strain values are shown in Figure 5.26, and as an isometric view (Figure 5.27).

- The maximum subsidence is predicted to increase slowly in the middle area because of its conservative layout. This is an important aspect since the area encompasses the longest panels as well as containing some dykes which were identified at the Bulli seam level. The subsidence over Longwall 509 after the extraction of Longwall 514 is only 20% higher than the measured subsidence of Stage I.
- The predicted absolute maximum subsidence, 272 mm over Longwall 511, is considered to be very small.
- The tensile strain, as a maximum average, is predicted to be 0.35 mm/m. If a correction is made taking into account factors from CISPM calibration details, the maximum tensile strain could reach 0.55 mm/m for structure free ground.

5.4.4 Incremental Profile Method

The Incremental Profile Method was used for the prediction of subsidence over the Cataract area, based on work they had carried out in the Southern Coalfield. (Rickard & Partners Pty Ltd., 1990-1993)

Using a large amount of monitoring data from the Southern Coalfield, it was observed that the incremental subsidence profiles after each additional incremental longwall were remarkably similar (the incremental subsidence profile is obtained by subtracting the cumulative subsidence profile before extraction of a longwall panel from the cumulative profile on the completion of the panel). The core of this method consists of a set of graphs which allow the maximum incremental subsidence and its location and the shape of incremental subsidence profile for each panel (first, second and third and-on panels), to be determined as functions of panel width, pillar width, cover depth and extraction height. Having the incremental subsidence profile and its position for each panel the final subsidence profile over a series of longwalls is found by adding the separate increments from each panel. The incremental subsidence curves are then used to derive the incremental tilts, curvature and strains.

The method was derived empirically and consequently it can be used with confidence within the ranges of longwall panel and pillar widths, depths of cover and seam thickness that were used to develop this method.

CISPM LW505-514 Longitudinal Predicted Subsidence

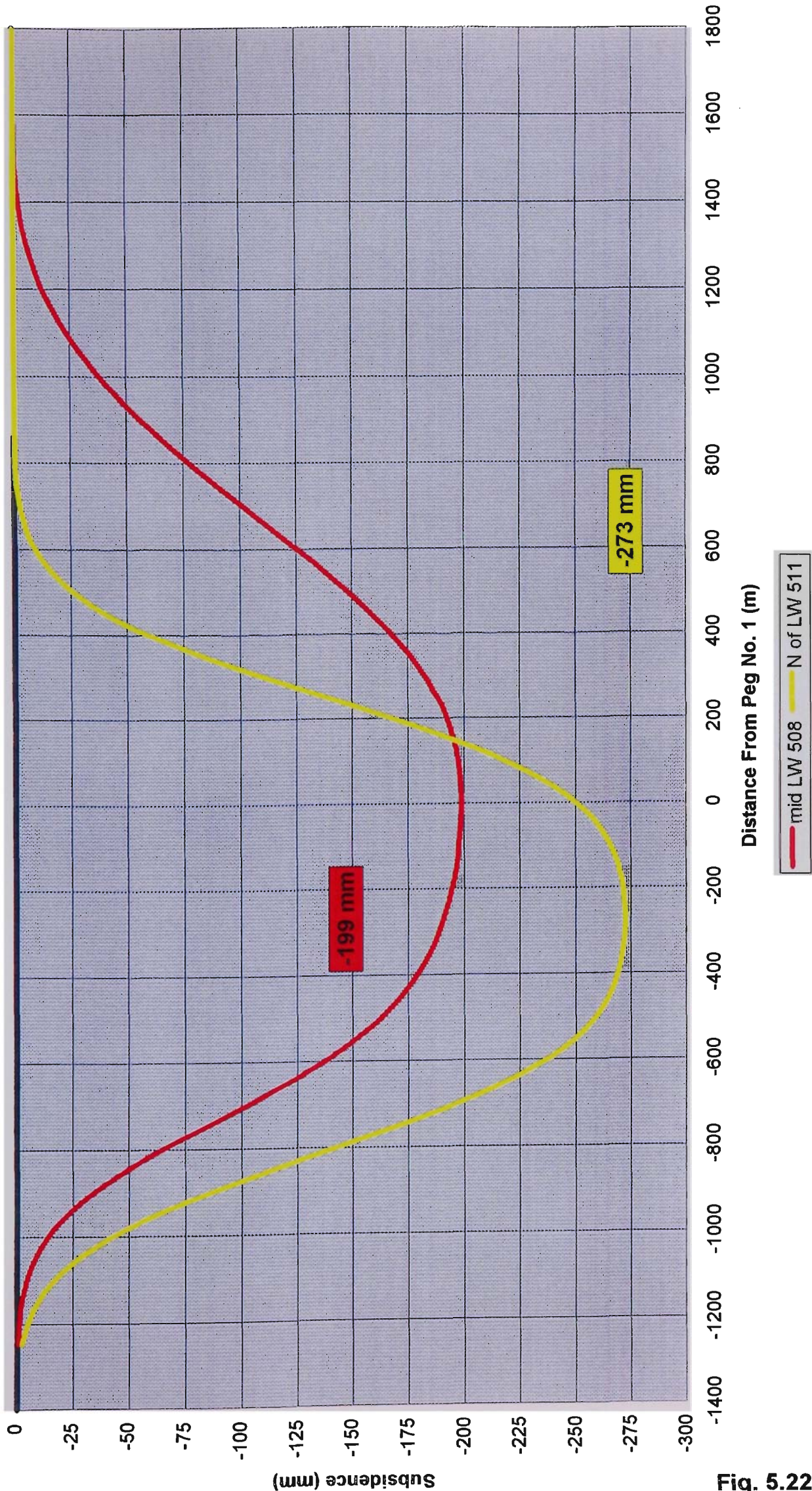


Fig. 5.22

CISPM LW505-514 Longitudinal
Predicted Strain

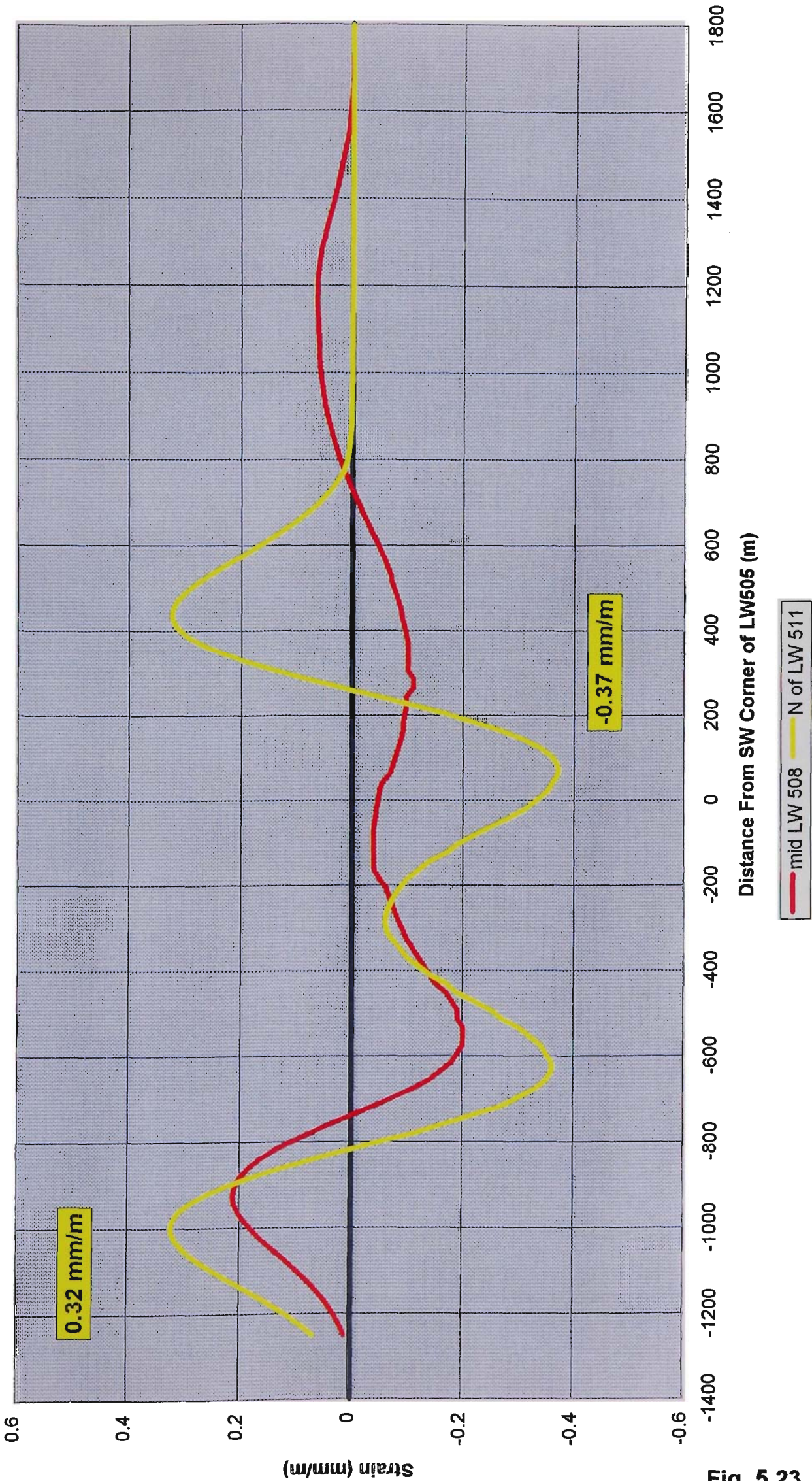


Fig. 5.23

CISPM LW504-513 Longitudinal Predicted Subsidence

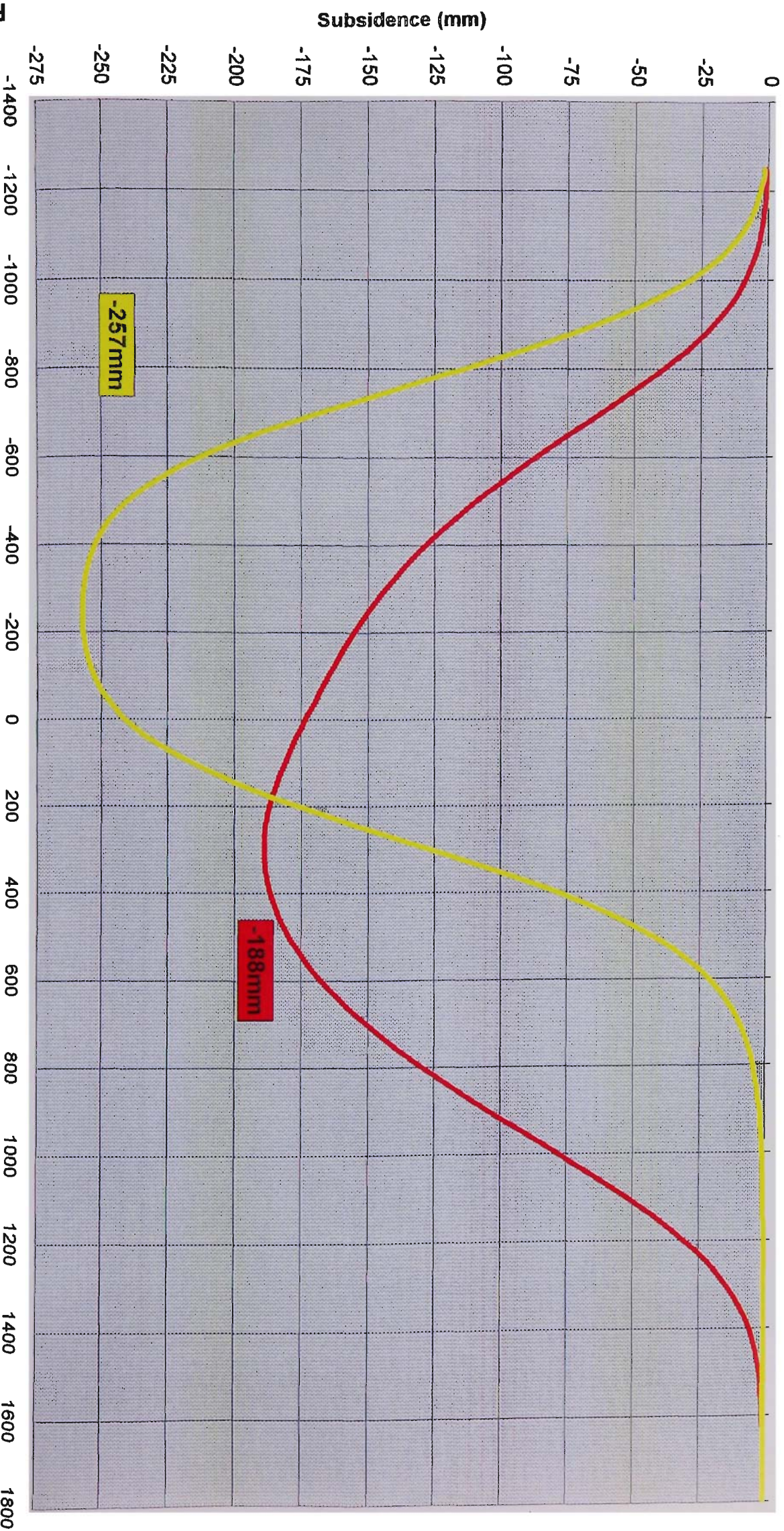


Fig. 5.18

CISPM LW504-513 Longitudinal Predicted Strain

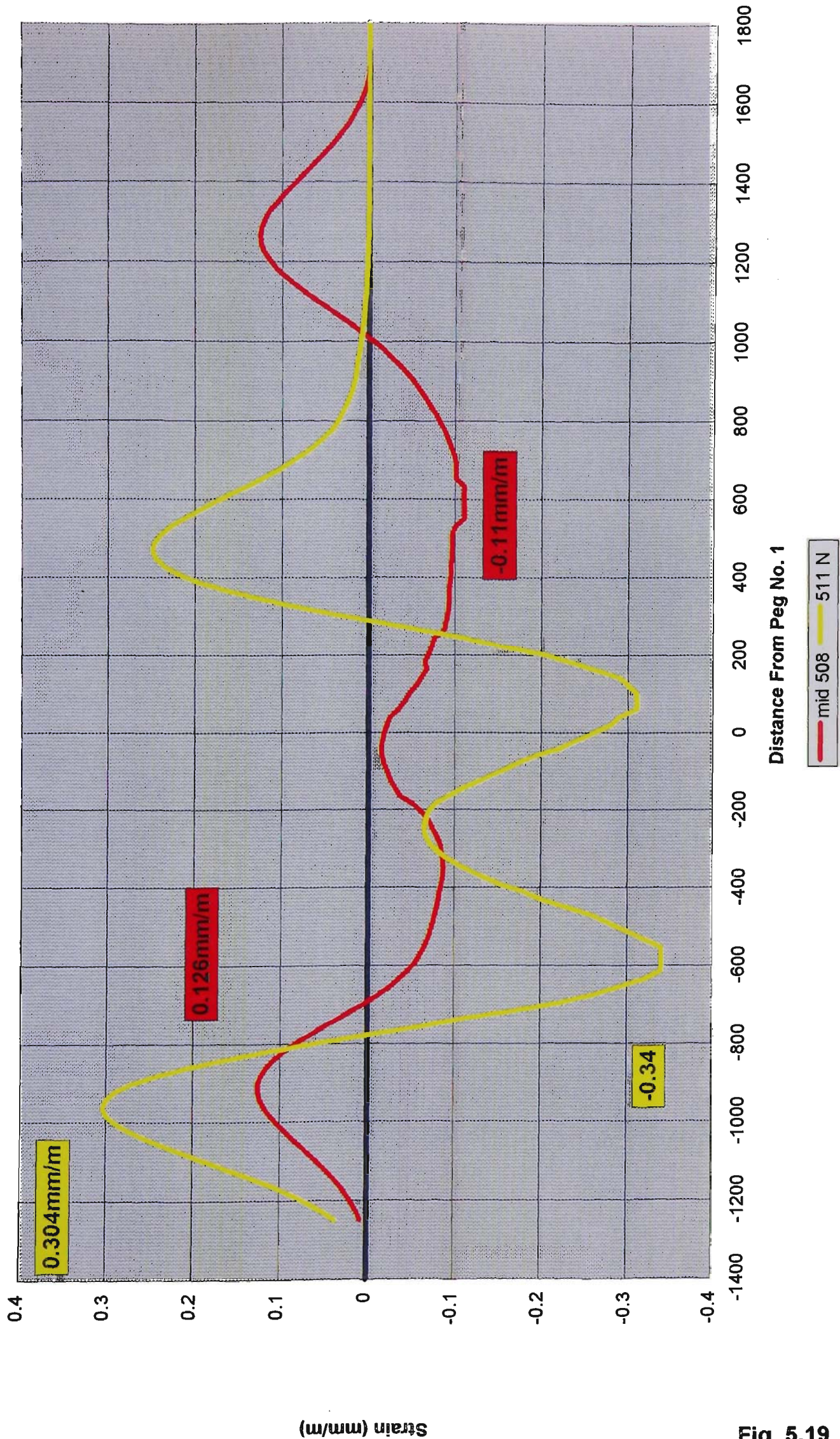


Fig. 5.19

CISPM LW505-514 Crossline Predicted Subsidence

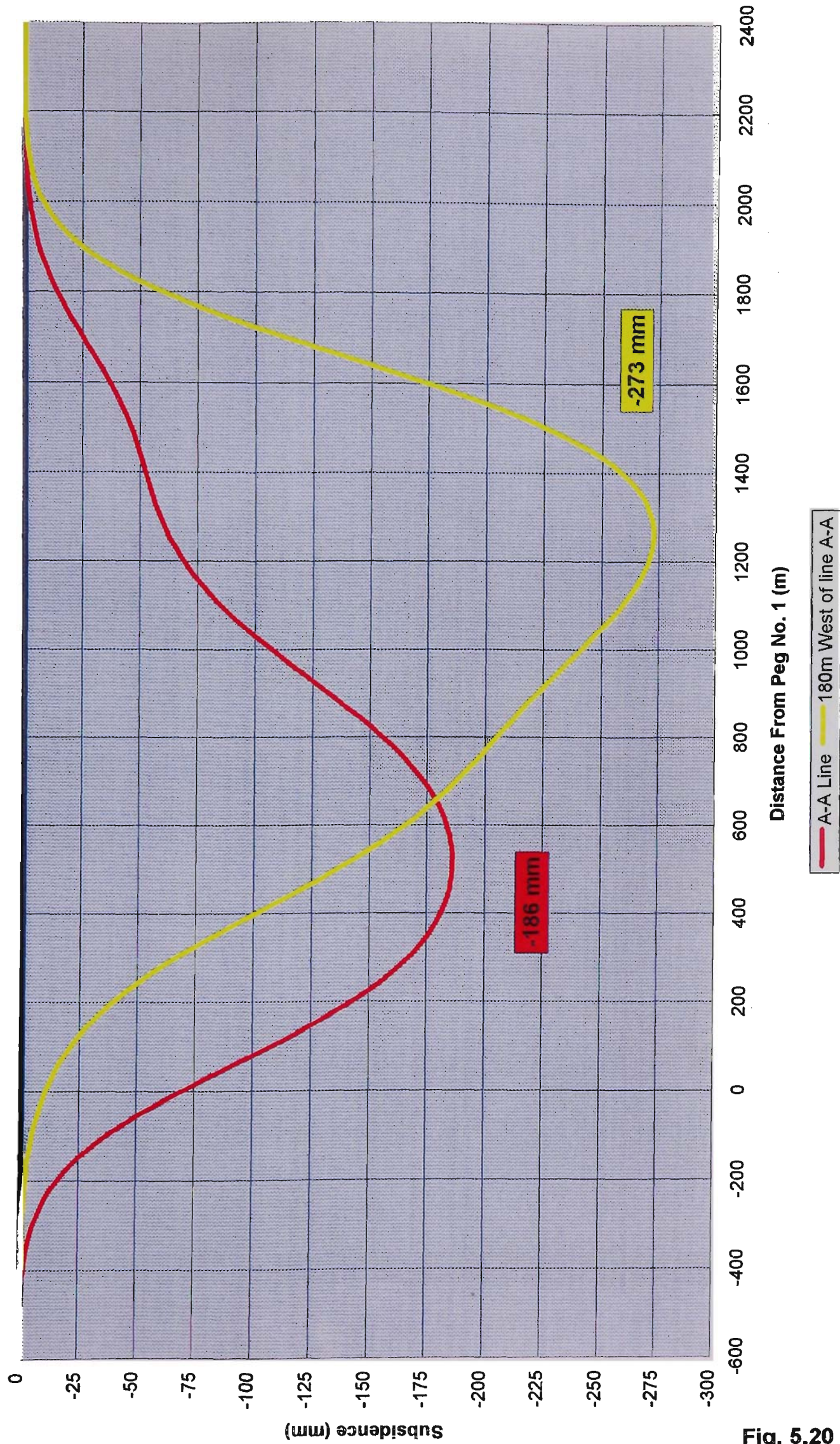


Fig. 5.20

CISPM LW505-514 Crossline Predicted Strain

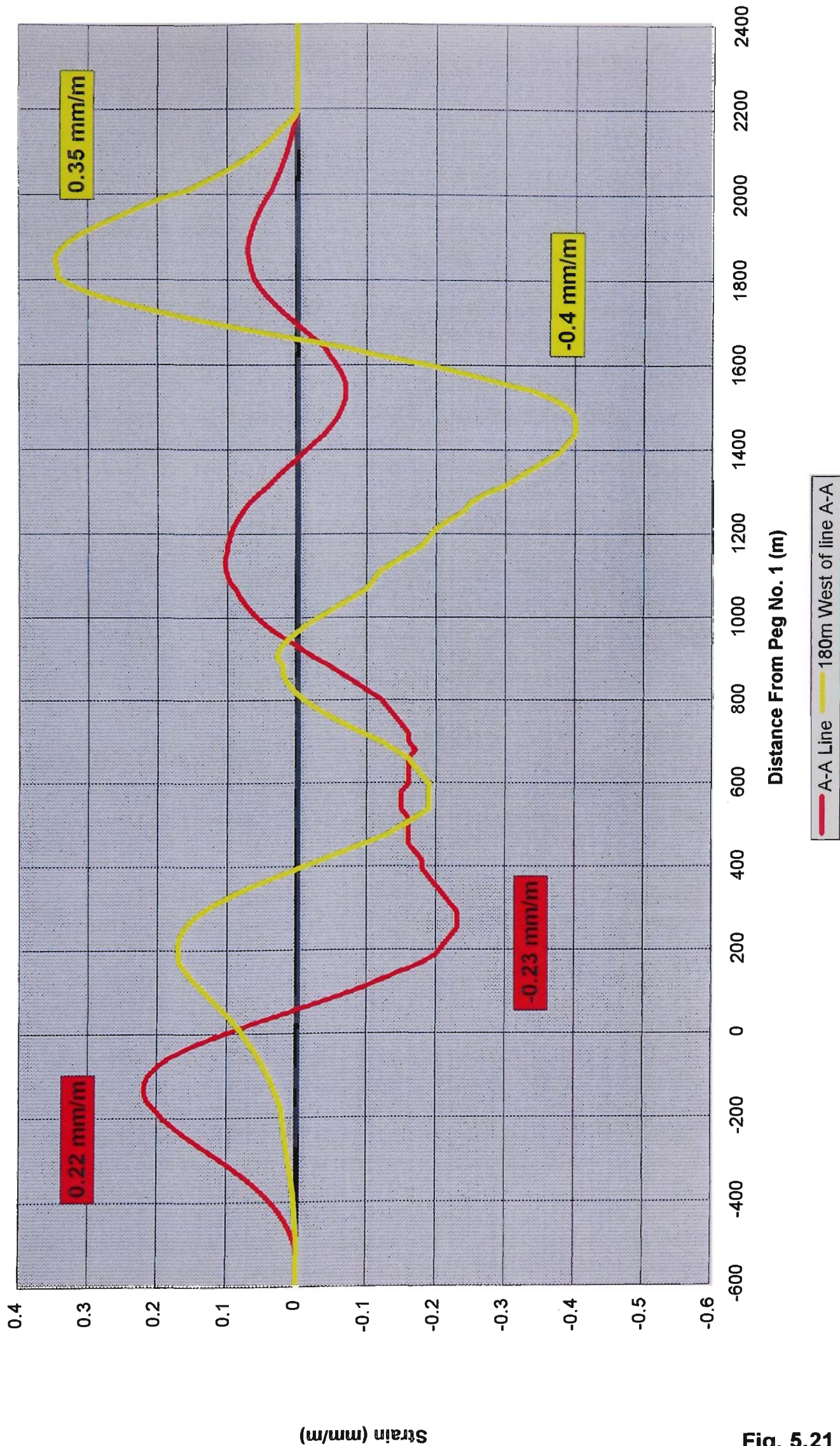


Fig. 5.21

CISPM Contoured Predicted Subsidence

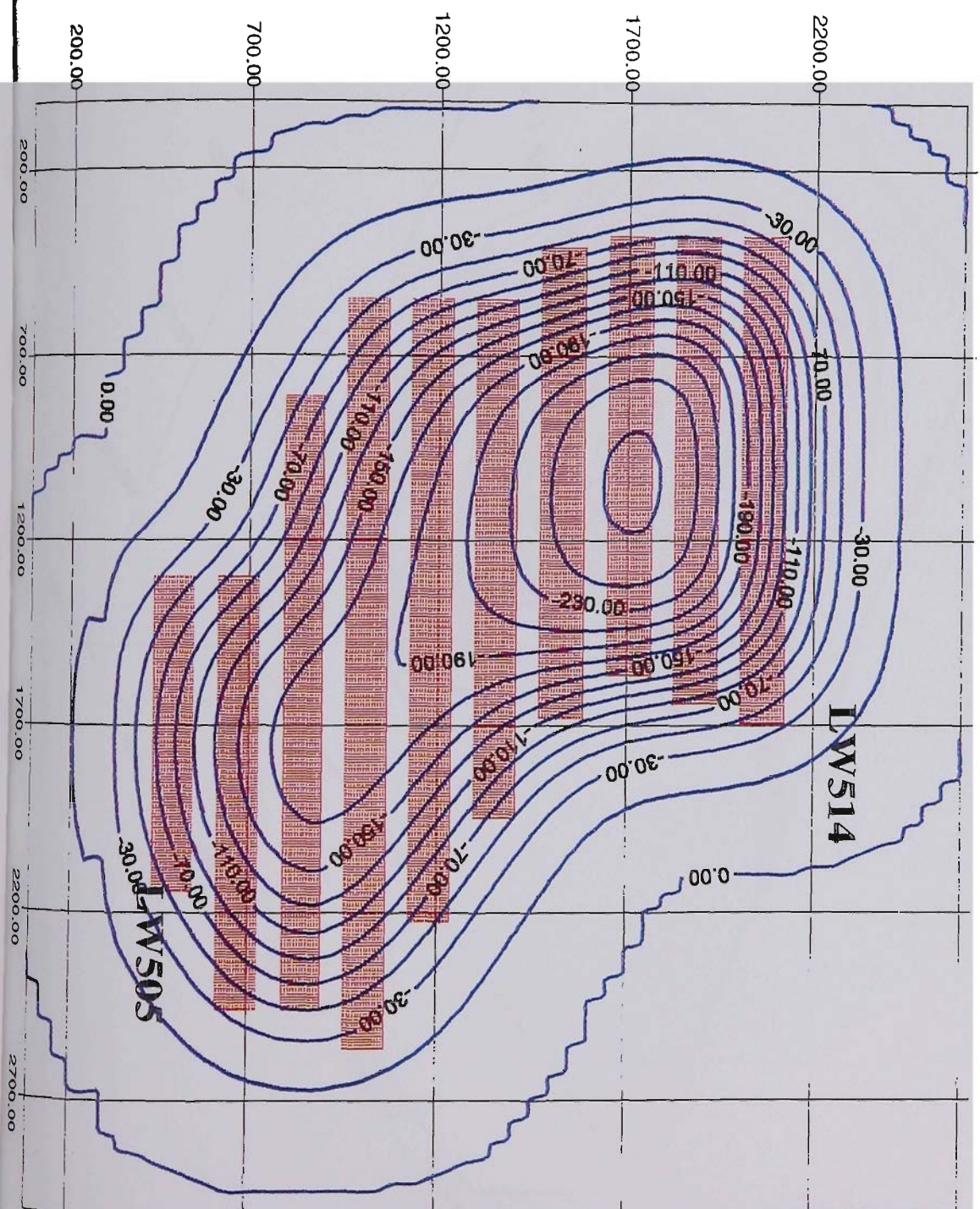


Fig. 5.24

CISPM Isometric Predicted Subsidence

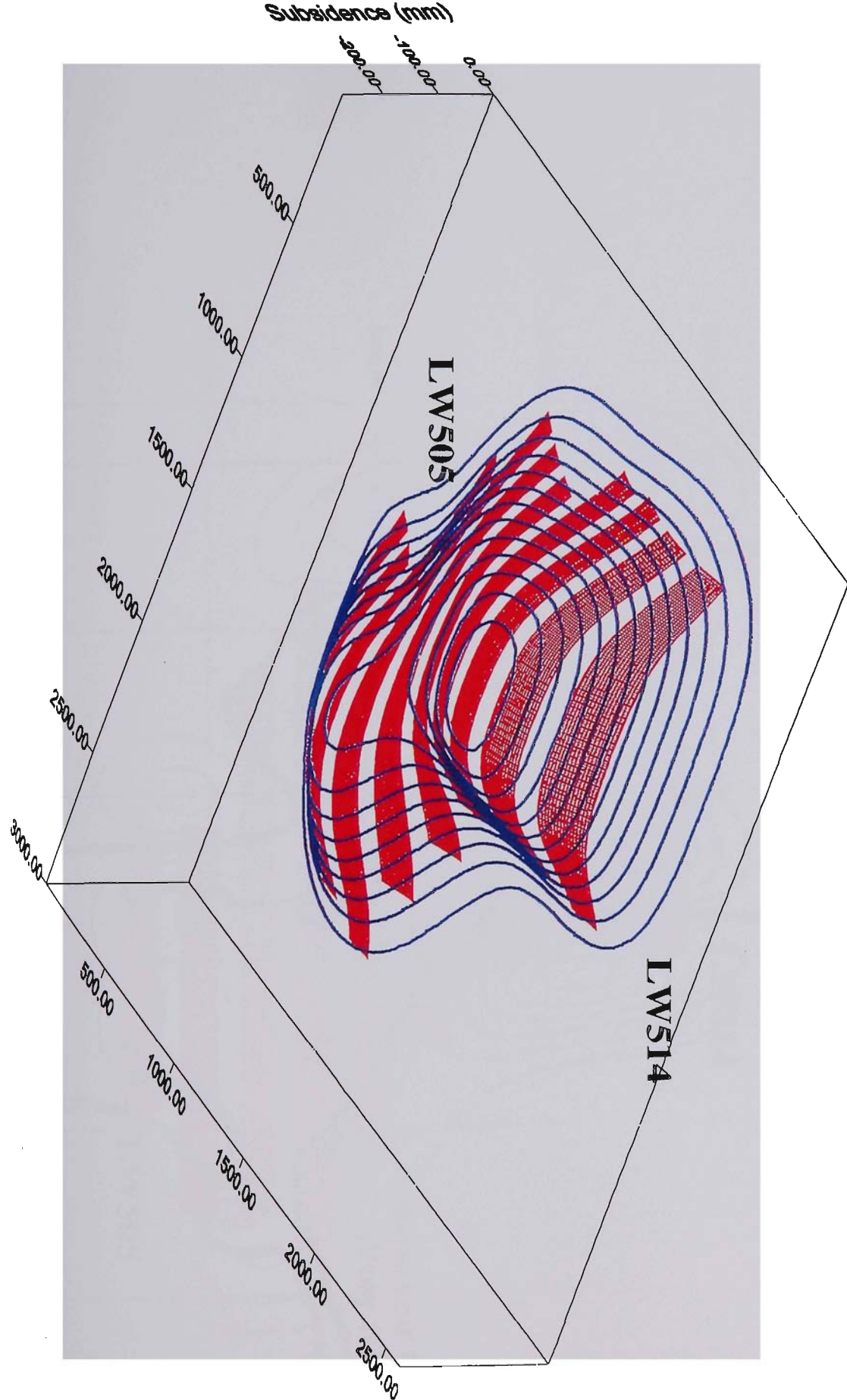
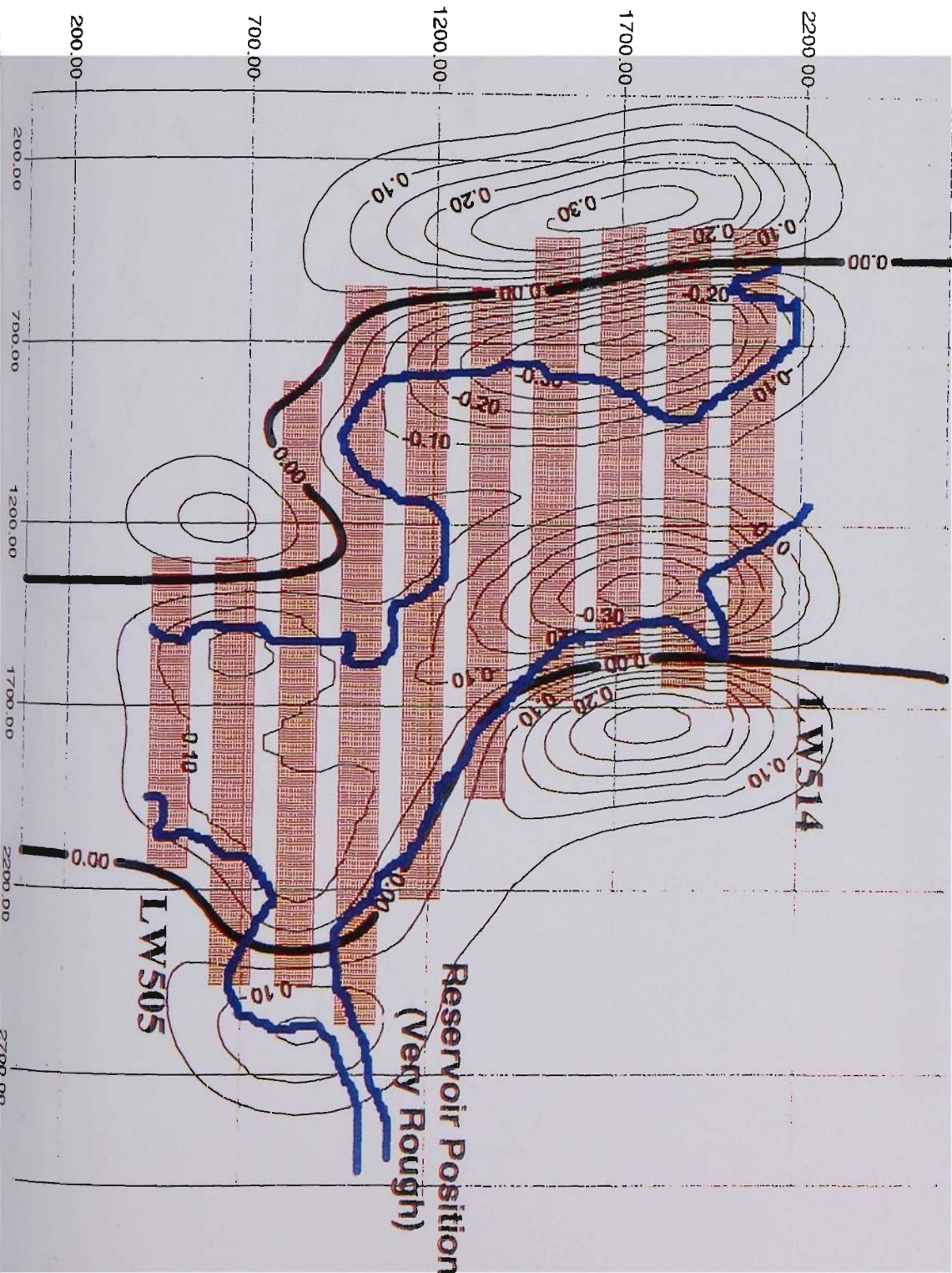


Fig. 5.25

CISPM East-West Contoured Predicted Strain



CISPM East-West Isometric Predicted Strain

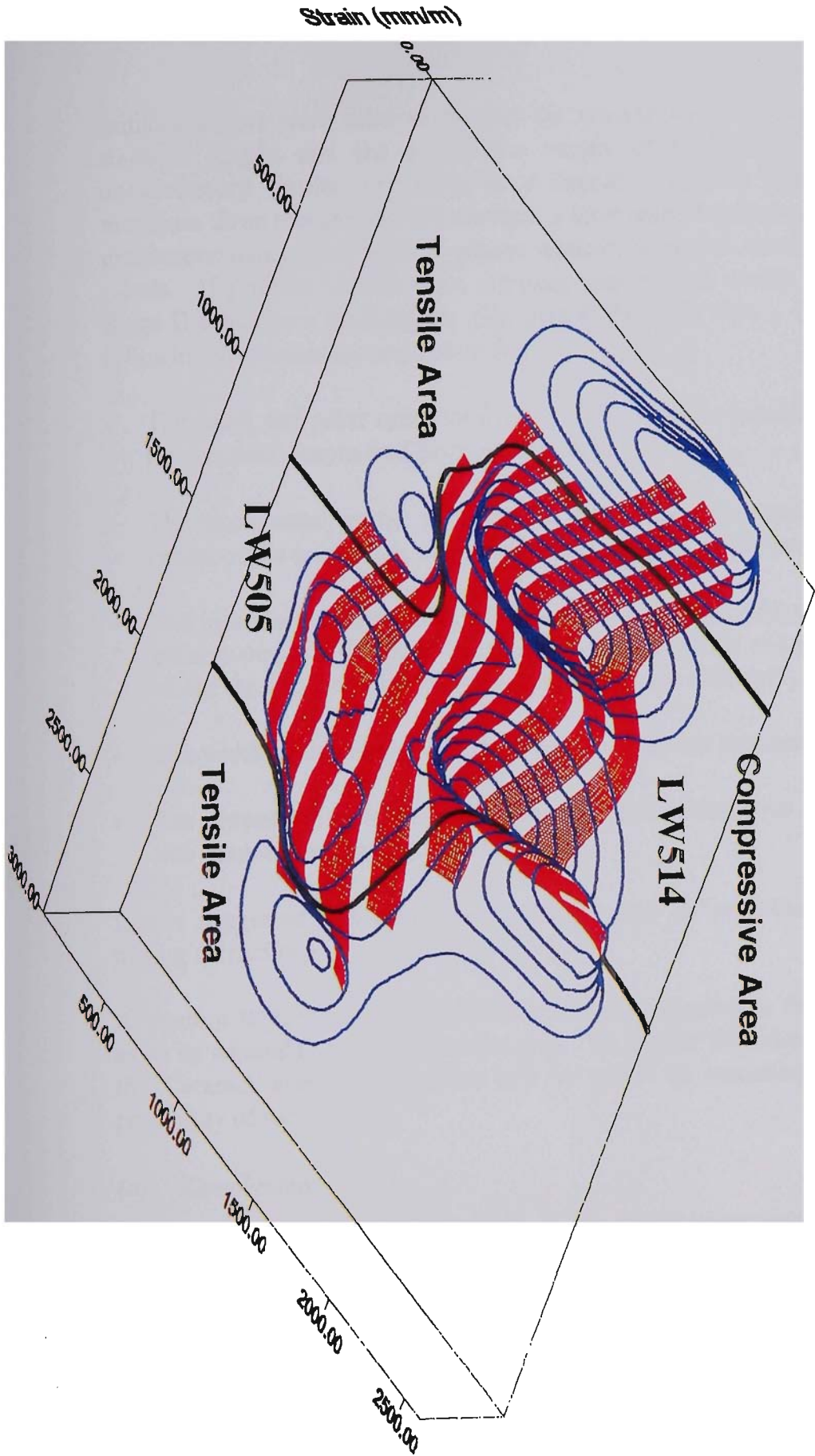


Fig. 5.27

Initial attempts were used to predict the subsidence for Longwall 503 based on the standard graphs and the subsidence results of Longwalls 501-502. Because of unsatisfactory results, explained as a limitation of two panel data instead of the minimum three required by the method, a later study focused on the comparison of the predictions using the standard graphs against measured subsidence for the first three panels. If positive results were obtained the method would be used further for the Stage II subsidence predictions. (Rickard & Partners 1995.) During the last study the following discrepancies were identified:

- The panel and pillar ratios of Longwall 501-503 lie outside of the range for which the standard graphs had been constructed.
- The incremental profile for the first panel was not symmetrical in relation to the centre of the panel; this was not the case at other collieries.
- The incremental subsidence profiles from Longwall 501 to 503 panels follow the general shape of standard third-and-on panels and do not differ, unlike other mines where the 1st, 2nd and 3rd panel increments are different.
- The width of the measured incremental subsidence profiles is wider than predicted.
- The proportion of incremental measured subsidence over the advancing goaf edge was double compared to other collieries.

It was suggested that these deviations are due to the influence of the surrounding mining extractions.

At present Bellambi is not proceeding with the program as there is no clear indication as to its suitability for the Cataract area. As further subsidence data is obtained from the Cataract area consideration will be given to resuming investigations into the possibility of future use.

(a) Conclusions

Empirical Method predictions (after Holla, 1988) were used to determine maximum subsidence for the next stage of extraction. This was complimented by numerical modelling and the Influence Function Prediction Methods.

Taking into account the results of these methods the predicted maximum subsidence for Stage II is 280 mm and will occur above Longwall 511 (during the Stage II extraction). The "middle" area which contains the longest panels will have a transitional subsidence between the maximum subsidence of Stage I and Stage II. The maximum predicted subsidence for Stage II is considered to be relatively small.

The tensile strain, which is the most important factor, will not exceed 0.8 mm/m. This figure is well below the tensile strain failure values of the Hawkesbury Sandstone. Additionally, the area with maximum tensile strain is predicted to occur outside of the Reservoir Full Level Supply, although some tensile strain will exist under the reservoir south of Longwall 501, and north of Longwall 514.

5.5 Chain Pillar Stability

Pillar stability beneath the Cataract Reservoir is seen as important primarily in its role of protecting the reservoir from subsidence and strain magnitudes which could lead to possible loss of water from the storage.

Pillar design consists primarily of an attempt to control ground movement as well as preserving good roadway conditions. The pillars control the surface movement through their size and the panel width. When pillars are stable, residual subsidence should not increase greatly with time.

It is however relevant to acknowledge that the roadway stability in the Cataract area has been excellent. No secondary support is used in either the maingate or the tailgate when the longwalls retreat, which was not possible in the 200 series to the west. Primary roof support is also less than was used previously in the west. Partly this is a function of the wider chain pillars which protect the roadway from unduly high stress concentrations, and partly due to the apparent absence of high horizontal stresses in the Cataract area.

5.5.1 Pillar Strength Calculations

Although methods of designing coal pillars have existed for many years, it was the Coalbrook Colliery disaster of 1960 which led to the development of more scientific methods of analysis. These commenced with the study by Salamon and Munro into South African pillar behaviour. This study involved examining 98 intact and 27 collapsed pillar geometries in small pillar bord and pillar workings.

The result of this study included the well-known equation, which has since been modified slightly by other researchers. In the equation (reproduced below), pillar strength was seen as a function of coal strength, and pillar geometry. The relationship is not quite straightforward due to the difference in strength between a small laboratory sample of coal, and the in-situ coal mass, which contains a much higher number of cleats, structures and other factors which reduce the strength.

$$\sigma_p = \sigma_c \frac{w^{0.46}}{h^{0.66}}$$

Where σ_p is Pillar Strength (MPa), σ_c is coal strength, w is the width of a square pillar (m), and h is the height of the pillar (m). (Salamon & Munro, 1963.)

It is important to note that due to the empirical nature of the formula it should not be used outside the range of data from which it was derived. In practice, this means that it should not be used beyond a depth of cover of 220 m and pillar width to height ratio of 3.8, to list only two of the data ranges. In the case of the Cataract area, this would mean that the formula would not be applicable for pillars more than 10.26 m wide. The formula was designed for room and pillar workings, another factor which makes it unsuitable for the design of the Cataract chain pillars separating longwall panels.

Researches recently completed as part of AMIRA Project P351 "Coal Pillar Design Guidelines" have demonstrated that confinement of coal, which increases from the rib to the core of medium to large pillars, significantly improves the pillar strength. In fact, yielded coal which remains in a confined state is also capable of withstanding substantial loading, up to 70% of the intact strength of the coal (Figure 5.28).

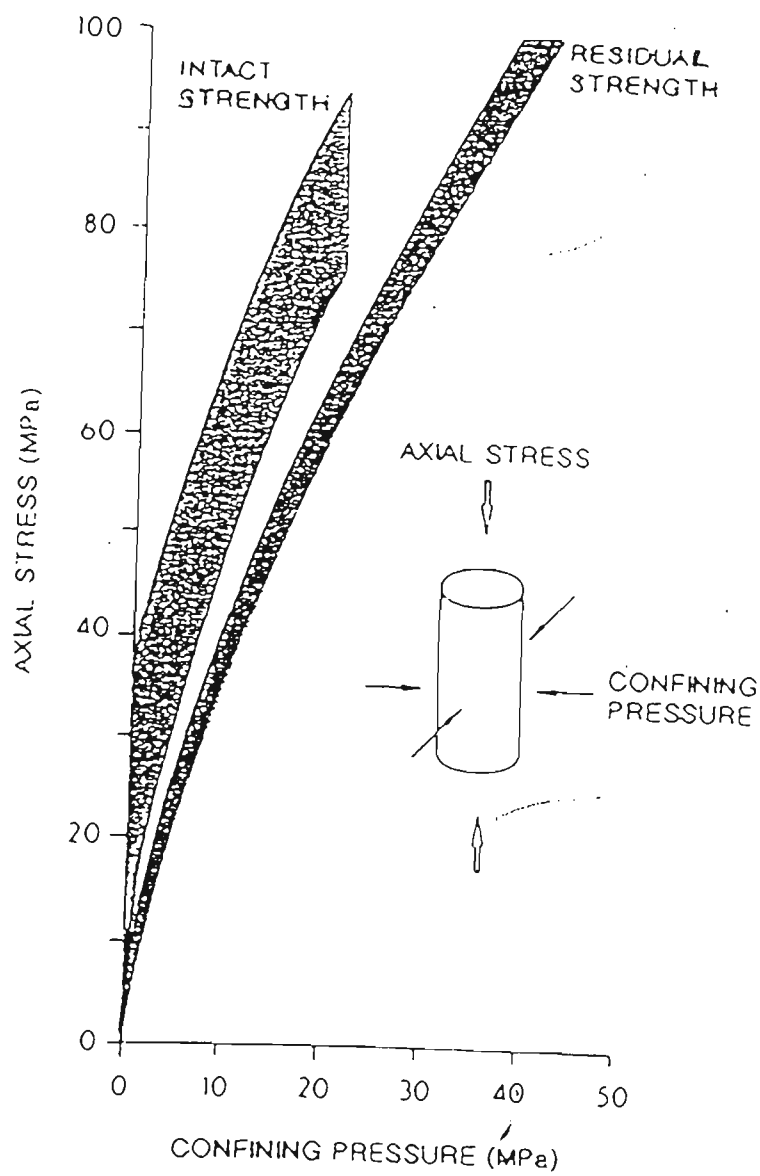
In the case of the Salamon-Munro formula, the pillars were not confined at the ribs, nor were the pillar cores due to the small width/height ratio. In contrast, the Cataract pillars are flanked by goaf, and the good roof and floor conditions (as detailed earlier in this document) combined with the high width-to-height ratio should develop extremely high confinement to the pillar core. As such, the Salamon-Munro formula (and other similar formula derived from and for similar circumstances) cannot be used for the design of the Cataract chain pillars, due to the totally different manner in which confined coal pillars behave when under load. Two formulae which do deal with confined pillars are the Salamon Squat Pillar formula, and the modified Bienawski formula proposed in the AMIRA Coal Pillar Design Guidelines project.

5.5.2 Roof, Floor and Coal Strengths

The consideration of pillar strength through formula such as the Salamon Squat Pillar formula and the AMIRA Pillar Design Project formula, depend on the assumption that the weakest element in the roof/coal/floor system is the actual coal seam, and that the roof and floor are sufficiently strong and intact to provide good confinement to the coal pillar. If this assumption is false, and the roof and/or floor are weaker than the seam, then the pillar strength will be reduced, as the pillar may punch into the roof or floor, or may not be able to maintain sufficient confinement to the pillar core to allow it to mobilise its potential strength.

The experience of roof and floor conditions in the Cataract area, along with anticipated conditions during the Stage II area, suggest that roof and floor strata will be stronger than the coal. As a result the Salamon Squat Pillar and AMIRA formulae can be used, as the coal pillars will be suitably confined, and will not punch into the roof or floor.

The most recent subsidence survey (1994) of the 300 series panels indicated that the existing 47 m and 51 m wide pillars have stabilised surface ground movement.



Bulli Coal Laboratory Strength Envelopes
(N.B. Axes at same scale).

5.5.3 AMIRA Coal Pillar Design Project P351

a) Influence of Pillar Shape

For practical purposes most coal pillars are either square or rectangular in plan. The Cataract chain pillars are rectangular, while most pillar strength equations deal with square pillars. A number of researchers have considered that the strength of a rectangular pillar is greater than that of a square pillar with the same minimum dimension, due to greater axial confinement in the elongated dimension.

There exists a variety of formula which "convert" a rectangular pillar into an equivalent square pillar for use in the various design formula. Despite this work there is no universal agreement on just what increase in strength a rectangular pillar provides. Some of the common formula are given below. These are also plotted in Figure 5.29 to indicate the relative differences between the formula.

$$eq = \sqrt{W \times L}$$

$$eq = 4A / c$$

$$eq = W^{0.85} \times L^{0.15}$$

Where W_{eq} = width of a square pillar with equivalent strength to the rectangular pillar.

W = width of rectangular pillar

L = length of rectangular pillar

A = plan area of rectangular pillar ($=W \times L$)

c = circumference of rectangular pillar ($=2 \times W + 2 \times L$)

As reported previously, a recent ACIRL productivity study indicated possible benefits in increasing the cut through spacing from 100m to 150 m (a 50% increase). These recommendations have already been implemented. This means that from the above equation, the equivalent square width of a 60 m x 145 m pillar is 68.49 m.

Due to the lack of agreement on just what increase in pillar strength occurs, have the last equation (proposed by Professor Syd Peng, University of West Virginia) was used with the AMIRA-modified Bienawski formula. As Figure 5.29 shows, this allows the most conservative increase in equivalent pillar width. This is only a 14% increase, which is very conservative in comparison with the findings of the AMIRA report which considered that at maximum possible vertical loading (ie. the maximum load that the pillar is physically capable of withstanding, which may be much higher than the maximum load which is ever *actually* applied to the pillar), the vertical stress distribution in the pillar increases from zero at the ribside to a maximum at a point in the pillar centre. In the case of a long rectangular pillar, the strength is likely to be up to 50% higher than a square pillar of the same width (Figure 5.30).

Rectangular-Square Pillar Conversion (60m Pillar)

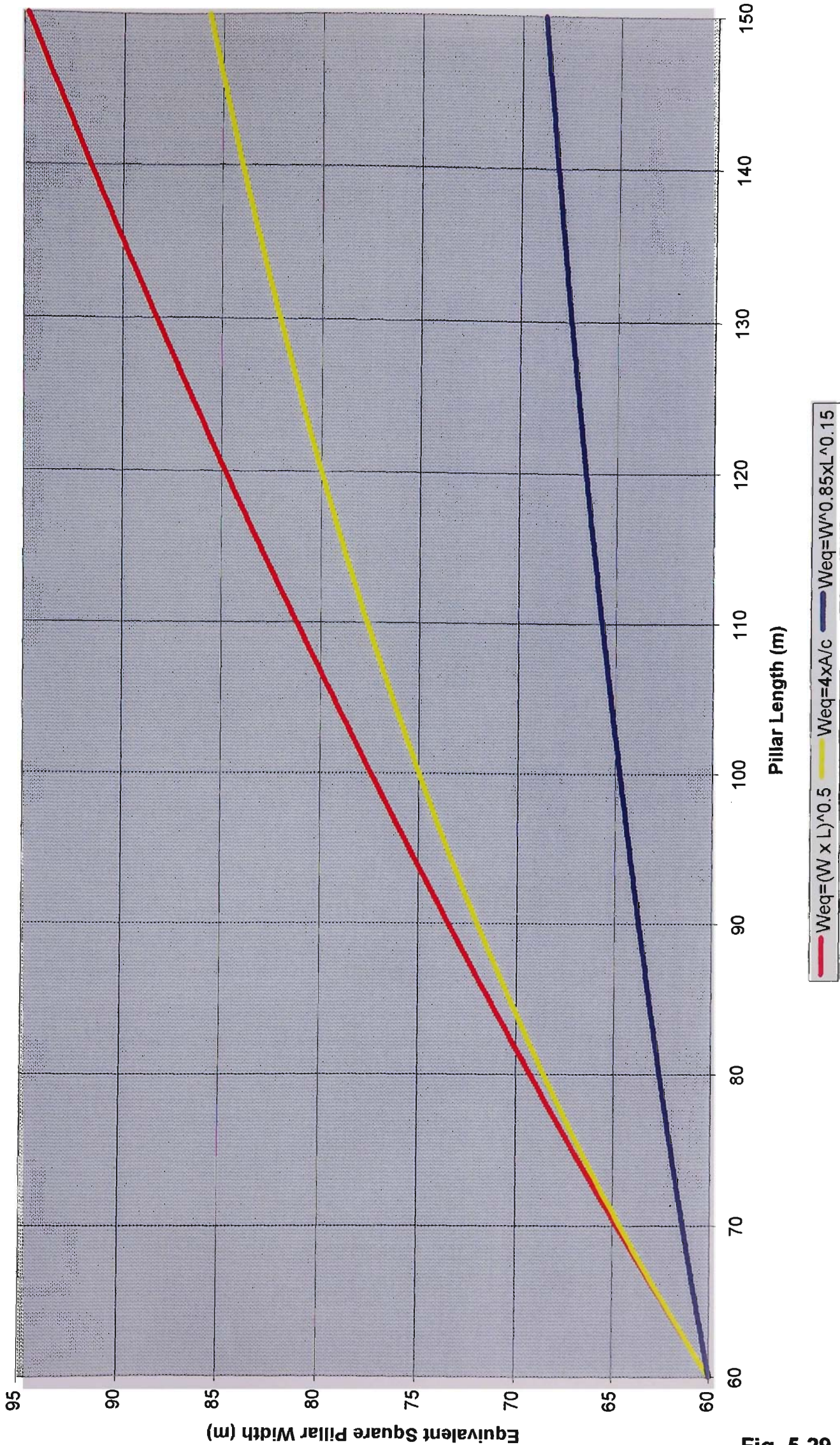
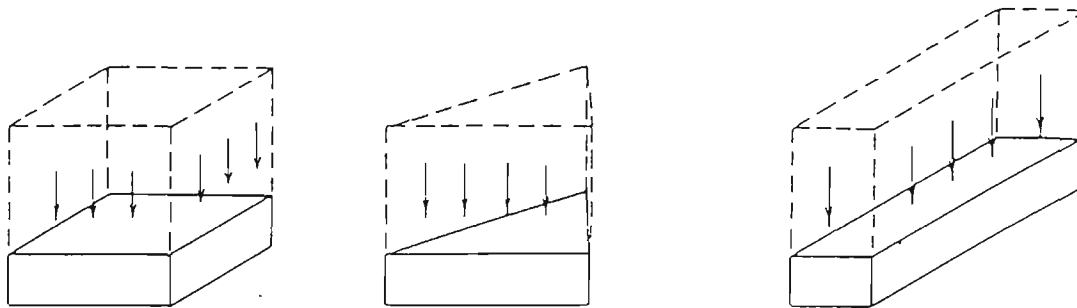
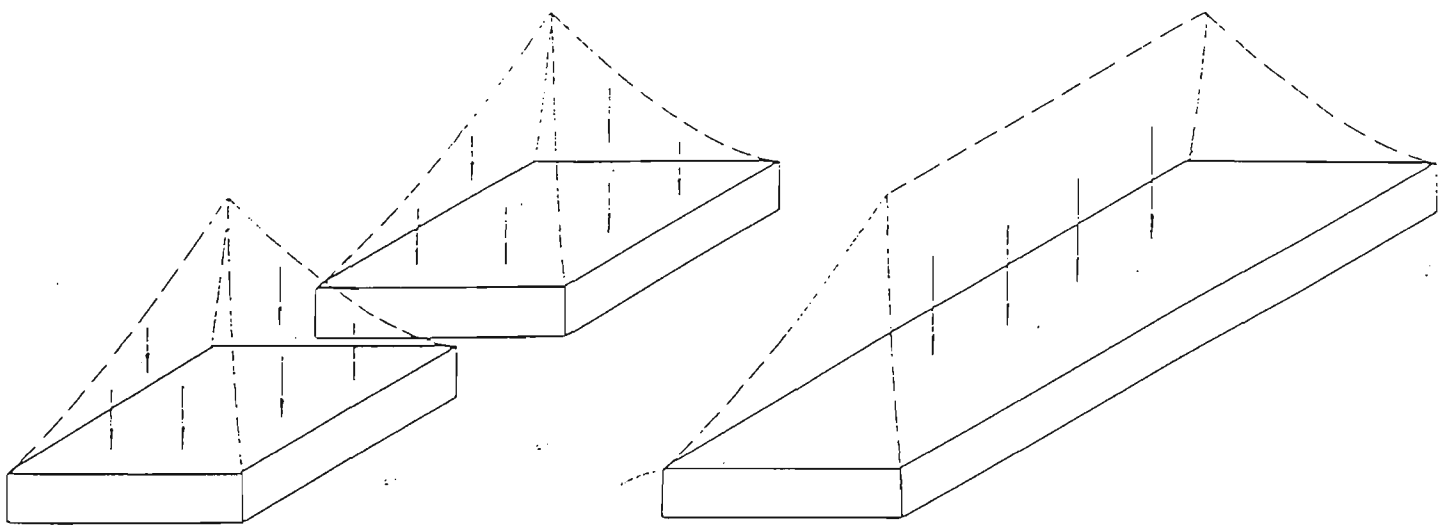


Fig. 5.29



SMALL PILLARS - UNIFORM LOAD DISTRIBUTION AT PEAK LOAD
AREA INFLUENCES STRENGTH

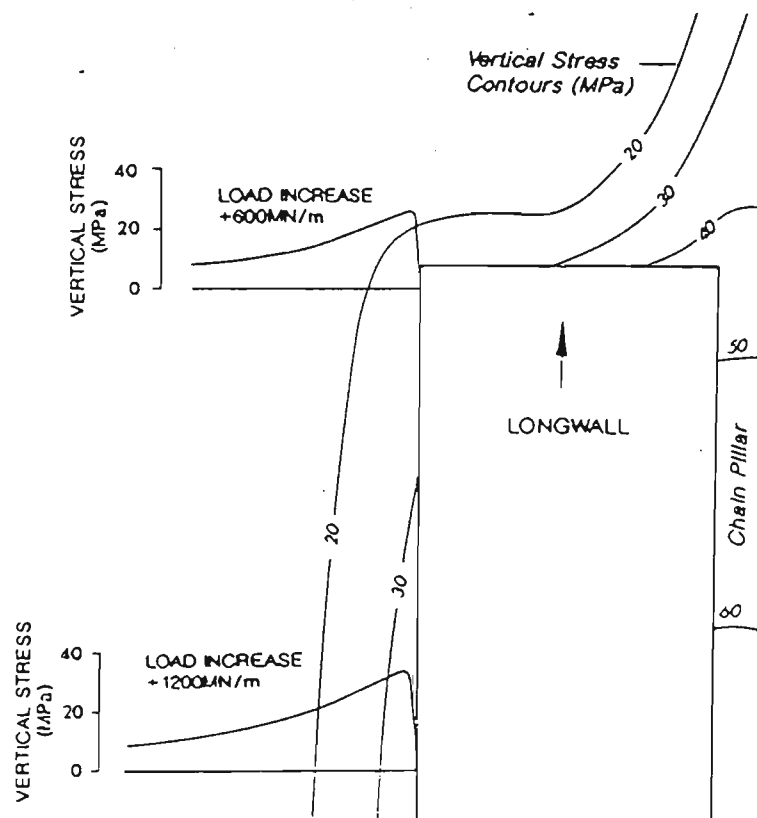


STRENGTH REDUCED BY CUT-THROUGH

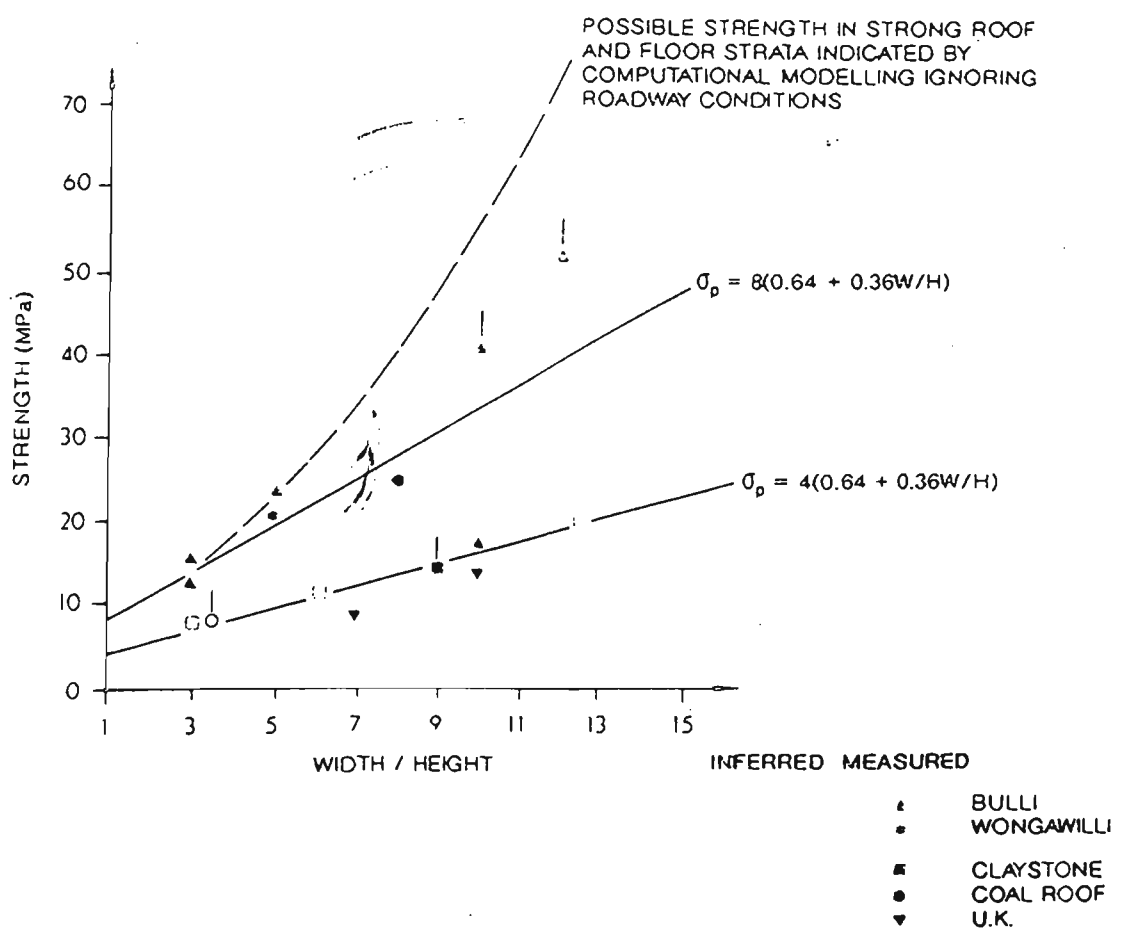
STRONG

LARGE PILLARS - NON UNIFORM LOAD DISTRIBUTION AT PEAK LOAD
AREA AND SHAPE INFLUENCE STRENGTH

Load Distributions at Peak Load.



Vertical Stress Distribution about Typical Deep Longwall



Pillar Strength Measurements

Note that this is used only in the AMIRA pillar strength calculations, and not in the Squat Pillar strength calculation, as the latter predicts higher strengths than the AMIRA formula, even without modification of the equivalent pillar width.

b) AMIRA-Modified Bienawski Formula (AMIRA, Winton, Gale, Mills, 1995)

Over the last four years the above project has been carried out in Australia, with additional data from the U.K. and New Zealand contributing to the project. The project aimed to provide guidelines for coal pillar design which would be more appropriate for Australian conditions than those previously used

The project proposed that the pillar strength could be determined using variations of Bienawski's pillar design formula (Figure 5.31). The strengths measured/inferred fell within a band defined by the following formulae;-

$$\begin{aligned} \sigma_p &= 8 \times (0.64 + 0.36W/H) \\ \text{and} \quad \sigma_p &= 4 \times (0.64 + 0.36W/H) \end{aligned}$$

The first formula corresponds to measurements taken where roof and floor strata were sufficiently strong to be capable of providing good confinement to the coal. The second formula relates to measurements taken from sites where only limited confinement could be applied by roof and floor strata. Examination and testing of roof and floor strata from the Cataract area indicate that the first formula above is the more appropriate to use.

Use of the formula predicts strengths of 78 MPa for the Cataract chain pillars.

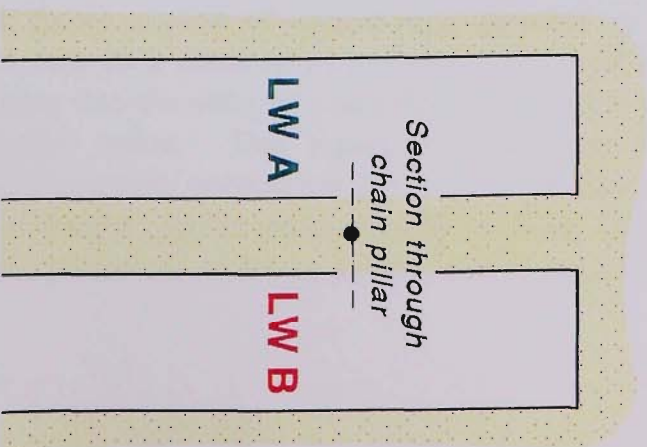
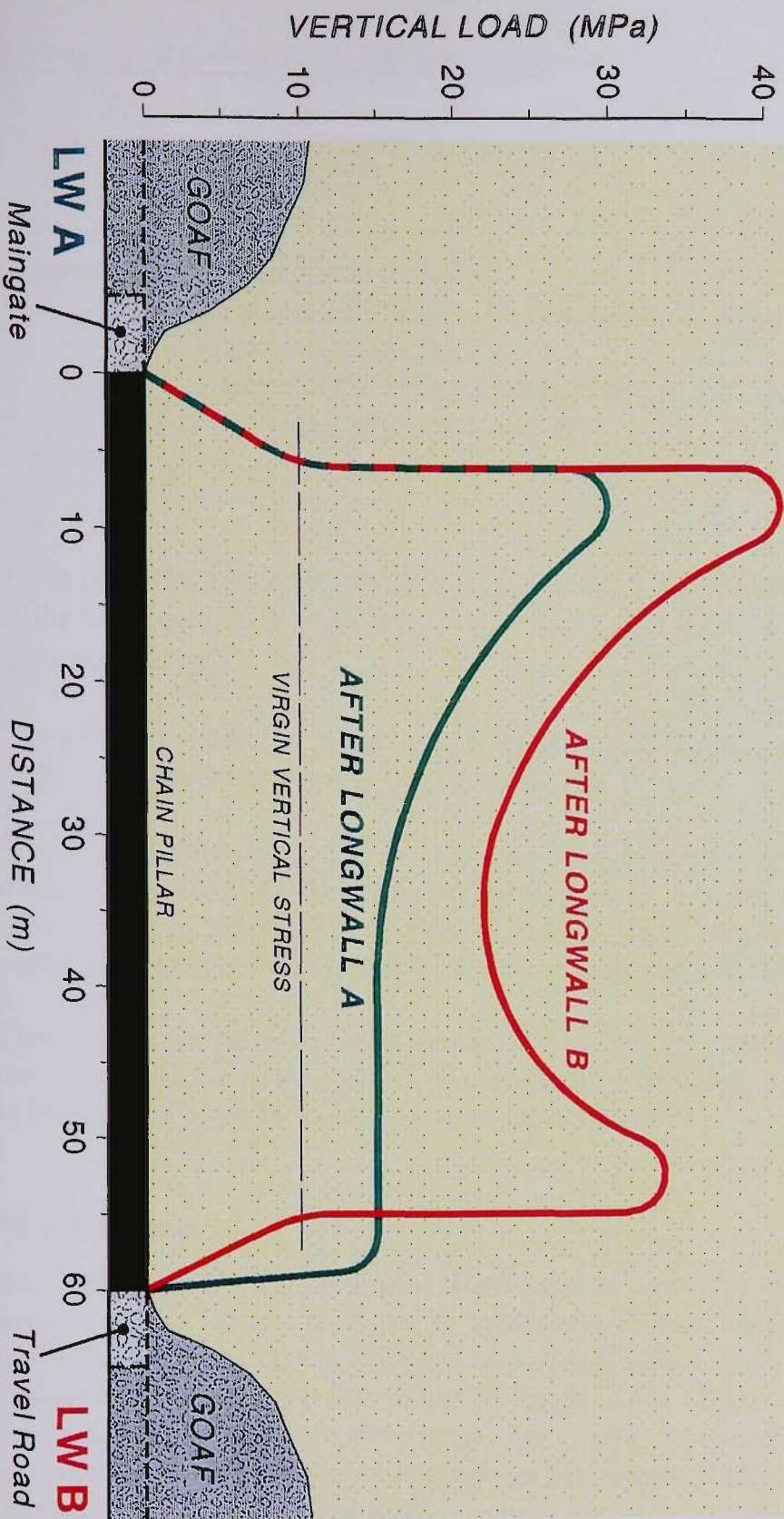
The report confirmed that the load on chain pillars isolated in the goaf was difficult to measure, however the few available measurements indicated that the strength of large width-to-height ratios in a strong roof-floor environment may be significantly greater than strength estimates using the above design formulae. Computational modelling supported the findings and indicated the development of high levels of confinement (see top curve of Figure 5.31). This explains the discrepancy between the calculated pillar strengths predicted by the two methods of analysis (AMIRA and Squat Formula).

c) Salamon Squat Pillar Formula

Salamon recognised that his published formula was not applicable to pillars having a high pillar width to height ratio, and as a result published an extension to his formula to allow it to be applied to a wider range of pillars. The new formula has become known as a squat pillar formula due to the nature of the pillars it applies to and is reproduced below;-

$$\rho_{\text{squat}} = \sigma_c \frac{R_o^{0.5933}}{V^{0.0667}} \left(\frac{0.5933}{\epsilon} \left[\left(\frac{R}{R_o} \right)^\epsilon - 1 \right] + 1 \right)$$

SOUTH BULLI COLLIERY TYPICAL CHAIN PILLAR LOADING



Where σ_{psquat} = Pillar Strength (MPa)
 R_o = Critical Pillar Ratio (The maximum width-to-height ratio at which the pillar will fail)
 R = Actual Pillar Width-to-Height Ratio
 V = Volume of Pillar ($=W \times W \times H$)
 ϵ = Laboratory-determined constant

Various laboratory and model tests were carried out in order to obtain suitable values in the calculation of chain pillar strengths for R_o and for ϵ . $R_o=5.0$ and $\epsilon=2.5$ for coal were used (Madden, 1993).

Use of the formula for the proposed Cataract chain pillars (width-to-height ratio of 22.2) predicts a pillar strength of 107 MPa.

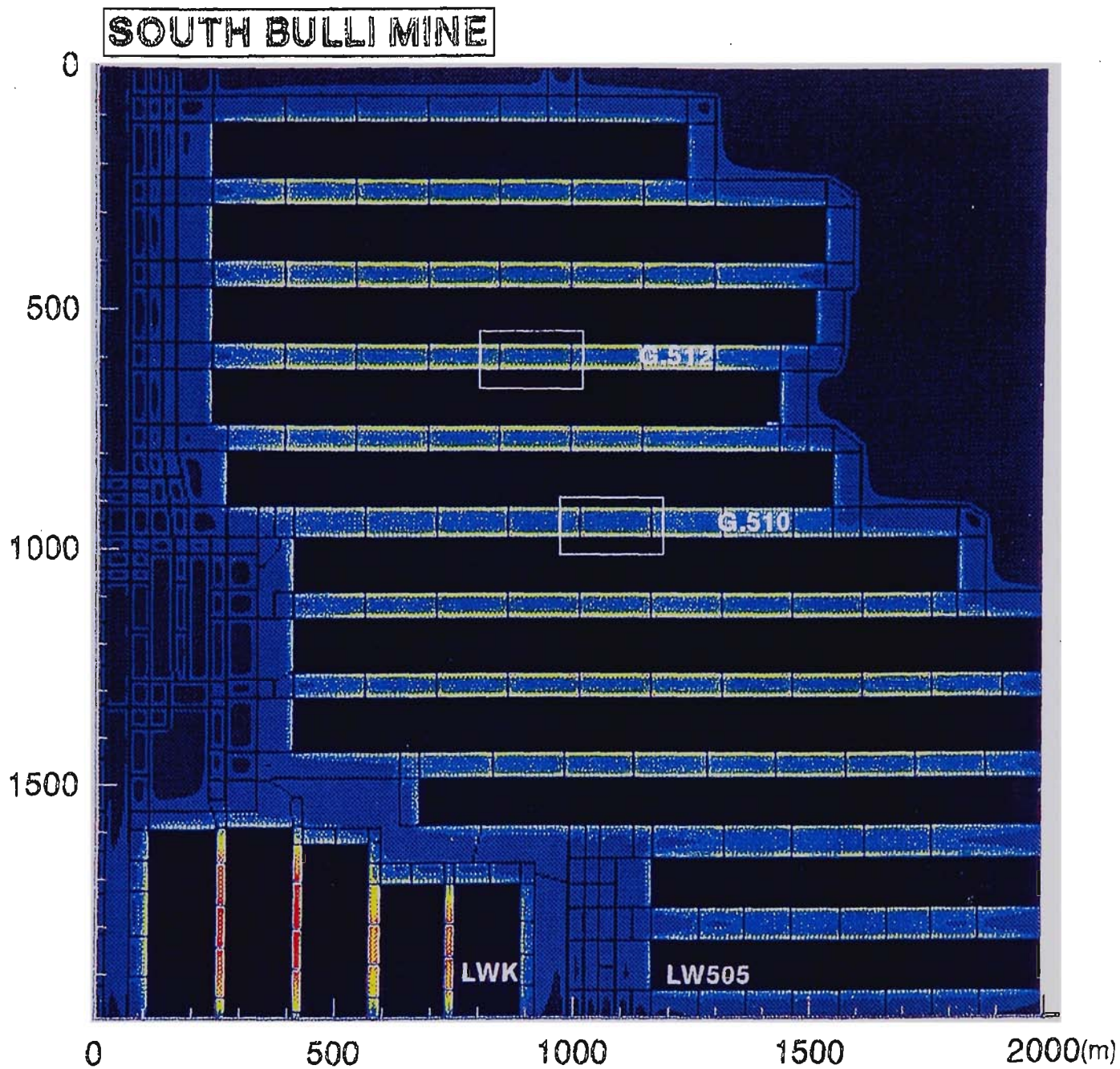
The accurate prediction of pillar strengths for wide pillars cannot be carried out with the same degree of confidence as for narrow pillars. Largely this is due to the lack of failure of wide pillars, which gives in itself a higher confidence of these pillars to withstand whatever loads are applied, even if these can only be estimated.

The application of Salamon's Squat Pillar and the AMIRA-modified Bienawski formulae seem the most appropriate documented formulae, given the very high width to height ratio of the proposed Cataract chain pillars.

5.5.4 Pillar Loading

One limitation of pillar strength calculations is that they only provide an average strength of the pillar, which can be misleading unless loading on pillars is constant across them. In the case of longwall or longwall pillars this is unlikely to be the case. Typical load distributions are shown in Figure 5.32. These show the changing load distribution on a longwall chain pillar from virgin conditions, through development driveage, the extraction of one longwall, and subsequently the second longwall, leaving the chain pillar isolated in the goaf.

The final profile shows a zone of yielded coal adjacent to the roadway, with load building up from zero to a maximum just beyond the yield zone. Load then decays progressively further into the pillar to a minimum value either equal to the pre-longwall loading or a higher value. The significant feature is whether the yield zone progressively and continually encroaches further into the core of the pillar (pillar creep) when the width-to-height ratio is small, thereby reducing its strength. In the case of the Cataract chain pillars the width-to-height ratio is excessively high. Additionally,



Mincad: Pillar loading contour map

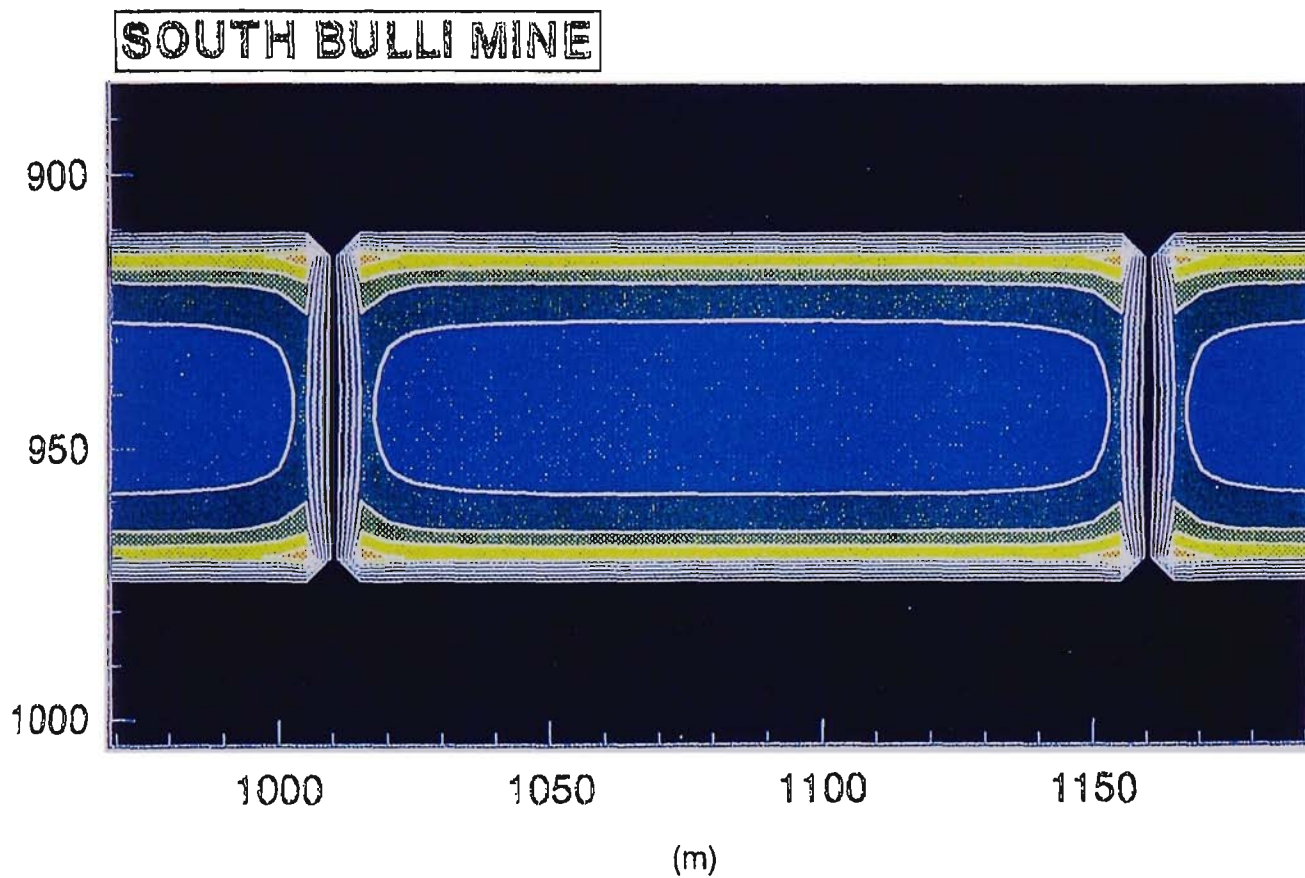
results from the chain pillar monitoring indicate relatively low loads developing, and MinCad modelling of the layouts also suggest a very limited yield close to the pillar edge.

MinCad Systems recently carried out an analysis of a 50 m pillar by 120 m goaf layout. This was carried out using the same program and rock properties used in the analysis MinCad carried out for Sydney Water in 1992. Subsidence and strain results are reported Chapter 3, however pillar loading is discussed here. As the contour plots (Figures 5.33, 5.34 and 5.35) show, after Longwalls 1 to 13 have been extracted, the loading on all chain pillars is still very low. Maximum values of 35 MPa are obtained close to the pillar edge, while the pillar core indicates a load of 20 MPa compared with 8 MPa prior to extraction. A cross-section through a G510 chain pillar is shown in Figure 5.36. This chain pillar is 60 m wide, while the three rows of chain pillars on each side are only 50 m. This is a worse case than the proposed Stage II layout, however the modelled stress levels are still not high enough to cause concern. Average pillar loading is 24 MPa, which is a more important parameter than maximum loading when considering numerical modelling results. This average pillar loading is still well below the pillar strength calculated using either of the formulae used above.

In considering the load applied to the Cataract chain pillars, the approach of Whittaker was adopted as a suitably simple and conservative method. This theory states that the chain pillars have to take almost the entire weight of the overburden, as a dead load. An angle of goafing of 45° is assumed, based on the inferred goaf angle when maximum subsidence occurs (when extraction width is twice the depth of cover), and this goafed strata is assumed to lie on the floor of the goaf, and cannot contribute to the load taken by the chain pillars (Figure 5.37). The theory is therefore simply the calculation of contributing overburden volume converted into weight by the specific density of the overlying rock.

The effect of increasing the panel width by 20% from to 120m, does not equate to a 20% increase in average pillar loading. In the case of 60m pillars and 100 m panels, the pillars take the weight of a $100+60=160$ m wide section of strata, however, in the case of 60m and 120 m, the pillars take the weight of a $120+60=180$ m wide section of strata, which is only a 12.5% increase in loading. By widening the panel, slightly more load is taken by the goaf, and this is estimated at reducing the additional loading from 12.5% down to 11%.

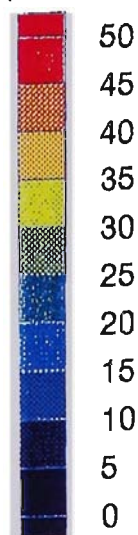
This method is conservative (ie overestimates the load on the pillar) for a number of reasons. The first is that the strata is considered a dead weight on the pillars, however in practice (in circumstances similar to the Cataract layout) at least some of the overburden will still be intact, and therefore capable of distributing load over a wider area than that overlying the chain pillars and extraction area. The theory is also



G.510

Mincad: Pillar loading contour detail G510

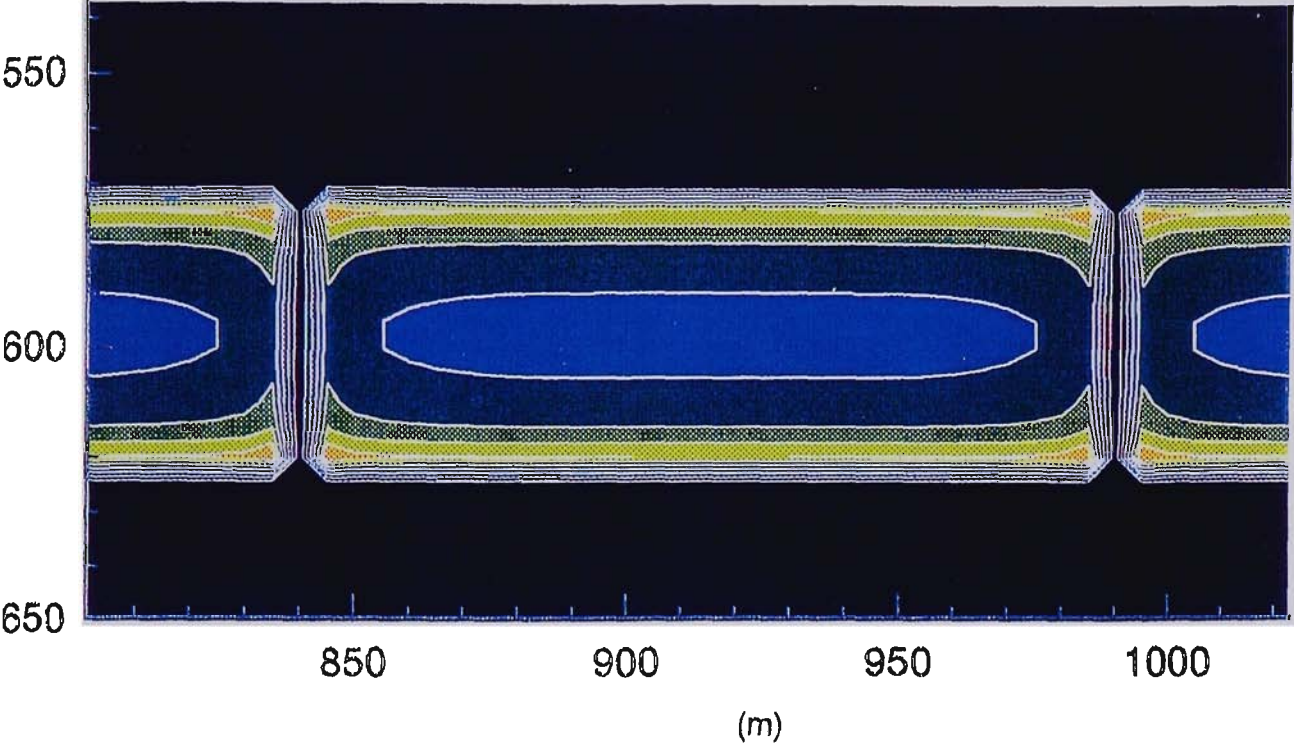
Vertical Stress (MPa) S_{zz}



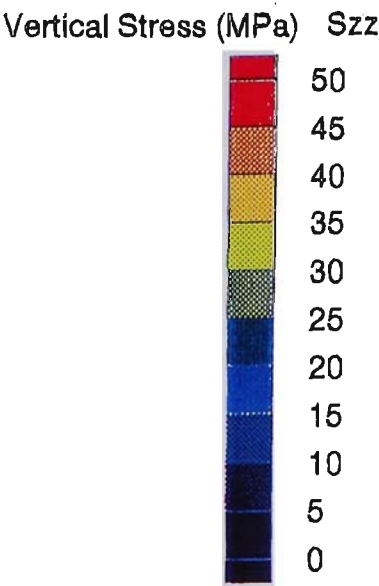
MINCAD

Fig. 5.34

SOUTH BULLI MINE



Mincad: Pillar loading contour detail G512



MINCAD

Fig. 5.35

MinCad : Pillar Loading Profile G510

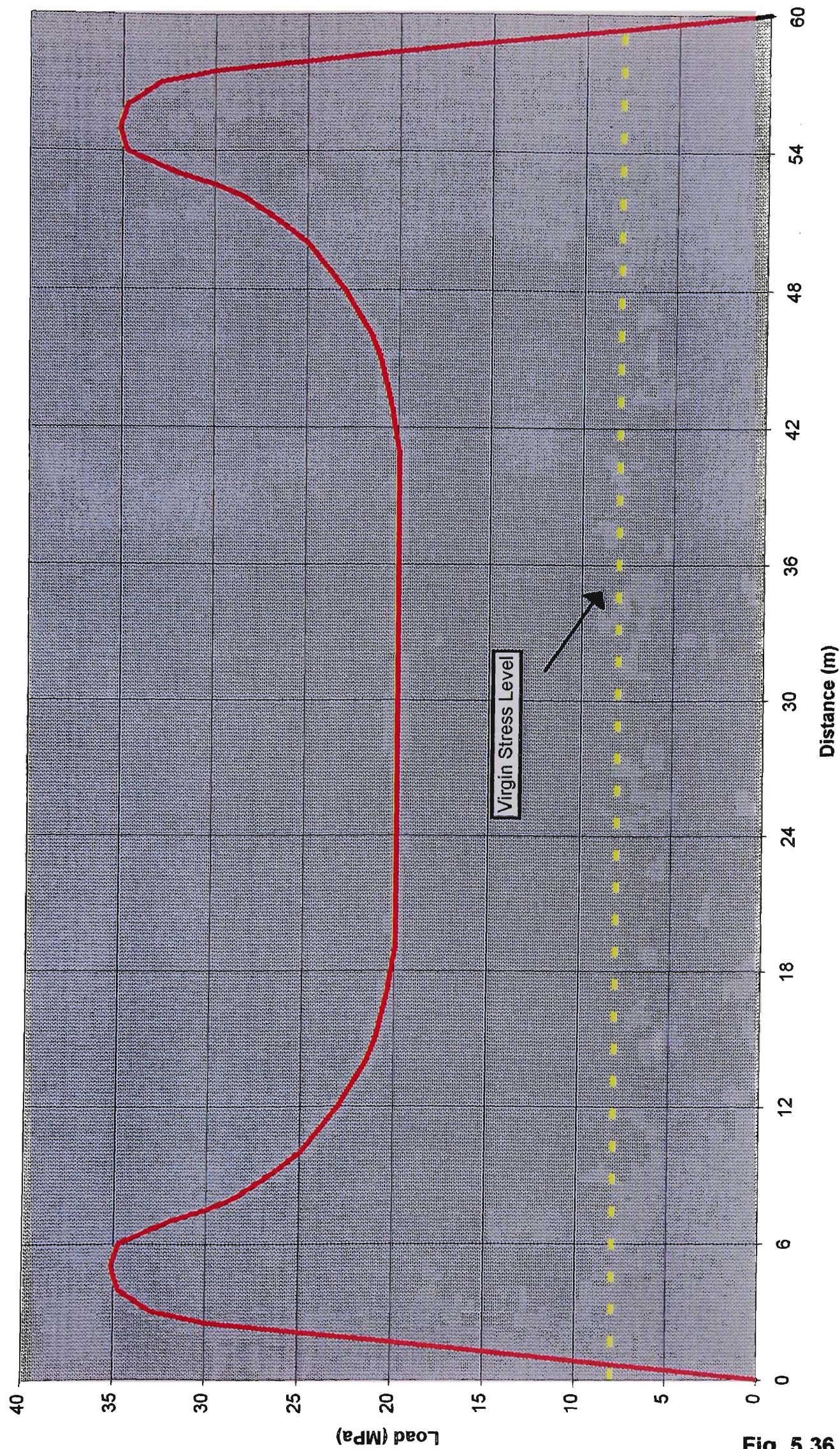
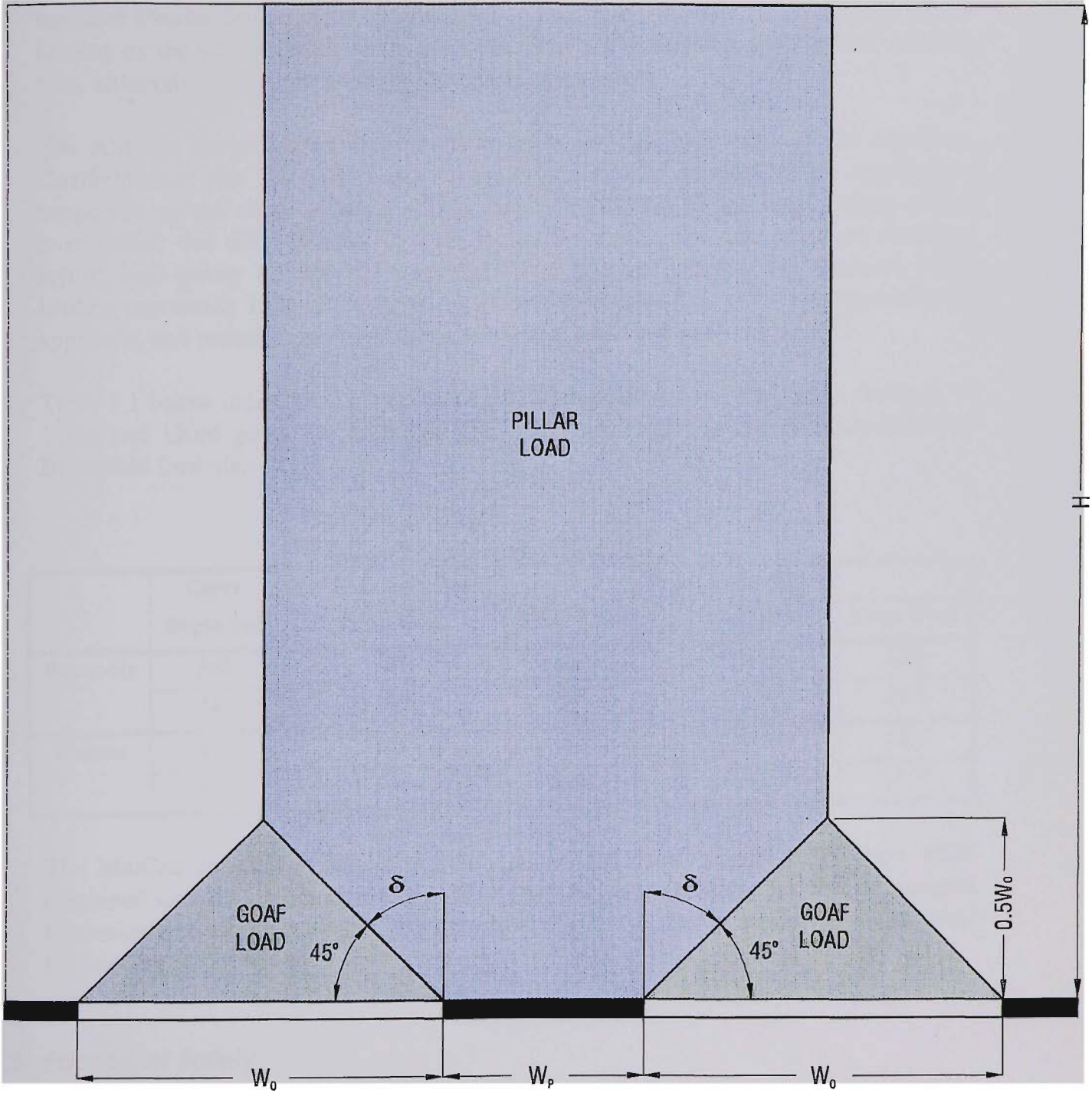


Fig. 5.36

ATTRIBUTABLE PILLAR AREA



- W_0 - panel width
- W_p - pillar width
- H - cover depth
- δ - angle of draw (after Whittaker)

Fig. 5.37

conservative in that there is not consideration of goaf loading other than self-loading by the caved strata. In practise it is likely that at least some of the weight of the subsided overburden is borne by the goaf. These both combine to reduce the actual loading on the pillars. Both of these mechanisms are thought to apply in the Cataract area, although it is not yet possible to quantify their effect.

The AMIRA report stated that in chain pillar geometries typical of the Southern Coalfield (not the Cataract area) longwall mines, the proportion of overburden supported by the chain pillars is of the order of 75-85% of the total weight of the overburden, the difference of 15-25% forms the goaf. For the proposed Cataract layout, and giving consideration to the above loading concept, the assumed pillar loading represents 95% of the total weight of the overburden. This is a conservative approach, and probably over-estimates the actual load applied to the pillars.

Table 5.1 below indicates the assumed loads acting on 60m wide pillars in the case of 110m and 120m goafs, for both the Squat Pillar formula and the AMIRA-modified Bienawski formula;-

Table 5.6 - Pillar Load Comparisons

	Cover Depth (m)	AMIRA Load (MPa)		Squat Load (MPa)	
		110m Goaf	120m Goaf	110m Goaf	120m Goaf
Reservoir	300	20	21	21.3	22.5
	380	25.7	27	26.9	28.5
Plateau	390	26.4	27.8	27.6	29.3
	450	30.6	32.25	31.9	33.75

The MinCad analyses which have been carried out over the last three years when combined with the results obtained to date from the pillar monitoring program, suggest that calculated strength of the Cataract chain pillars will greatly exceed the anticipated full loading.

5.5.5 Factors of Safety

Factor of Safety is defined as below;-

$$\text{Safety Factor} = \left(\frac{\text{Pillar Strength}}{\text{Pillar Load}} \right)$$

Pillars with a Factor of Safety less than one are expected to fail, while higher factors of safety suggest a lower probability of failure. A factor of safety greater than 2.0 is assumed to provide a suitable degree of probability of pillar stability.

To validate the use of the Squat Pillar formula (Madden, 1993) a back analysis was carried out of the dimensions of the chain pillars of South Bulli longwall panels (Table 5.1). It was observed that when the Safety Factor was less than 1.0 (load exceeding the estimated Squat Pillar strength) the pillars did not show up in the subsidence profile. When pillar dimensions were larger, ie 47 m and 51 m, between Longwall 303-305 (panel widths 140-180 m, cover depth 425-445 m), the presence of the pillars in the subsidence profile is apparent. The calculated Safety Factor for these pillars was 1.16-1.50, therefore the assumption that 2.0 is a suitable Factor of Safety for the Cataract chain pillars is confirmed.

Figure 5.38 shows the variation in Safety Factor with depth of cover for the AMIRA formula. Note that depth of cover beneath the Cataract varies from 300 m to 385 m, and that the higher depths of cover, and hence load, only apply to pillars beneath the plateau. These areas are also close to the barrier pillars, and it is likely that some of this load would be transferred onto these barrier pillars, thereby actually increasing the Factor of Safety in this area.

The figure shows two lines;- one for 110 m panels (ie Longwalls 508-510) and one for 120 m panels (ie Longwalls 511-514). G510 is unique, in that the panel on it's north side is wider than the panel on the south, and as a result, the actual Factor of Safety will lie somewhere in between the two lines. Taking the 120 m panels only, as they reduce the Factor of Safety more than the 110 m panels, the Factor of Safety under the reservoir varies from 4.7 to 3.7.

Figure 5.39 shows the variation in Safety Factor with depth of cover for the Squat Pillar formula. The comments made above in relation to the AMIRA Factor of Safety are also pertinent to this figure as well. In this example, the Factor of Safety below the reservoir varies between 3.7 and 2.9.

The two methods therefore predict a minimum Factor of Safety of 2.9 below the reservoir, and 2.4 on the surrounding plateau. These figures are both well above 2.0, and therefore it can be concluded that the pillars will remain stable in the short and long term. Note that these estimations include some conservatism as to the influence of pillar length on strength and pillar loading.

5.5.6 Pillar Instability

Following field measurements and computational modelling carried out as part of the AMIRA report, the conclusion was reached that for the occurrence of any large scale pillar instability, three conditions would have to be met:-

AMIRA Pillar Stability - Factor of Safety

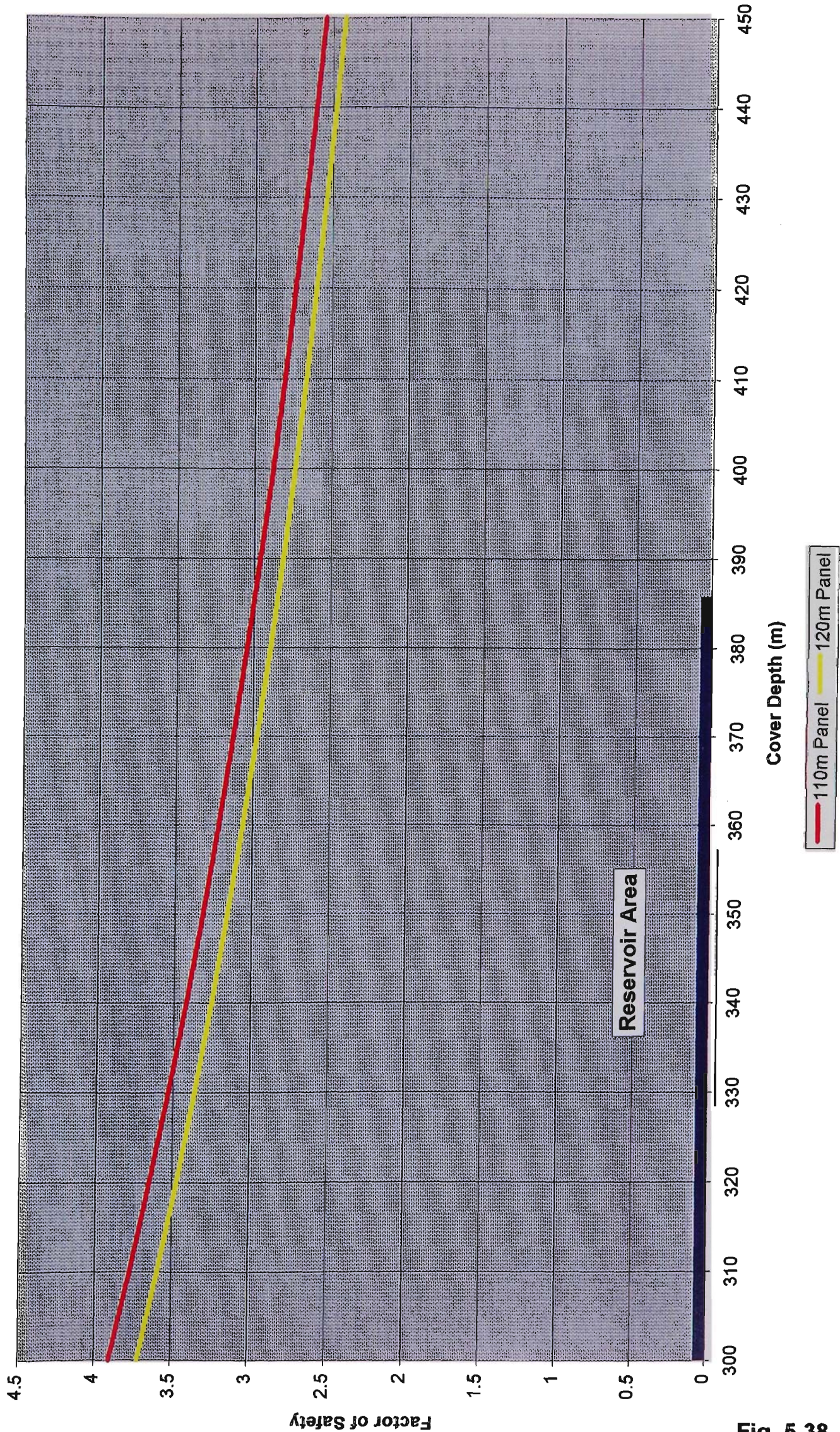


Fig. 5.38

Squat Pillar Stability - Factor of Safety

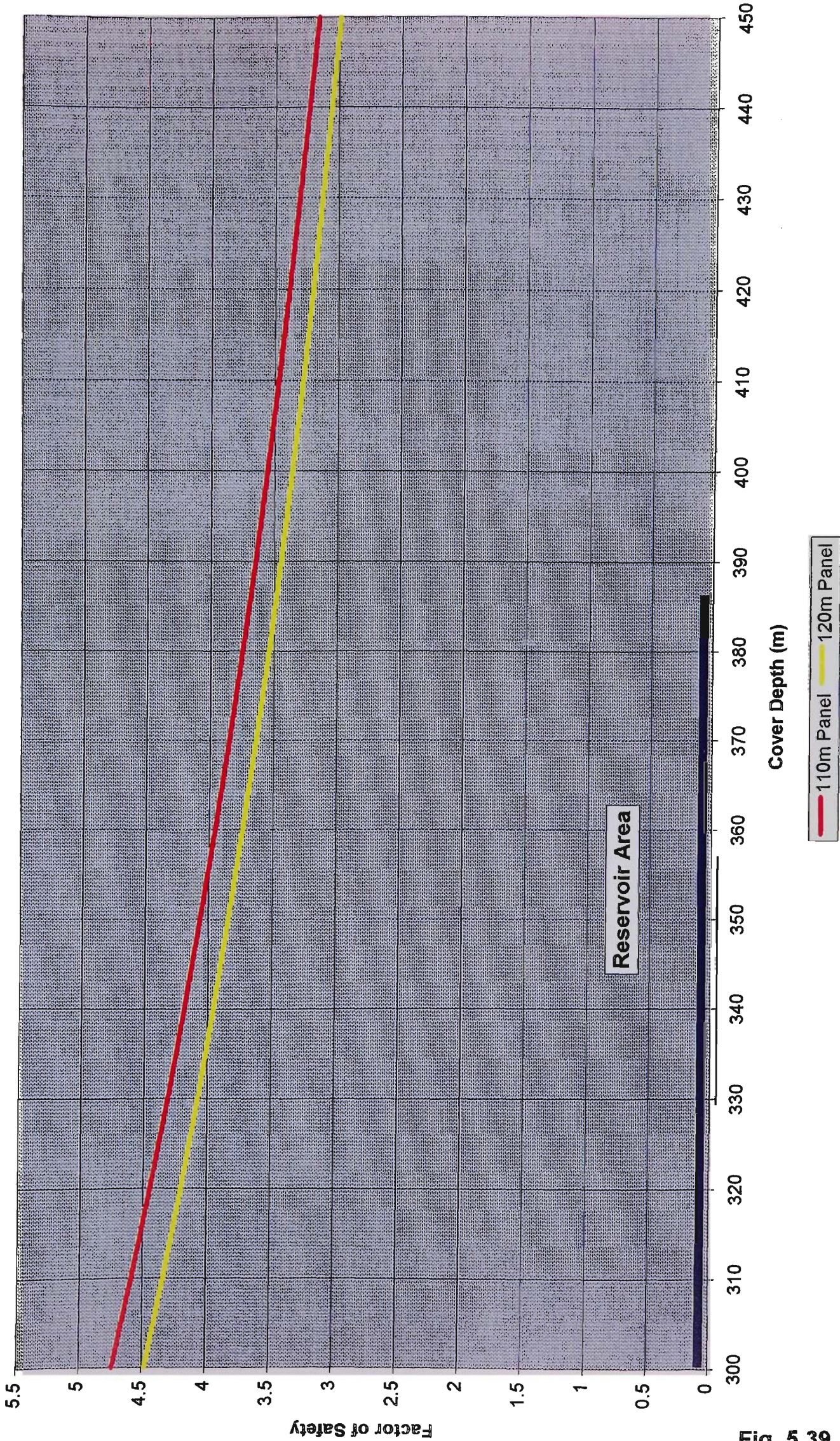


Fig. 5.39

Wardell, K., (1977), "Proposed Mining Beneath Stored Waters of Cataract Reservoir". South Bulli Colliery.

Watson, H.F., (1979), "Undersea Coal Mining in North East England". Proceedings of 10th World Mining Congress, Vol. III, Istanbul, Turkey

Whitfield, L.M., (1984), "Ground Movement from Coal Extraction in the Vicinity of Dams and Storages in NSW". 3rd International Conference on Ground Movements and Structures.

Whittaker, B.N., & Reddish, D.J., (1989), Subsidence, Occurrence, Prediction and Control. Elsevier

Williamson, W.H. & Thorne, C., (1990), Bulli-1 Monitoring Boreholes: Final Report of Effect of Extraction of Panels 1, 2 and 3 Southwest at Bulli Colliery 1983 to 1986. Dams Safety Committee, unpublished report.

Gale, W.J., Mills, K.W., (1995), "Coal Pillar Design Guidelines". Final Report on AMIRA Project P351. 19.1.95

Holla, L., (1985); "Mining Subsidence in New South Wales, 1 Surface Subsidence Prediction in the Southern Coalfield. Dept. of Mineral Resources, NSW

Holla, L., (1985); "The Minimisation of Surface Subsidence by Design of Mine Workings". AIMM Bulletin & Proceedings.

Holla, L., (1989); "Effects of Underground Mining on Domestic structures". Fifth Australia - New Zealand Conference on Geomechanics.

Holla, L., (1989), "Investigation into Sub-surface Subsidence". NEWDDP Report Number 689.

Holman, B., (1988), "Development of Pillar Design Nomograms", End of Grant Report Number 820

Kapp, W. A. & Kennerly, P., (1986), "Subsidence and Strata Control Under Stored Waters in the Southern Coalfield New South Wales". Aust. I.M.M., Ground Movement and Control Related to Coal Mining symposium, Wollongong August.

Mark, C., (1990), "Pillar Design Methods for Longwall Mining" Bureau of Mines IC 9247.

Orchard, R.J., (1975), "Working Under Bodies of Water" Mining Engineer Vol. 134, March 1975.

Reynolds, R.G., (1974), "Coal Mining Under Stored Water".

Schaller, S., (Geomechanical & Technical Design Aspects of Longwalls" Vol 1. ACA End of Grant Report.

Schaller, S., (1983), "Stability of Chain Pillars and Gate Roads". ACIRL Report 83-9.

Peng, S.S., (1992), "Surface Subsidence Engineering". AIME - USA. Department of Mining Engineering, College of Engineering and Mineral Resources, West Virginia Univ., Morgantown.

Singh, M.M. and Kendorski, FS., (1981), "Strata Disturbance for Mining Beneath Surface Water and Waste Impoundments". Proc. 1st Conference on Ground Control in Mining. West Virginia, Univ., Morgantown.

Singh, R., 1994 "Mine Water - Origin, Inflow Prediction and Control" Chapters 1, 13, 14 & 15.

Sydney Water Board Report, (1992), "A Seismic Monitoring System to Determine the Effects of Mining Induced Strains on Reservoir Structures".

- The pillar must lose strength when it yields (ie. small pillars, as large pillars will have greater strength in the core as a result of increased confinement high higher loading).
- One or more pillars must be loaded heavily enough to fail.
- The overburden strata be unable to redistribute the excess load generated by the failure to somewhere else in the loading system that can support it.

The most important condition of the three is the first one. If the pillars are large enough they will not fail, but will always contain a confined core capable of withstanding high loads.

The Cataract chain pillars have a large width-to-height ratio, between 22 and 25. Surrounding strata are strong enough for the coal to develop a satisfactory confinement.

The work carried out by Bellambi suggests that the proposed 60 m wide chain pillars in the Stage II area are still extremely conservative, and that they will deform elastically, apart from small yielded sections adjacent to the longwall goafs, thus long term stability of the pillars will be assured.

The second and third conditions listed above have already been partly addressed by MinCad's Phase IV report dated 6 May 1992. This reported the results of a study where the row of G503 chain pillars had all completely yielded, to a residual strength of 6 MPa. The study concluded that while increased loading on adjacent rows of chain pillars would occur as a result of the failure (due to the ability of the overburden to redistribute excess load), and increased subsidence would result, the failure of one row of chain pillars did not cause failure of adjacent rows of pillars.

5.6 Monitoring Programs

5.6.1 Monitoring Program Objectives

Although the proposed new layout will not pose a risk to the integrity of the water storage, this will be confirmed through a monitoring/investigation program, which has been designed to provide sufficient information on the geology of the Stage II area, and its response to mining-induced strains. The main points of the program are listed below;-

- Underground Mapping
- Geophysical Surveys
- In-Seam Longholes
- Surface Subsidence
- Ground Water
- Water Entry into Mine
- Tectonic Strain
- Chain Pillar Stability
- Water Analysis

The first three programs will ensure that any major structural features are detected, and their vertical extents delineated, although it is not anticipated at this stage that any features will come sufficiently close to the base of the reservoir to pose a risk. The last five programs will ensure that the behaviour of the strata is within predicted limits.

Based on the experience gained to date in the Cataract, parts of this program will be developed in further detail prior to implementation, and discussed with the Dam Safety Committee. A timetable for reporting results from the monitoring programs will be developed with the Dam Safety Committee.

5.6.2 Geological Features

a) Mapping

The routine of underground mapping which was established at the commencement of Bellambi-6 development will continue in this second stage at the same level of detail. Any underground structural features which are detected will be correlated (where possible) with the surface features. Geophysical surveys will be carried out if it is considered that there may be considerable vertical extent to any structures which are detected.

b) Geophysical Surveys

As described earlier, the contribution of two In-seam Seismic surveys in Stage I to identification was minimal. Generally these surveys show the existence of some anomalies, but without identifying their nature. To identify the feature of a suspected anomaly, it is necessary to intersect the area with a Continuous Miner and to document it geologically. Given this additional requirement the ISS survey is not yet considered to be an efficient tool to detect geological structures in front of future longwall blocks. This is best achieved by a combination of the detailed mapping of development workings and longhole drilling. As development is ahead of longwalling, any potentially troublesome structures can be identified well in advance of the longwall panels.

More importantly is the establishment of the location and the extent of the igneous intrusion identified by the Aerial Magnetic Survey in the 511-512 area. For this purpose the hole-to-hole Seismic Survey is considered suitable. Bellambi has already installed geophones in three boreholes in mid Bulli seam level, while three other deep holes have been left open to be used for shooting. Two shallow holes (50 m) were also drilled next to holes with geophones, and these may serve as additional shot holes.

Equally important is the detection of dykes, or major joint zones likely to represent the upward extension of dykes, within the top 100 metres of the overburden. It is anticipated that the most appropriate geo-sensing method(s) currently available will be used. Taking into account the stratigraphic succession and the subsidence characteristics of the overburden rocks, the vertical continuity of any underground discontinuity could have a practical importance only if it extended into this zone.

Drilling alone for this purpose would be prohibitive, so BHP Engineering have been approached to prepare and submit a detailed investigation program for the top 100 m of strata.

The variety of methods available is large, but the applicability of each appears to be subject to a particular set of conditions: magnetometer, electromagnetic (EM), VLF-EM, Horizontal loop EM, Ground Penetrating Radar, Thermal mapping and IR Spectrometer.

The program proposed by BHP Engineering is summarised below:

- Phase 1: A trial of combined magnetic, VLF-EM, Horizontal Loop EM and GPR over a small area of known dykes (The trial area should include at least a portion of the dry lake bed currently exposed).
- Phase 2: The main survey using the technique(s) selected from Phase 1.
- Phase 3: A drilling program to test the dykes at a depth of approximately 100 m. Drilling data should be integrated with the geophysical interpretation and this should be reviewed once the source of the anomaly is confirmed.

c) In-Seam longholes

As previously described, structural/gas data is being obtained in the Bellambi-6 area through the implementation of a longhole drilling program which complies with the requirements of special Section 63 outburst regulations. This program will continue throughout the Stage II development.

Longholes will be drilled regularly in the gateroad driveages to obtain structural information and coal samples for gas analysis, in advance of the development workings.

5.6.3 Subsidence

a) Surface subsidence

Monitoring of the existing cross lines A₇A' and D-D' will continue via surveys carried out at the completion of each longwall panel, until the incremental subsidence between surveys decreases to a level indicating that subsidence has stabilised at a maximum value.

In Stage II, as in Stage I, the existence of the Reservoir in the middle of the extraction area restricts the choice of location of subsidence lines. The results from Stage I showed that the survey lines established along the centre lines of the panels would not indicate the maximum subsidence, nor the complete shape of the subsidence trough.

Bellambi has indicated to the Dam Safety Committee that the subsidence line E-E' which was intended to be established along the centre line of Longwall 507 could be beneficially replaced with a subsidence grid over Longwall 508 on the headland north east of longwalls K to O. The subsidence grid over Longwall 508 will be in the vicinity of the Water Board's KO3 station (Figure 2.15), which will allow improved correlation between Bellambi subsidence, the Water Board tectonic surveying and the CSIRO tectonic strain programme.

This grid may be augmented by a cross line over Longwalls 511-513, however the topography in this location (which is the most suitable in terms of a straight line distant from the face finish position) is not favourable for allowing accurate levelling. It may be better to establish a number of points to the west of the reservoir whose reduced levels would be obtained by GPS surveying. These would not have the accuracy of existing subsidence levels (Lines A-A' etc), only being accurate to approximately ± 2 cm, however this may be more accurate in absolute terms than a line along Longwalls 511-513.

Instrumentation to be used for surface subsidence measurement will be the same as was used in Stage I, although much greater use will be made of Electric Distance Measuring to survey the subsidence grid, as this is the only practical option. Accuracy at the grid will be higher than the Electric Distance Measuring used on lines A, B and C, due to the possibility of surveying a greater number of points.

b) Sub-Surface Subsidence

Data concerning the response of the overburden between the Scarborough sandstone (85 m above the base of the seam) and the Hawkesbury sandstone (90 m below the surface and 40 m below the base of the Reservoir) was indirectly obtained by the monitoring of the groundwater régime above Longwalls 501/502. This monitoring program will continue through Stage II, and be supplemented by the establishment of an additional groundwater monitoring program.

The ground lift measured at the northern end of cross line A-A' after the completion of Longwall 501 and Cordeaux Longwall 20 has prompted the question of just how the upper strata beyond the panel boundaries are deforming.

The vertical extensometers installed in the tectonic strain boreholes over Longwalls 503 and 508 which cover the interval between the Reservoir floor and the surface should provide a good indication of behaviour of the sub-surface Hawkesbury Sandstone.

5.6.4 Water

The monitoring program will deal with both the groundwater régime and underground water make.

a) Ground Water

The automatic logging of the piezometers installed in the bore holes drilled over Longwall 502 will continue through the Stage II extraction. The groundwater régime is very close to being stable at present, however the monitoring scheme will remain in place to confirm that this continues.

An additional groundwater borehole will be established over the Stage II area and will target the base of the Bulgo Sandstone to determine the vertical extent of the zone of linked fractures from the caved areas above the longwall extraction.

b) Water Entry into Mine

The monitoring system initiated in Stage I to monitor water balance in the Cataract will continue through Stage II. Inflow and outflow will be automatically measured and recorded. It is anticipated that the pattern of Stage II results will be similar to those already recorded, with most of the water pumped in to the Cataract leaving the area via the conveyor belts, moisture in the air flow or percolation through the floor. It is possible that some small inflow of water from the Scarborough Sandstone may occur during the Stage II extraction, depending on the magnitude of earlier disturbance to this unit. Any such inflow would be very small and well within the capacity of the existing pumping system.

5.6.5 Tectonic Strain

The strainmeters installed in 1993 will continue to be monitored automatically throughout Stage II. The main objectives during Stage II will be;-

- measurement of strain in the borehole above Longwall 503 and Longwall 508, once these areas achieve supercritical extraction.
- correlation between surface strain measurements on Line A-A' and the tectonic strain at the borehole above Longwall 503 where possible.
- to establish the pattern of strain during dynamic subsidence.
- monitoring of strain at Station Y, close to the dam wall.

The results of this program will be correlated with those of the surface subsidence surveys and the groundwater monitoring program.

5.6.6 Inter-panel Chain Pillar Stability

A pillar monitoring station will be installed in a cut-through of G509, with the aim of monitoring the stability of the chain pillars in the Stage II area. Further details of the program will be established later, once a full assessment of the performance of the Stage I pillar monitoring program has been carried out.

It is anticipated that the monitoring of the pillars would consist of a stress profile across the pillar, in conjunction with monitoring of deformation of the first 15m or so of the pillar edge (measured from the side of the roadway), which is considered to extend much further into the pillar than any possible depth of yield.

5.7 Conclusion

The test programs, investigations and modelling predictions support the changes to the panel width and the further extraction under the Cataract Reservoir.

There are no major faults expected in this next stage, however the presence of a large dyke and sill structure is continuing to be defined. This will alter the original extraction zones planned for the mine and may alter some of the subsidence profiles as areas will not be mined.

Surface Subsidence prediction in the Southern Coalfield (Holla, 1988), indicate values of 1.5 mm/m for tensile strain and 3.5 mm/m for compressive strain. The maximum average predicted is 0.8 mm/m for tensile strain and 1.2 mm/m for compressive strain, this is based on the actual values that have been determined on the Stage I area for the Stage II layout.

During Stage II, work will be done to determine the accuracy of other prediction modelling tools. These are the CISPM Model and the Incremental Profile Method (Rickard & Partners). This correlation work will determine their suitability for future use.

The Cataract chain pillars have a large width to height ratio of between 22-25. The chain pillars are very stable with a peak loading of 32-35 MPa occurring 10-12 MPa from the pillar edge, and a stable core situated 30-35 m reaching a load of 15-20 MPa. These values are well below the prediction models of 107 MPa - Salamon-Squat pillar formula and 78 MPa - AMIRA - modified Bienawski formula. The results indicate that the design is very conservative and the longterm stability of the pillars has a high margin of safety.

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The current project work being undertaken at South Bulli is part of the learning process that started over 20 years ago with the Government commissioning the Reynolds enquiry. During this period minor modifications to the original guidelines were made and a more open working relationship developed between government departments and with the industry.

South Bulli and the Coal Reserves under the Cataract Reservoir represented the first real opportunity to test the theories and confirm with some innovative monitoring programs what was actually happening to a large number of parameters in the strata. With the correct monitoring programs and substantiated data, the original layout and mining plan can be altered to:

- a) minimise risk and
- b) maximise coal recovery

6.2 Conclusions

The investigation programs were extensive throughout the entire project to monitor the theoretical predictions of strata behaviour, stability on the surface and underground to actually what was happening.

The core programs need to stay the same ie:

1. surface geological mapping
2. underground seam mapping
3. in seam seismic surveys
4. seam floor study
5. aerial magnetic survey
6. surface drilling
7. geomechanical testing of rock samples
8. surface subsidence surveys

In addition the following programs were modified to selectively target specific information.

1. In-situ strain to determine the differing effects of pre, actual and post-mining events on the Water Boards surface structures.
2. Piezometers to determine hole and strata integrity and establish the height of fractures as a result of caving activities.

3. Water analysis to determine the origins of water at the surface, in intermediate strata and just above the coal seam itself. This proved to be the most difficult task as the mine design was so conservative that no major roof drippers were in evidence to obtain a representative sample for testing.
4. Chain pillar testing to determine the extent of loading and failure zones and optimise the pillar design.

6.3 Recommendations

Investigation programs need to be designed so that the initial planning and design work can be optimised. It is essential for the safety and integrity of the reservoir structure and the underground workings that no incident occurs to alter this - however parameters need to be determined, to allow maximum coal recovery whilst maintaining full structural stability.

It is recommended that programs should be designed to determine:

- a) chain pillar strength and failure zones to verify the pillar design parameters.
- b) chain pillar design fixed and variations to the width of extraction. This will allow the parameters for panel width/depth cover ratios to be refined and establish the caving height with borehole piezometer testing.

This program may be difficult to complete as one parameter at a time should be altered and time allowed to achieve a steady state before altering the next. South Bulli may not have enough longwall reserves to complete the second recommendation.

REFERENCES

Anderson, D., Stapledon, D.H.S., and Mattes, N.S.W. (1989), Coal Mining beneath Reservoirs, New South Wales, Australia, 1979-1989. Dams Safety Committee, unpublished Report.

Aston, T., and Whittaker, B.N. (1985), Undersea Longwall Mining Subsidence with Special Reference to Geological and Water Occurrences in North East of England. Mining Science and Technology, Vol.2, No 2, April.

Bembrick, D.S., & al. (1973), Structural subdivisions of the New South Wales Portion of the Sydney-Bowen Basin.

Bieniawski, Z.T. (1984) "Rock Mechanics Design in Mining and Tunneling". A. A. Balkema.

Bieniawski, Z.T. (1987), "Strata Control in Mining Engineering". A. A. Balkema.

Bieniawski, Z.T. (1992), "Ground Control", SME Mining Engineering Handbook, 2nd Ed. Hartman (senior ed.), Society of Mining, Metallurgy and Exploration, Inc, Littleton, Colorado, USA.

Brady, B.H. & Brown, E.T. (1985), "Rock Mechanics for Underground". George Allen & Unwin.

Budavari, S. (1983), "Rock Mechanics in Mining Practice". The South African Institute of Mining and Metallurgy.

Bunny, M.R. (1972), Geology and Coal Resources of the Southern Catchment Coal Reserve, Southern Sydney Basin, N.S.W., Bull. Geol. Soc. N.S.W., 22.

Dams Safety Committee

- Coal Mining Beneath Reservoirs, NSW, 1979-89
- Annual Report 1987/88, 1988/90
- Notes on the Administrative Role of Dam Safety Committee in the Granting of Coal Leases and Approval by Mining Applications, May 1990
- Mining Restricted Zones of Prescribed Dams, May 1990
- Summary Report on Mining within the Restricted Zone of Bannans Creek Dam. 1990
- Summary Report on Mining Applications within the Restricted Zone of Cataract Storage. Bulli - 1; Bulli - 3; Bulli - 9; Bulli - 11.
- Remarks on Dam Safety Committee Policy By Zsolt Kesseru. 1989.
- Remarks, Proposals on Under-mining Water Storages / Dams Relating to the Questions of Dam Safety Committee, By Zsolt Desseru. 1988.

Holla, L., (1985); "Mining Subsidence in New South Wales, 1 Surface Subsidence Prediction in the Southern Coalfield. Dept. of Mineral Resources, NSW

Holla, L., (1985); "The Minimisation of Surface Subsidence by Design of Mine Workings". AIMM Bulletin & Proceedings.

Holla, L., (1989); "Effects of Underground Mining on Domestic structures". Fifth Australia - New Zealand Conference on Geomechanics.

Holla, L., (1989), "Investigation into Sub-surface Subsidence". NEWDDP Report Number 689.

Holman, B., (1988), "Development of Pillar Design Nomograms", End of Grant Report Number 820

Kapp, W. A. & Kennerly, P., (1986), "Subsidence and Strata Control Under Stored Waters in the Southern Coalfield New South Wales". Aust. I.M.M., Ground Movement and Control Related to Coal Mining symposium, Wollongong August.

Mark, C., (1990), "Pillar Design Methods for Longwall Mining" Bureau of Mines IC 9247.

Orchard, R.J., (1975), "Working Under Bodies of Water" Mining Engineer Vol. 134, March 1975.

Reynolds, R.G., (1974), "Coal Mining Under Stored Water".

Schaller, S., (Geomechanical & Technical Design Aspects of Longwalls" Vol 1. ACA End of Grant Report.

Schaller, S., (1983), "Stability of Chain Pillars and Gate Roads". ACIRL Report 83-9.

Peng, S.S., (1992), "Surface Subsidence Engineering". AIME - USA.

Singh, M.M. and Kendorski, FS., (1981), "Strata Disturbance for Mining Beneath Surface Water and Waste Impoundments". Proc. 1st Conference on Ground Control in Mining. West Virginia, Univ., Morgantown.

Singh, R., 1994 "Mine Water - Origin, Inflow Prediction and Control" Chapters 1, 13, 14 & 15.

Sydney Water Board Report, (1992), "A Seismic Monitoring System to Determine the Effects of Mining Induced Strains on Reservoir Structures".

Wardell, K., (1977), "Proposed Mining Beneath Stored Waters of Cataract Reservoir". South Bulli Colliery.

Watson, H.F., (1979), "Undersea Coal Mining in North East England". Proceedings of 10th World Mining Congress, Vol. III, Istanbul, Turkey

Whitfield, L.M., (1984), "Ground Movement from Coal Extraction in the Vicinity of Dams and Storages in NSW". 3rd International Conference on Ground Movements and Structures.

Whittaker, B.N., & Reddish, D.J., (1989), Subsidence, Occurrence, Prediction and Control. Elsevier

Williamson, W.H. & Thorne, C., (1990), Bulli-1 Monitoring Boreholes: Final Report of Effect of Extraction of Panels 1, 2 and 3 Southwest at Bulli Colliery 1983 to 1986. Dams Safety Committee, unpublished report.