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Rock Fracture and Rockbursts

an illustrative study

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Contents

FOREWORD

During my involvement in rock mechanics over a period of almost 30 years, I have interacted with many worthy colleagues and David Ortlepp is one of those with whom I have had a close and lasting association. I am proud and privileged to have worked with him and value this opportunity of writing a foreword to his book. Throughout his career he has never ceased to apply his mind towards the understanding of rock behaviour in mining and in particular to the phenomenon of rockbursts and the search for practical solutions to the serious problems which they present.

His probing intellect and the way in which he approaches "ivory tower" research and tackles the "nuts and bolts" practicalities of applied research in the underground situation, has made an impression on all those who have known him. I have personally found this contact exciting and thought-provoking.

We have spent many very stimulating evenings together, after underground observations of particular events, "solving" these problems, only to find that subsequent observations provided alternative solutions. It is only possible to study and re-study such complex phenomena if high quality records, and associated detailed descriptions of the scenes and situations, are available.

The photographic records and notes contained in this book are chosen from a collection of thousands taken over some 40 years, and represent examples of his efforts to facilitate the study and analysis of these complex processes. They show the meticulous and painstaking approach he has to the subject and provide quality documentation of rock failure mechanisms which occur in deep-level mining, but which are often not observed and seldom captured so clearly. Anyone who has been involved in underground mining will appreciate how difficult it is to obtain good quality photographs in the working environment. They will know of the discomfort of deep level conditions where high temperatures and humidity cause lenses and spectacles to mist up and where access is often difficult, sometimes dangerous and invariably uncomfortable. Under these trying conditions Dave Ortlepp persevered and produced the special collection of photographs and records presented here, some of which are superb examples of their kind. Some of these date back more than 30 years, which means that he has systematically collected, tiled and annotated photographs, negatives and sketches over a long time.

Readers of this remarkable book will be able to compare the case studies with their own observations; and perhaps be persuaded to re-evaluate their previous opinions. I even dare to hope that perhaps some will become sufficiently intrigued to promote or actually undertake similar studies or research. It is important that attempts should be made to try to answer the provocative questions posed by some of the captions and text and which will continue to challenge mining engineers wherever hardrock mining is undertaken at depth.

I believe that this book will become a collector's item to be visited and revisited whenever the topics of rock failure and rockbursts are discussed or researched: perhaps to become a legacy that will benefit the international rock mechanics community for many years to come.

TR STACEY

МОЖНО УПОДОБИТЬ ВСЯКОЕ ЗЕМЛЕТРЯСЕНИЕ ФОНАРЮ,
КОТОРЫЙ ЗАЖИГАЕТСЯ НА КОРОТКОЕ ВРЕМЯ И ОСВЕЩАЕТ
НАМ ВНУТРЕННОСТЬ ЗЕМЛИ, ПОЗВОЛЯЯ ТЕМ САМЫМ
РАССМОТРЕТЬ ТО. ЧТО ТАМ ПРОИСХОДИТ.

An earthquake is like a lighthouse: its penetrating beam sweeps by,
briefly illuminating the Earth to yield, for a moment,
a view of the interior and a fleeting glimpse
of its inner form and content.

PREFACE

The passage opposite is a free and somewhat embellished translation of a thought expressed in 1960 by Russian geophysicist and academician B.B. Golitsin. The essence of the translation is due to Aleksander Mendecki, seismologist, innovative thinker and friend who brought the original quote to my attention several years ago to describe the power of the science of seismology. Responding to a recent request from me, Aleksander kindly sought out the original text and made a brief and, I am sure, accurate interpretation of the original. Any elaboration or distortion of Golitsins idea that might have occurred since, is mine. It would reflect my need to convey adequately the abiding impression it made on me at the time. The metaphor aptly illustrates how the study of transmitted and reflected wave energy through the earth's crust first gave clarity and dimension to the hypothesis of a planet made up of concentric layers of rock-like materials surrounding a massive metallic core.

The image that was evoked and which has remained in my mind, is one of an impenetrably large, totally opaque sphere with the interior momentarily but dimly illuminated whenever a large earthquake occurs. I am reminded of how, on a dark summer night, the shapes of the clouds of an approaching thunderstorm would be fleetingly out-lined by the half-hidden lightning behind them. Later, surrounding detail would be intermittently and vividly revealed by the repeated vivid brilliance of the ensuing electrical storm.

In recent years the application of proper quantitative seismology to the study of the problem of rockbursts and mine seismicity has revealed much of the profound hidden processes and structure and also of the mechanism of failure within the opaque rock mass surrounding mine openings. However, the effects of these transient phenomena often remain obscure. They can usually be viewed only in extremely difficult, sometimes dangerous circumstances where the simple tools of measuring tape and note book sketches are totally inadequate, albeit that they served the classical early students of earthquakes so well.

Good photographs can usually overcome these deficiencies, but often the camera or the necessary skills are not available at the time that the observations are first made. As photography has been a hobby of mine for many years, it followed naturally that I would use it also to supplement the observations I needed to make in pursuing my enduring interest in rockbursts and rock fracture. An accumulation of several thousand negatives resulted from some thirty years involvement in mining rock mechanics. Most of these recorded actual rockburst damage or highly-stressed conditions and instances of rock failure. In the selection of a few hundred photographs that make up this book, there is a heavy bias towards hard rock mines which range in depth from deep to very deep. The bias is a result of an almost obsessive preoccupation with the effects of the very high stress that is inevitably a consequence of mining at such depths and with the occurrence of violent failure that usually follows if the surrounding rock mass is strong and brittle. Because 1 am convinced that these problems are so important and the attendant risks to safety are so crucial that together they will ultimately determine the practicable limit to the depth of future mining, I feel it unnecessary to apologise for this narrow focus.

Many colleagues and friends who have seen some of these photographs expressed the view that they should be exposed to a wider audience. The most persistent persuasion came from my respected colleague Dick Stacey and from my wife Rosemary who separately urged that the exposure should take the form of a book or atlas. To them I owe my thanks for its eventual emergence. My particular gratitude goes to my wife for her continued support, encouragement, patience and fortitude in enduring the long wait for its completion.

My earnest hope is that this selection of some of the more informative photographs and the further study that they have initiated will, rather like an earthquake reverberating through the earth, shed some light into the obscure world of rockbursts and unstable rock fracture and thereby contribute to the much needed understanding of one of the most complicated and challenging problems facing the world's deep mines. At the very least, hopefully sometimes with the brilliance of a lightning flash, the pictures should reveal clearly some of the detail of the damage inflicted by the onslaught of a rockburst or caused by the sometimes slow but inexorable passage of a more static stress change.

ACKNOWLEDGEMENTS

Most of the photographs in this book were taken during a long and happy association with Rand Mines Ltd which started over 40 years ago. Continual challenge and encouragement was provided by the head of the Group's ventilation and mining research department, Mr Misi Barcza, and the Technical Director, Dr F G (Pinky) Hill, probably the most notable patron of South African mining research then, and up to the present time. An intellectually stimulating milieu which prevailed in those early years was, to a considerable degree, fostered by these two people and also by other colleagues in research, such as Neville Cook, Evert Hoek and Miklos Salmon.

Although my contact with some of these persons was sometimes peripheral, it all conspired to excite my curiosity and to help develop the enquiring approach hat would ultimately play a major part in the conception and execution of this work. I consider that these influences were important in my early development and I am grateful for them.

The managers and officials of the mines of the Group which were the source of much of the material in the book, invariably facilitated and encouraged the enquiring mind -- an important part of which was the use of the camera as an objective eye and a retentive memory. In particular, East Rand Proprietary Mines (ERPM), where I spent an important formative period of eight years as the rock mechanics engineer, made an especially important contribution to the understanding of rockbursts and rock fracture by driving new tunnels on three occasions, specifically and exclusively for research purposes.

It is the normal custom and courtesy in the case of a book of more usual format, where a few photographs illustrate a preponderance of text, for the author to acknowledge the source of each of the photographs and illustrations. In the case of this collection it has not bean possible, for various reasons, primarily because of the large number of photographs, to comply faithfully with this procedure. Rather than offer tedious excuses, I hope to find acceptance and understanding of any omissions in this regard in the explanation that I needed to get the book, which has taken far longer to produce than was first envisaged, published without any further delay. The wish to increase understanding of the hostile environment of deep underground mines and thereby improve the safety and welfare of those who work there, has been my only motivation and intent. I hope that the owners and officials of the mines outside South Africa, whose underground workings I have been privileged to visit, will also be understanding in those cases where I have failed to acknowledge the source of the material I have used.

Of all the corporate influences that have played a part in the creation of this book, that of Steffen, Robertson and Kirsten, Consulting Engineers Inc, with whom I have been happily associated for several years, is the most important. The firm has unstintingly provided material support in the form of secretarial services and photocopying facilities. The stimulus and security of working in such an organisation with friendly colleagues of similar outlook on continually challenging problems, has proved invaluable. The untiring patience of Michelle Hugo who typed and retyped the manuscript more often than can be remembered, is fondly appreciated. The greatest single stimulus has been provided by my good friend and respected mentor, Dr Dick Stacey, to whom I owe unqualified gratitude. It is almost certain the book would not have been completed, perhaps not even started, without Dick's support and the efforts of my other SRK colleagues.

The assistance and patronage of the South African Institute of Mining and Metallurgy who arranged the publishing of the book and underwrote its production costs, is sincerely acknowledged.

The great majority of the photographs were laboriously processed by hand in a darkroom kindly made available to me at no cost by Dirk Albrecht of In Depth Video Productions (Pty) Ltd. The fact that I was able to produce prints cropped and dodged the way that I wanted at virtually no cost other than time and effort has resulted in better pictorial quality and considerably lower final cost than would have been possible if the photographic processing had had to be done commercially. For this generosity I owe Dirk a great debt of gratitude.

The unfailing interest shown by my wife Rosemary and the unflagging effort she has put into correcting the
spelling and grammar and the reading of the final proof, has been a constant comfort and a major help.

Finally, with fond memory, I acknowledge the profound influence of my father who, more than 50 years ago, introduced his two sons to cameras and the fascinating crafts of the darkroom. He thereby created an abiding interest in photography, without which the essential substance of this collection, the photographs, would not have existed. Without them, the idea of presenting my thoughts on rockbursts in a more conventional way, would never have occurred.

1 INTRODUCTION

INTRODUCTION

The violent failure of rock has always been a serious threat to engineering activities such as tunnelling or underground mining.

In the driving of tunnels and the construction of other civil engineering works in hard rock, rockbursting is often a nuisance and sometimes a significant threat to the safety of workers. It is always a superficial problem in the sense that it is confined to the surface of the exposed rock. It is manifest only during the period of excavation and has usually disappeared by the time the permanent lining has commenced.

In mining, on the other hand, the considerable areal extent of the activity can perturb regional stresses in the rock mass in a way that can induce significant and continuing seismicity even at moderate depths. In the extreme, in certain mining districts where the mines are very deep and the rock is hard and strong, the occurrence of rockbursts presents a major threat to the safety of underground personnel, to the infrastructure and sometimes even to the existence of the mine.

Fracturing of brittle rock is invariably involved in the manifestation of rockburst damage, even if it does not always occur at the seismic origin. It seems natural therefore to bring the studies of rockbursts and rock fracture more closely together.

In some countries rockbursting in mines has been a serious problem for almost a century and formal research, on a significant scale, has been in progress for almost half that time. Despite this earnest effort, no complete solutions have been found anywhere.

Part of the reason for the lack of success must lie in the inherent difficulties of making proper observations and in adequately recording the complete circumstancas of an occurrence. In most underground rockburst situations, purely visual observation is seriously hampered by poor illumination, spatial constraints and often by extremely uncomfortable and often dangerous surroundings. More often than not the evidence is soon obscured or destroyed by the continuation of the destructive process that is the essence of mining. Under these conditions photographs can document the evidence and make it available for detailed study in more comfortable circumstances. As the theoretical bases for understanding of fracture phenomena are developed, their validity can be established by comparing evidence no longer available except in the form of a photograph. Sometimes the photograph itself directly provides the clue to understanding, even years after the event.

It is believed that another important reason for the disappointing progress in rockburst research is the lack of conceptual understanding which, at least partly, derives from an inadequate technical vocabulary. So many descriptive words exist in mining terminology, all of them more picturesque than precise, such as *bumps, quakes, blasts, shakes, tremors, pressure bursts, strain bursts* etc.. . that a common perception fails to emerge. A working commission on rockbursts has recently been instituted by the International Society for Rock Mechanics, one of whose tasks is to create a common terminology.

It is the author's belief that an important first step towards the understanding of rockbursts is to preserve a dichotomy that distinguishes two related, but often separate, aspects of the problem: that which concerns the source mechaaism and that which deals with the ***mechanism of damage***. Broadly, the first part can be seen as the ***cause*** and the second part as the ***effect***.

Much of the insight into the first part will be provided by seismology and the study of the mechanics of the stability of fault blocks and large-scale failure processes. Mining strategies to mitigate the problem will involve major decisions concerning stoping layout and sequencing with comprehensive recognition being given to the nature of regional geological structure and probable stress regimes.

To understand and control the effects of the seismicity, namely the damage to the excavations, is conceptually the easier part. Understanding requires fundamental appreciation of rock engineering precepts of how mining configuration and excavation geometry determine the redistribution of stress and the occurrence of fracturing, and control requires the proper implementation of already established procedures and also the development of innovative support technology.

This book is essentially a phenomenological or descriptive study intended to increase understanding rather than to discuss methods of control. Recognition of the close association between rock fracture and rockbursting and adherence to the dichotomy between source mechanism and damage mechanism, have determined its structure. The range of phenonema depicted extends from the commonplace to some extremely rare, possibly even unique, examples of processes of failure and fracture that have occurred at life-size scale in real underground situations. Depending on the level of understanding which is sought, these phenomena may be viewed matter-of-factly, simply as expressions of rock failures whose deeper mysteries need not be known or explored further, or they may be seen as deeply intriguing puzzles as obscure as any in the behaviour of the upper portion of the earth's crust.

For the most part the introductory notes and captions do not attempt to provide any explanations of the physics of the phenomena. The text is limited to descriptive captions and a brief explanation of the 'geography' and geology of the surrounding rock space. Categoric conclusions are mostly avoided. This is done for two main reasons: firstly, the theoretical basis for fracture occurrence and morphology is often not well established or is controversial and it would therefore be imprudent for the humble observer to venture beyond his depth. Mainly, however, the brevity of text is intended to afford sufficient space to emphasize the purely visual impact of the phenomena that have been illustrated. The justification for doing this is the belief that, as with all the other natural sciences, proper observation is a necessary preliminary to understanding. Where deeper understanding is desired, more detailed explanations should be sought in the referenced material.

Hopefully most readers will enjoy many of the photographs for their simple visual impact. Perhaps some will also be sufficiently interested by the views expressed in the captions to be encouraged to look for alternative explanations or, possibly, to recall examples in their own experience that support or contradict the ideas offered in the text.

Increased awareness of the powers of observation and deduction that may be aroused could lead directly to improved understanding on the part of the reader. The mental stimulation involved in formulating contradictory arguments could also open up new avenues of enquiry which might lead on to significant advances in the whole study of rockbursts and their solution. If any of this should occur, it would be ample reward for the effort that has gone into producing this book.

2 ROCK FRACTURE

2.1 INTRODUCTION

From the time of the fashioning of the first flint tools, the fracturing of rock has been of great importance to the evolution of mankind and it will certainly continue to be of interest in the technological world well into the future. For the purpose of this study fracturing means the development of a new surface of discontinuity through a previously intact portion of the rock. It specifically excludes sliding or separation across a pre-existing surface such as a joint or bedding plane.

Not surprisingly, Leonardo da Vinci was associated with some of the earliest research into rock material behaviour although it was Galileo (1564 - 1642) who was considered to be the first to experiment with rock in a systematic way (Gramberg, 1988).

The modern study of rock fracture has been vigorously pursued by researchers in several different disciplines notably geologists, geophysicists and civil and mining engineers. Work in the first two sciences was motivated by the need to gain a better understanding of earth-forming processes whilst engineers involved with deep mines and with large tunnels and dams were concerned mainly with the pursuance of safer working conditions and the avoidance of potentially disastrous failures in rock masses.

Any comprehensive bibliography on the topic of brittle rock fracture and earthquake mechanics would almost certainly include references to the works of P W Bridgman, W F Brace, E T Brown, J D Byerlee, Z T Bieniawski, N G W Cook, C Fairhurst, Y Fujii, J Gramberg, E Hoek, J C Jaeger, C D Martin, D D Pollard, T R Stacey, R Sibson and D H Trollope amongst many others.

Important state-of-the-art reviews in the two broad areas of endeavour were given in two text books entitled *Fracture Mechanics of Rock*, and *Rock Mechanics in Engineering Practice*. In his introduction to the first of these works, Atkinson expressed the view that the study of brittle and semi-brittle rock fracture lagged seriously behind developments in the understanding of plasticity and solid state flow of geological materials. He attributed this lag partly to the "... complex nature of fracture in crystalline materials..." but emphasized also that "... evidence of brittle phenomena in the natural laboratory of the earth is often obliterated or obscured by other geological processes...". Studying fractures in a deep mine, while it may often be uncomfortable, does give the observer the distinct advantage that the evidence is fresh and usually uncorrupted.

Probably the single most important contribution to the understanding of brittle fracture has been the theoretical work of A A Griffith in the 1920's. Grifith's essential contribution is neatly and critically appraised by J Gramberg in the introductory section of his own valuable exposition of how these fundamental theories are expressed in rock fracture processes which may be studied in the academic laboratory and also seen in the 'laboratory' of underground coal mines.

The ways in which Griffith's theoretical analyses have been incorporated into engineering understanding and design procedure are clearly discussed in E Hoek's chapter entitled The Brittle Failure of Rock in Rock Mechanics in Engineering Practice, 1968. A more academic and comprehensive exposition of the fundamental importance of Griffith's work to the science of fracture mechanics and the understanding of brittleness is given by T R Wilshaw in Fracture of Brittle Solids, 1975.

Emerging as the common thread of perception running through all the work briefly reviewed above, is that the essential fracture process in rock is one where pure tensile failure commences initially at the tip of an elemental crack or flaw and further breakdown of the continuity of the material thereafter proceeds as an extension or indirect tensile fracture growing in the direction of the maximum principal stress.

It is thought probable that most of the people whose names are listed above would support the notion that extension fracture would be the most likely mechanism of failure of intact rock under the conditions prevailing around man-made structures at all depths in the earth's crust.

The paucity of photographs of direct tensile fracture, where the separation surface follows a path between grains or crystals, suggests that it is very seldom encountered as a stress-induced phenomenon in deep underground mines.

The collection of visual evidence which has been gathered from the underground 'laboratory' of hard rock mining and which is presented in Chapter 2 will confirm this view by showing how ubiquitous extension fracturing is around most underground excavations.

Indeed, with the notable exception of the dynamic rockburst rupture, which is by no means prevalent on every deep mine, it can probably be said that all fracturing in these deep underground mines is extensional in nature. The definitive evidence is not easily shown on the type of photograph which forms the majority of this collection, but it is easily seen with the aid of a hand-lens on any freshly fractured surface particularly if the rock is quartzitic. The fracture surface will tend to be macroscopically planar and will show that pebbles or grains are cleaved or split right through and that the original rounded surface of the grain or pebble does not protrude above the plane. If the clean, intra-granular appearance is not present and a whitened abraded surface with comminution or striations is seen instead, then these are almost certain to be secondary effects resulting from subsequent differential movements on the original fracture surface.

Whether or not shear fracturing can be a primary mode of rock failure in the rock mass surrounding underground openings is a matter of considerable academic interest and perhaps even of some practical importance. A further brief discussion of this problem is given in section 2.4.

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Fracture Mechanics of Rock. Edited by B K Atkinson. Published by Academic Press, London 1987.

Rock Mechanics in Engineering Practice. Edited by K G Stagg and O C Zienkiewicz. Published by John Wiley and Sons, London, 1968.

Fracture of Brittle Solids. T R Wilshaw. Published by Cambridge University Press, 1975.

A Non-conventional view on Rock Mechanics and Fracture Mechanics. J Gramberg. Published by AA Balkema, Rotterdam, 1988.

2.2 Extension fractures

2.2.1 Borehole break-out

Captions

(a) Close view of a circular drill hole through a detached rock slab which originally formed part of the sidewall of a tunnel at depth in a gold mine. The rock was a coarse-grained quartzite, of UCS probably > 250 MPa. The diameter of the drill-hole was approximately 45 mm.

(b) Close detail of the break-out notch. Extension fractures parallel to the notch surface are easily visible.

(c) Tracing of fracture detail around upper break-out notch (4 times). Parallelism with the probable local stress direction strongly suggests that failure is due to the indirect tensile or extension fracture process.

(d) Illustration of distribution of tangential, $\sigma_{\theta\theta}$, and radial, σ_{rr}, stresses around a circular opening in a hydrostatic stress field (from Brady and Brown, page 162)

(e) Equations for determining the elastic stresses in (d)

References

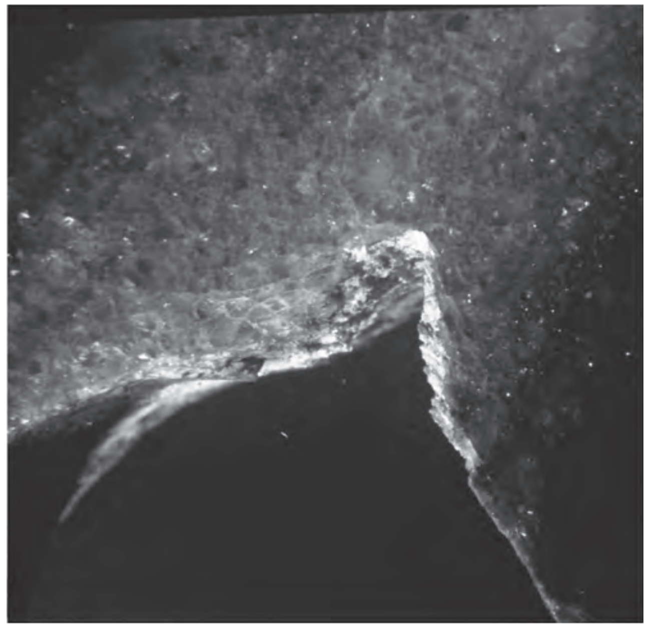
Rock Mechanics for Underground Mining,
BHC Brady and ET Brown.
Published by George Allen and Unwin,
London 1985.

$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right) - (1-K)\left(1 - 4\frac{a^2}{r^2} + 3\frac{a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma\theta\theta = \frac{p}{2}\left[(1+K)\left(1+\frac{a2}{r2}\right) + (1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_r\theta = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2} - \frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

(e)



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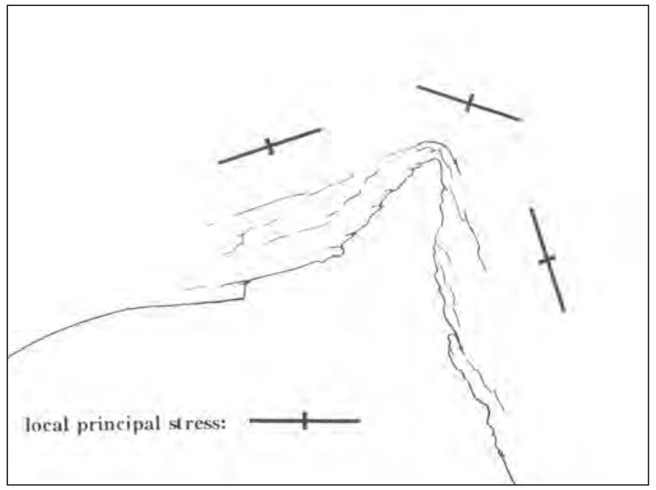
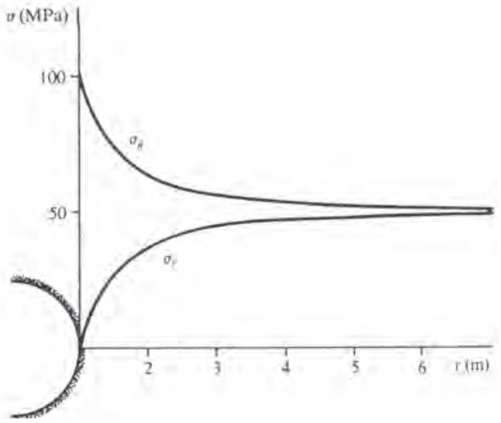


(c)

cos 2θ|

2θ|



(d)

page 1

(a)

2.2.2 Tunnel wall break-out

Captions

(a) View along a non-explosively excavated 3.5m diameter tunnel at a depth of 420m below surface in the underground research laboratory (URL) of AECL Research, Manitoba.

The rock is medium-grained massive granite, completely without joints or visible flaws. The uniaxial compressive strength is reported to be 150 MPa.

The extent of the break-out notch is markedly greater in the roof than in the floor. The lower break-out was revealed only when the lightly-compacted accumulated debris in the floor was cleaned out. The failure process continued while the debris was being removed indicating that very little confining stress was sufficient to inhibit fracturing. The robust similarity with fig (a) on page 1 is strikingly evident.

(b) Close view of wall of a vertical, 1,5m dia. bored shaft about 2m deep, in the close vicinity of tunnel (a). The initiation of the fracturing process by buckling and spalling of 'micro-slabs' is clearly visible along the line of tangency with the σ_{max} stress direction.

(c) Illustration of the strong stress-concentrating effect of the sharp notch and the role played by gravity in tending to make the notch self-propagating - refer also to page 3. The magnitude and direction of the principal field stresses indicated by the vector arrows are values measured in the vicinity on 420 level.

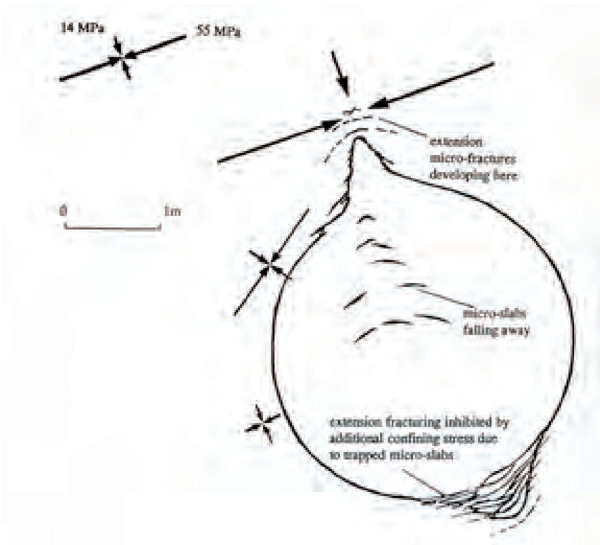
References

C D Martin and G R Simmons. The Underground Research Laboratory. *ISRM News Journal* Volume 1 Number l , September 1992.

Acknowledgement

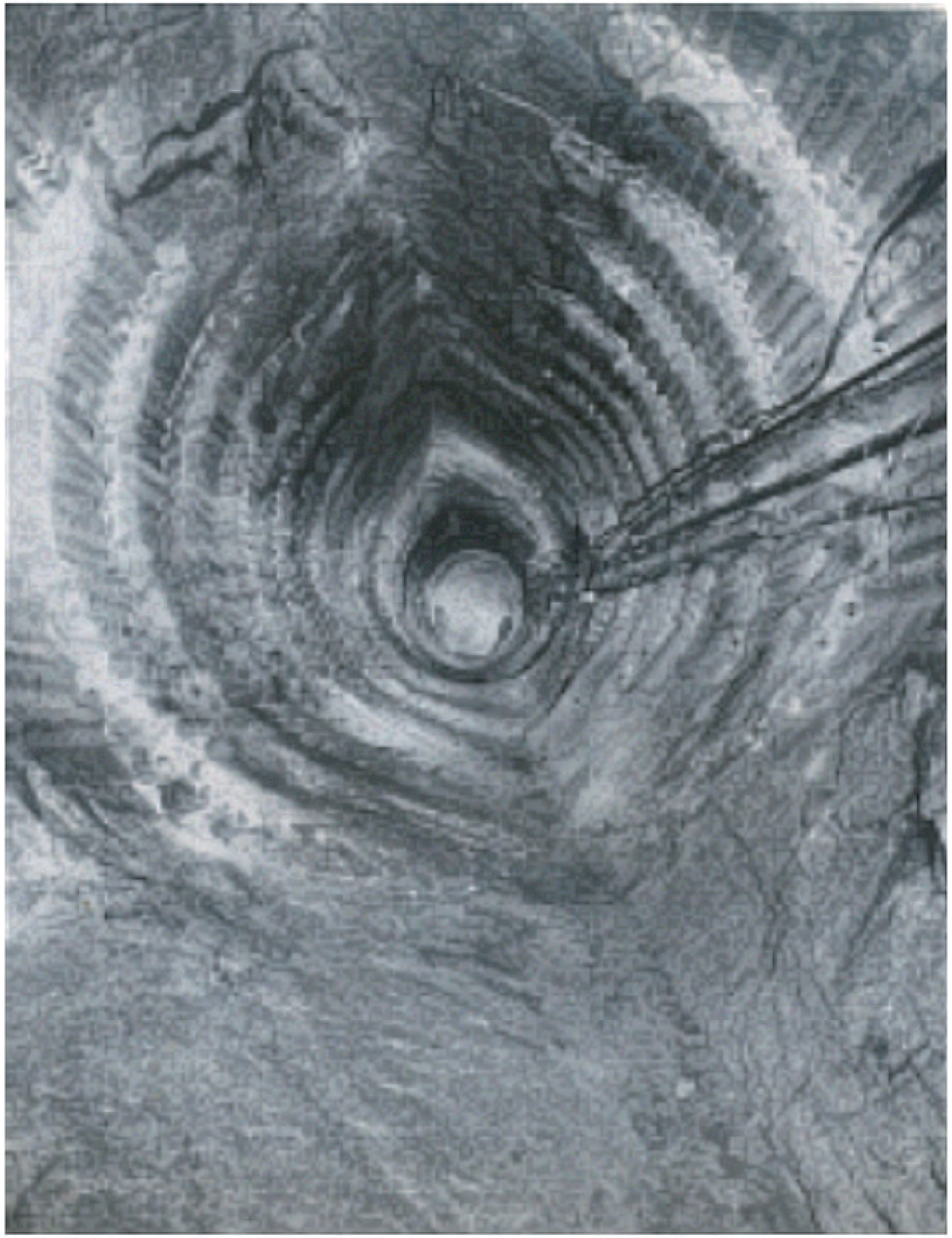
Photographs (a) and (b) were kindly supplied by C D Martin of AECL.

(b)



(c)

page 2



(a)

2.2.3 Effect of tunnel shape

Introduction

Durban Roodepoort Deep Mine (DRD) is the westernmost of ten large contiguous mines that extend along 45km of the continuously-mined Main Reef horizon and which constitute the Central Witwatersrand goldfield in South Africa. The geology of the area is characterized by a thick succession of very strong, relatively massive quartzites which dip southwards and persist to great depths, with comparatively few major faults.

Captions

(a) View north-eastward towards advancing face of 56 level hanging wall haulage on DRD mine, at a depth of 2900m below surface. The location of the tunnel in relation to the overall mining configuration is shown on p 5. Rock is strong massive quartzite dipping at 70 ˚S.

This tunnel was earlier blasted to a symmetrical D-shaped profile when severe slabbing and buckling occurred above the springline on the south side.

Based on the rationale that the best excavated shape would be one which most closely approximated the profile that nature dictated, the blast-hole pattern was deliberately changed to form a tilted elliptical outline as shown in (c). Over much of the profile, extension fracturing developed parallel to the excavated surface and, over the back and northern sidewall, soon stabilized. A micro-slabbing/buckling break-out process commenced in the top south-side corner and continued for more than 1m until a vertical sidewall almost 5m high was formed.

(b) View of south-side top comer showing the whitened trace of the micro-slabbing 'notch' and the pronounced vertical slabs formed by secondary extension fracturing parallel to the overall free surface
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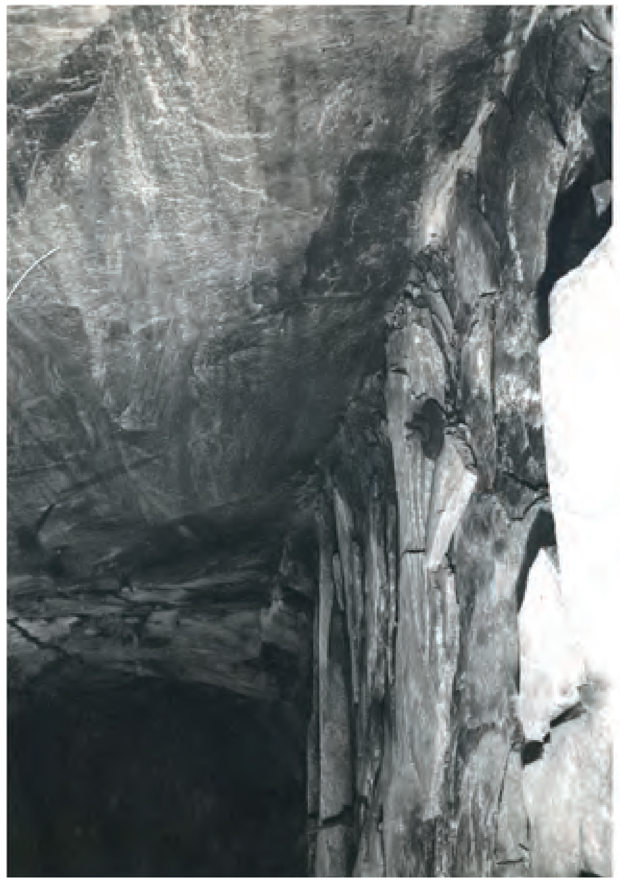
(c) Comparison of blasted and actual outlines. The stress vectors suggested as the possible primitive stress field were derived from over-cored door-stopper in situ stress measurements made 280m above and about 500m to the West.



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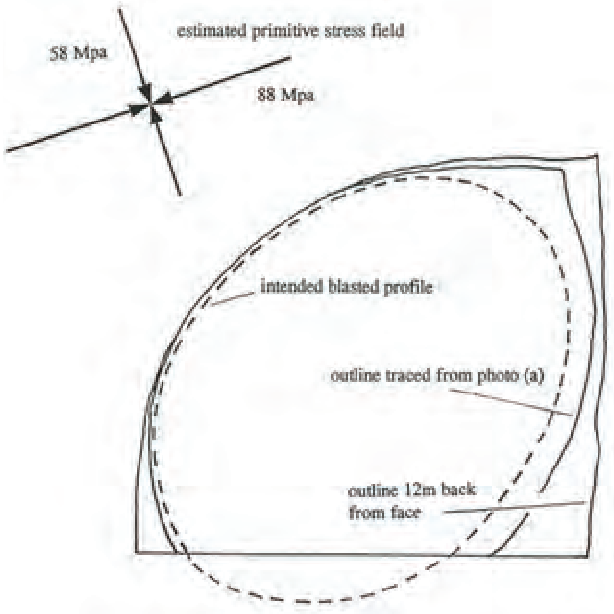


(c)

References

T Oakley-Brown. Contribution to paper by W D Ortlepp et al. Support methods in tunnels. *Assoc. Mine Managers of South Africa Papers and Discussions*. 1972 - 1973, page 196.

page 3

(a)

2.2.4 Effect of gravity

Self-mining in vertical-reef stope

page 4

Captions

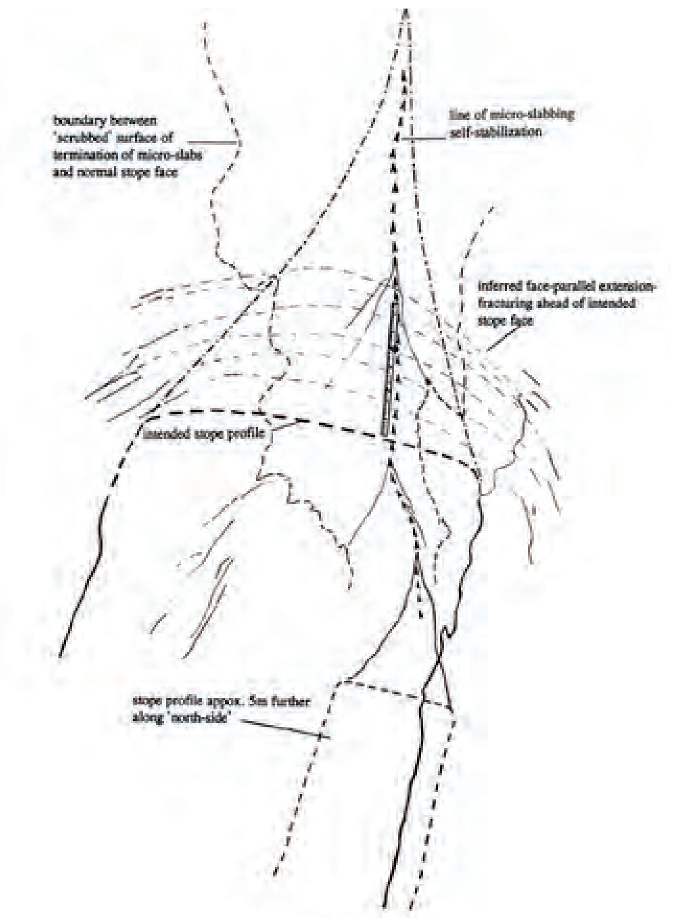
(a) View westward along the strike of steeply dipping Main Reef in 56^W 22^E stope in DRD mine. The camera axis is tilted slightly above horizontal. The original stope face was parallel to strike, forming the 'north-siding' ahead of the long over-hand portion of the main stope face.

The pre-mining field stress would probably have been similar in magnitude and orientation to that shown for the haulage tunnel in Fig (c) on page 3.

The relatively large area of the near-vertical stope would tend to rotate the primitive, σ_{max} stress in the vicinity of point x of fig (c) towards the direction perpendicular to the stope plane and enhance its magnitude by a factor of two or more. Thus the stress ahead of the north-siding stope would cause extensive fracturing to occur parallel to the slope face. Any additional small stress concentrator would tend to localise the slabbing into a punch-like shape. The extreme stress-concentrating effect of the notch would dominate and, together with gravity, would initiate and sustain a self-propagating extension-fracturing process. This process will continue until the curvature of the micro-slabs is so acute that they remain wedged in place.

(b) Interpretative line drawing of fractures traced from photograph (a).

(c) Longitudinal vertical projection of slope showing extent of 'north-siding' ahead of main stope and the position and direction of photograph (a). The regional extent of mining is shown on page. 5.



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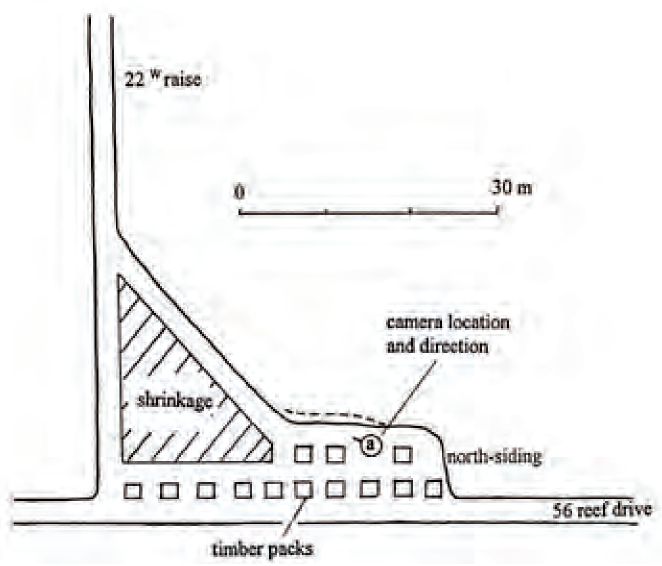
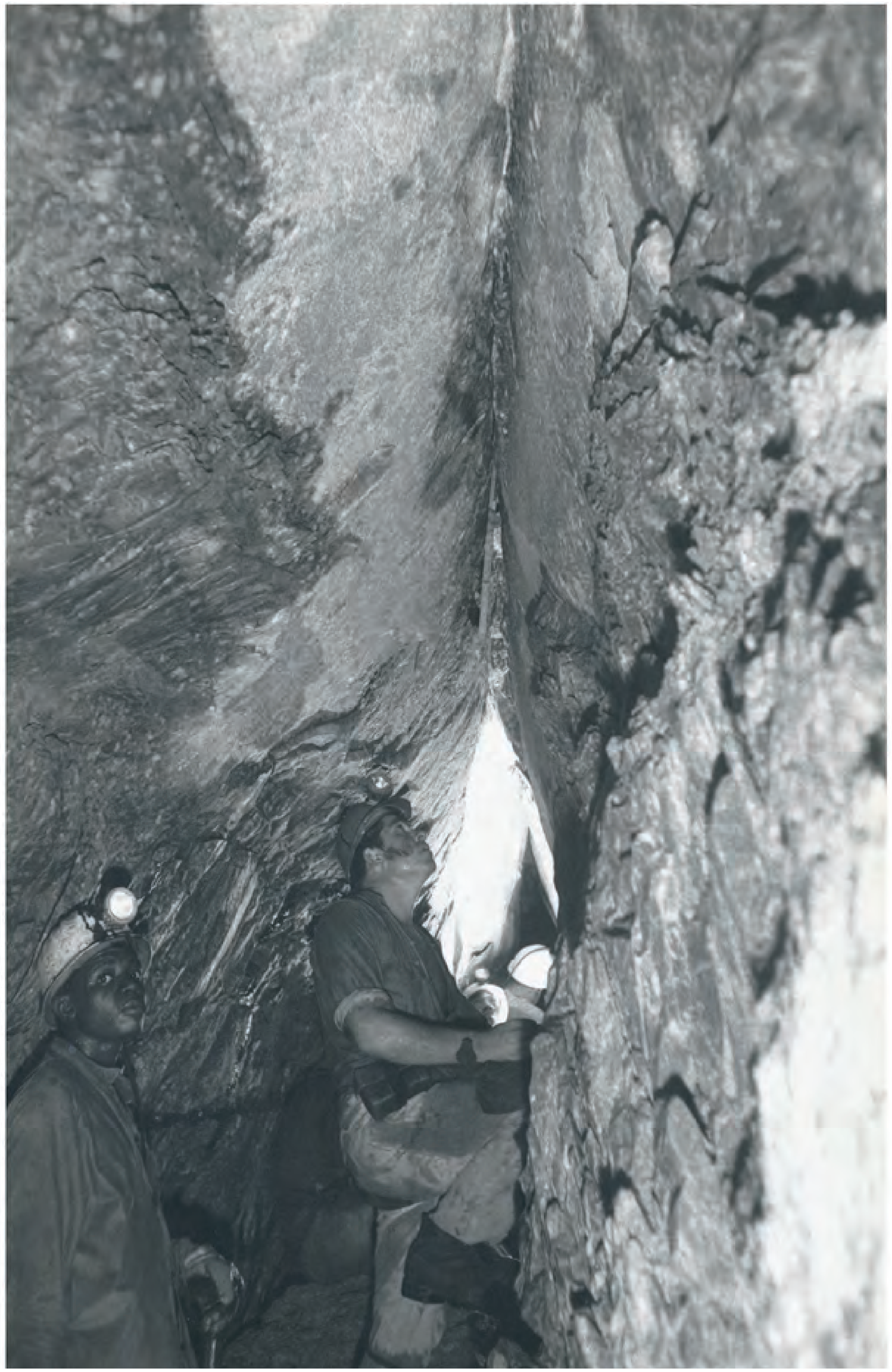


(c)



(a)

page 5

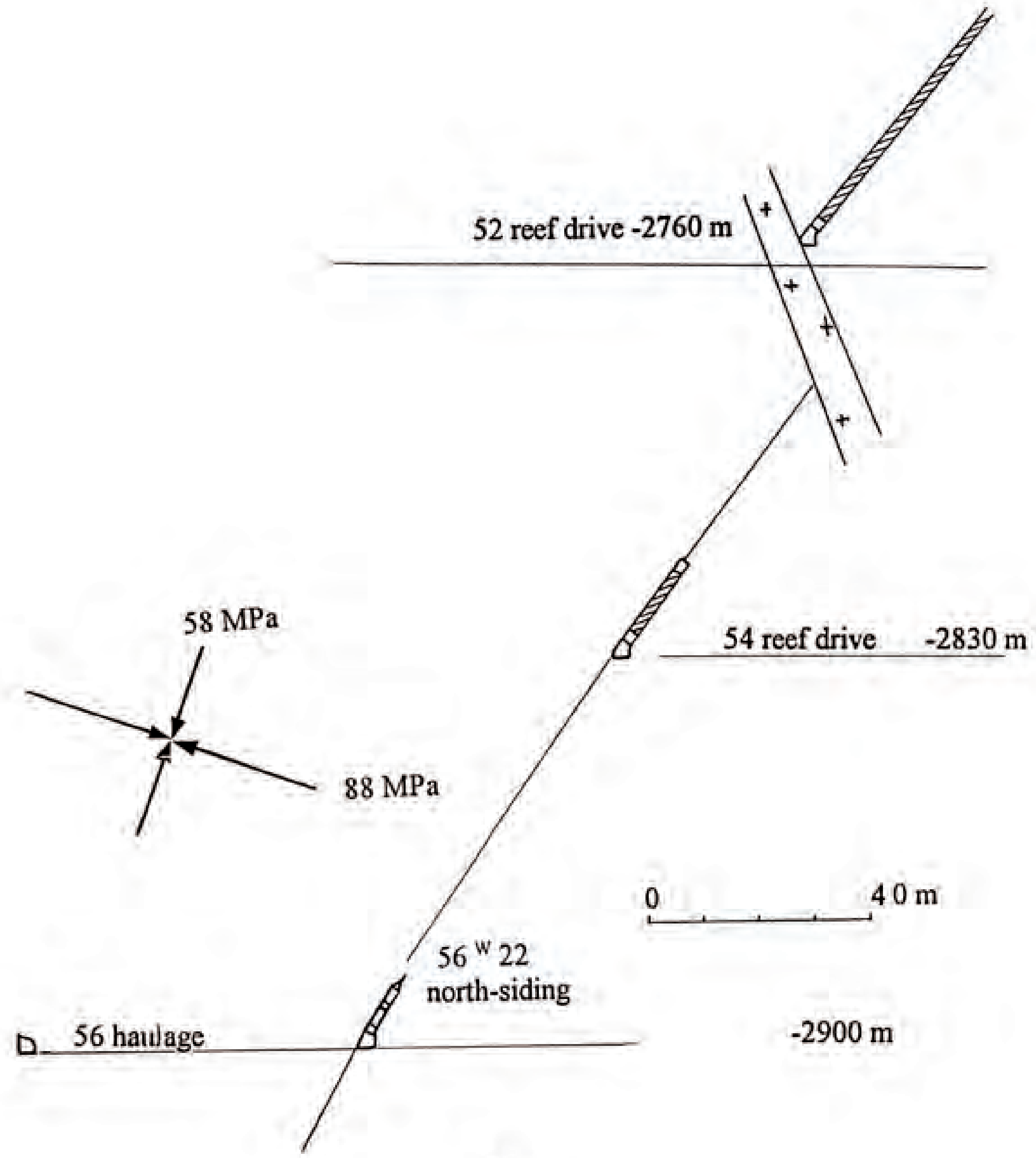
2.2.4 Effect of shape and gravity

Geometry of mine openings and location of photographs

Captions

(a) Plan view of stoped-out areas which would determine the induced stress environment for mid-1972 at the excavations described on pages 3 and 4.

(b) Vertical dip section 30m east of west 22 raise line.



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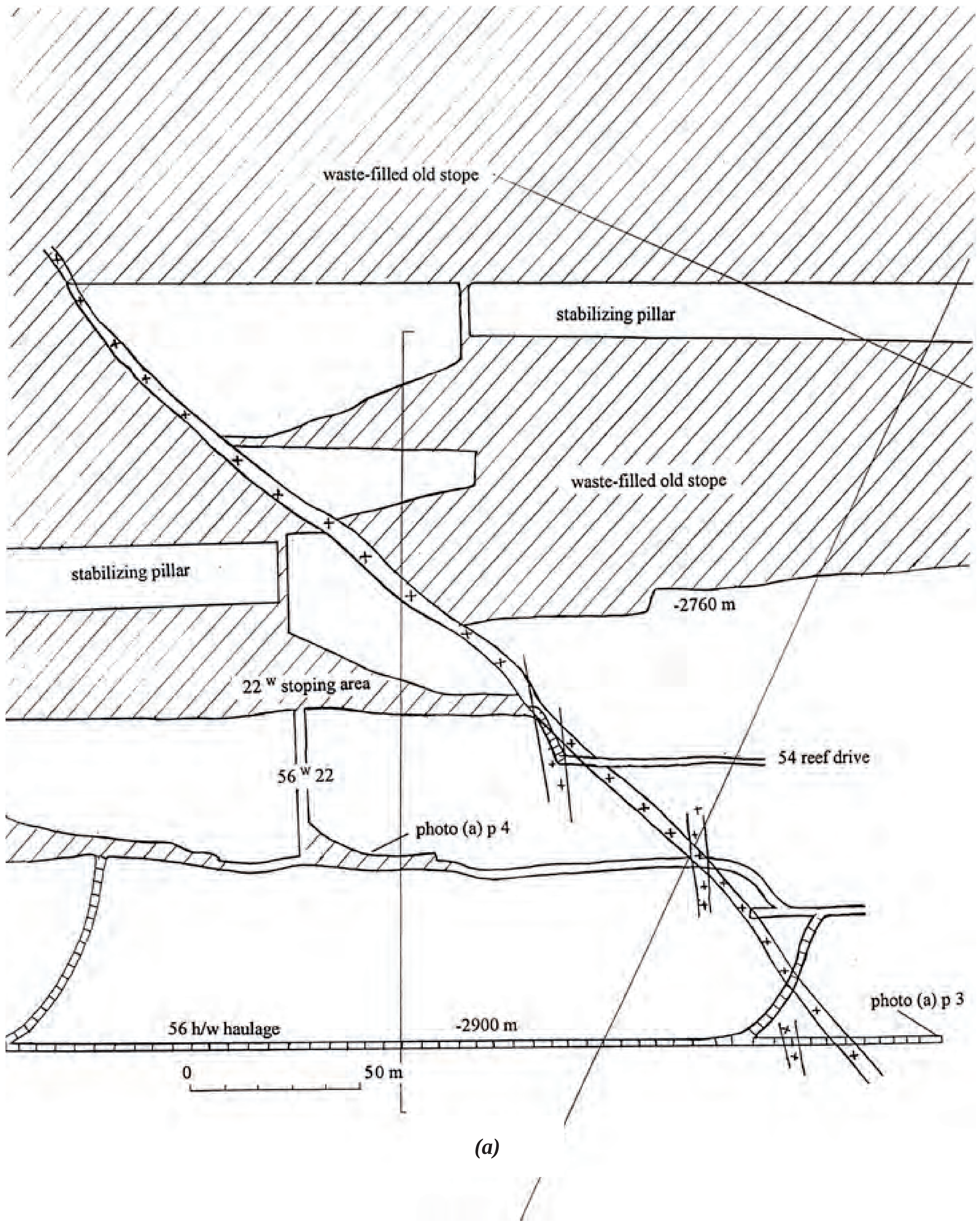


(a)

2.2.5 Micro-slabbing deterioration of crown pillar

Introduction

Unlike its neighbouring mines to the east, DRD mined extensively on the Kimberley Reef conglomerates more than 1000m stratigraphically above the Main Reef series.

Captions

(a) View eastward of underside of crown pillar of 28^{W} 9 Kimberley Reef sub-level open stope on 5 October 1973. Blasting of the stope was just completed at this stage leaving an opening that extended for some 40m on strike along the crown pillar on 26 level and 100m along the sill pillar on 28 level (depth 1290m).

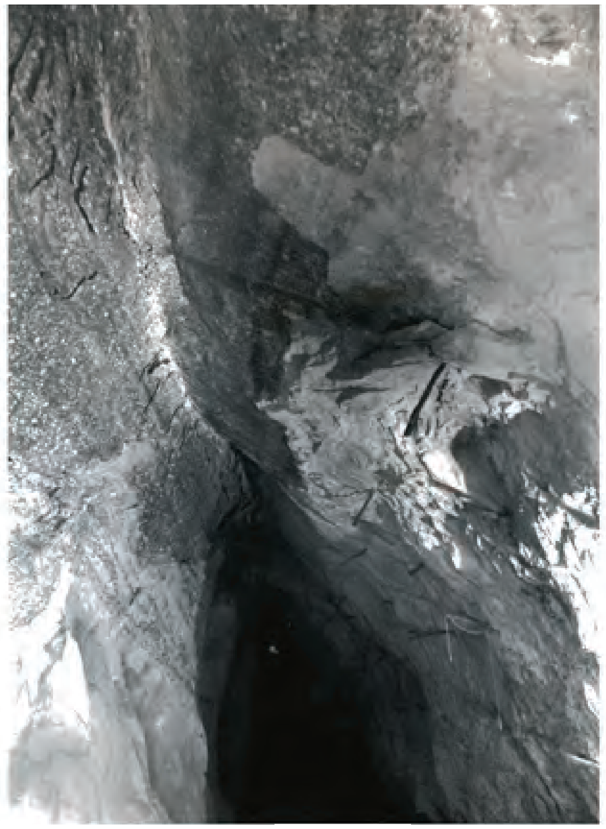
South top corner of original No 1 drill drive is indicated by upper line of grouted reinforcing ropes. Remaining portion of roof and side wall of drill-drift are conspicuously light in colour because of accumulated dust whereas whitened areas above result from abrasion due to fracture progression. Darker mottled areas are cleanly-cleaved extension-fractured surfaces through the conglomerate of the ore-body - see also fig (a) on page 7.

Locus of initiation of micro-slabbing is visible as a well-defined, very narrow zone of crushed appearance forming the acute 'peak' of the open stope.

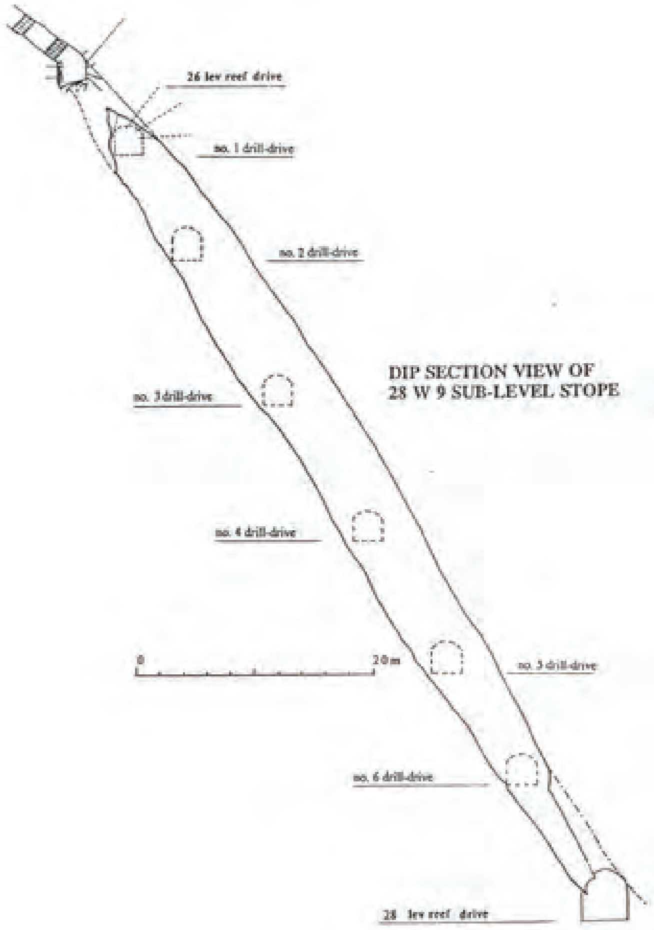
(b) Detail of the most acute portion of the peak just left of centre of (a). The extension fractures which form the micro-slabbing at the tip of the 'notch' or peak are so sharply curved as to give the appearance, in places, of over-folded laminated strata.

Larger secondary extension fractures, which detach bigger slabs extending away from the notch-tip, totally disregard the existence of the conglomerate pebbles.

(c) Cross-sectional sketch of the stope showing the relative positions of the six drill drifts.



(a)



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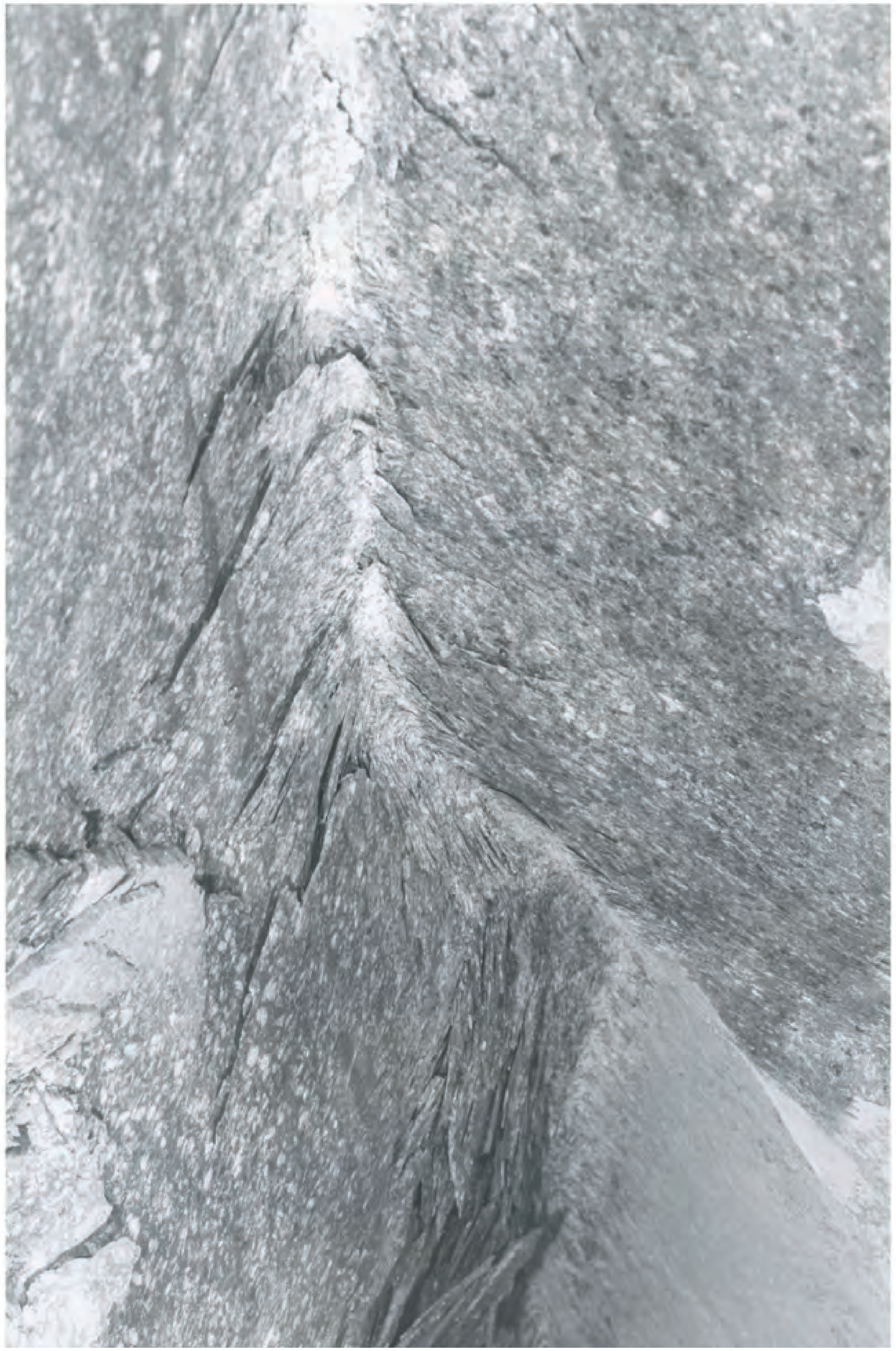
page 6



(b)

2.2.5 Micro-slabbing deterioration of crown pillar

Captions (continued)

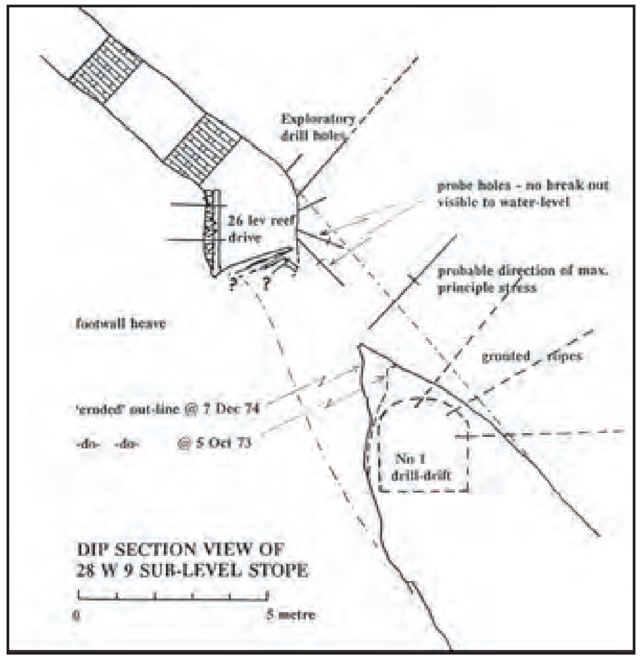
(d) View eastward below crown pillar on 27 March 1975 some 75 weeks after photographs of fig (a) and fig (b). The notch tip has progressed upwards by at least one metre leaving a clearly defined whitened 'scrubbed' surface - see also fig (c) of p10.

(e) View upwards of underside of crown pillar on 20 December 1974 about 62 weeks after completion of sloping, showing detail of the abraded surface referred to in (d).

There appears to be a marked tendency for the right-hand ends of the curved microslabs to 'scrub-off', possibly against a bedding plane, whilst the left-hand ends break off leaving a rougher 'scarp' marked by closely-spaced traces parallel to the 'crushed' locus of micro-slab initiation.

(f) Sketch of the cross-section through the crown-pillar which, by inference, is probably only 2,5 to 3,0m wide at this point. The upper three holes in the south side of 26 KR drive were probably exploratory holes drilled some years previously. As far as could be observed with cap-lamp illumination, there was no borehole breakout or 'dog earing'. Two further probe holes were drilled downwards early in December 1974, to the depth and inclination shown. When examined some 13 weeks later, these holes also showed no signs of breakout down to the level of the drilling water, which had not drained away. From this it could be concluded that the highly-stressed core of the crown pillar was impermeable and located below the bottom of the probe holes while the metre or so of rock in the immediate sidewall of the tunnels was de-stressed.

(d)



(f)

page 7

(e)

2.2.6 Initiation of micro-slabbing process

page 8

Captions

(a) View east along bottom drift of 28^{W} 9 sub-level open stope on steeply-dipping Kimberley reef on DRD mine.

Acute re-entrant shape along top north corner of drift marks the locus of extension fracture progression.

Additional stress concentration around the draw-point raise on left possibly localized and initiated the fracturing process.

(b) View west along bottom drift showing continuation of the micro-slabbing notch along northern top corner. Distant illuminated portion of tunnel is shown in detail in (c).

(c) Detail of portion of tunnel where the initiating notch has moved from northern corner to centre of roof arch. The central whitened patch shows the minimum distance that the notch progression has continued. Portions of the white 'scrubbed' surface appear to have scaled off by secondary extension fracturing parallel to the free surface.

Typical borehole breakout has occurred in two drillholes visible in extreme top left and slightly left of centre of photograph. Further detail is shown in fig (d) on page 9.

(a)

(b)

(c)

2.2.6 Initiation of micro-slabbing process

page 9

Captions (continued)

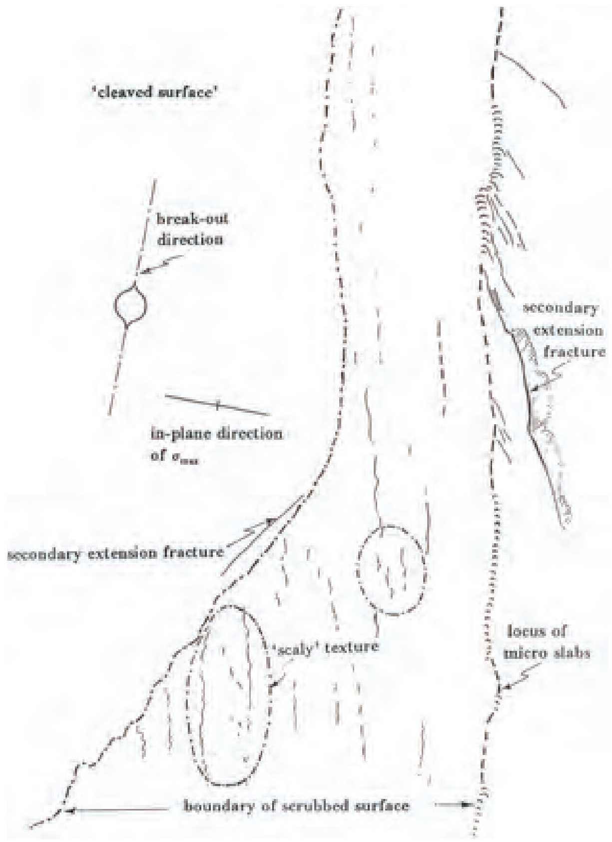
(d) Detail of 'scrubbed' appearance of whitened surface of fig (c) on page 8. This surface is characterized by a lineation parallel to the locus of the micro-slabbing, an abraded striation perpendicular to the lineation and a scaly texture in places.

The lineation appears to be the trace of the intersection of primary micro-slabs with the scrubbed surface. The striation reflects the way that the micro-slabs are pushed away from the crushed, micro-zone of dilatation.

(e) Interpretative tracing of (d) to Vi scale, showing how the diameter across the drill-hole break-out is sub-parallel to the lineation of the scrubbed surface.

Part of the scrubbed surface has been 'cleaved' away by secondary extension fracture. The direction of the maximum stress in the plane of the cleaved surface is perpendicular to the diameter linking the 'dog-'earing' or 'break-out' in the drillhole.

ff) View of the extent of the whitened scrubbed surface showing clearly how it maps the progress of the micro-slabbing notch which initiates the primary major extension slabbing.



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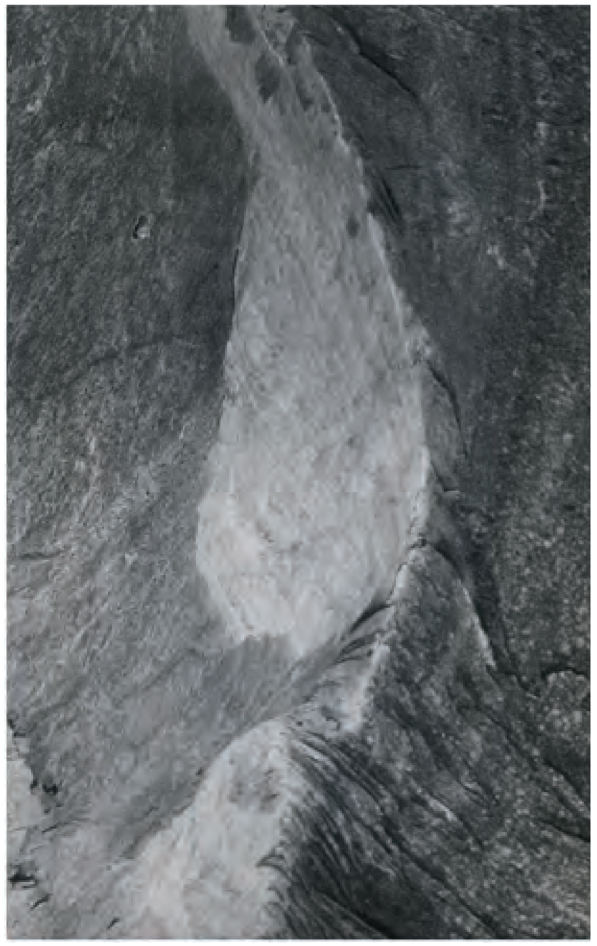


(f)

(d)

2.2.7 Face-parallel slabbing

page 10

Captions

a) View westward along the lowest drill drive of a sub-level open stope on DRD mine at a depth of 1450m in massive Kimberley Reef quartzitic conglomerate. The stope was in a well-advanced stage of preparation with drill-drive development nearly complete, but some months away from commencement of long-hole blasting. The drive had been temporarily abandoned.

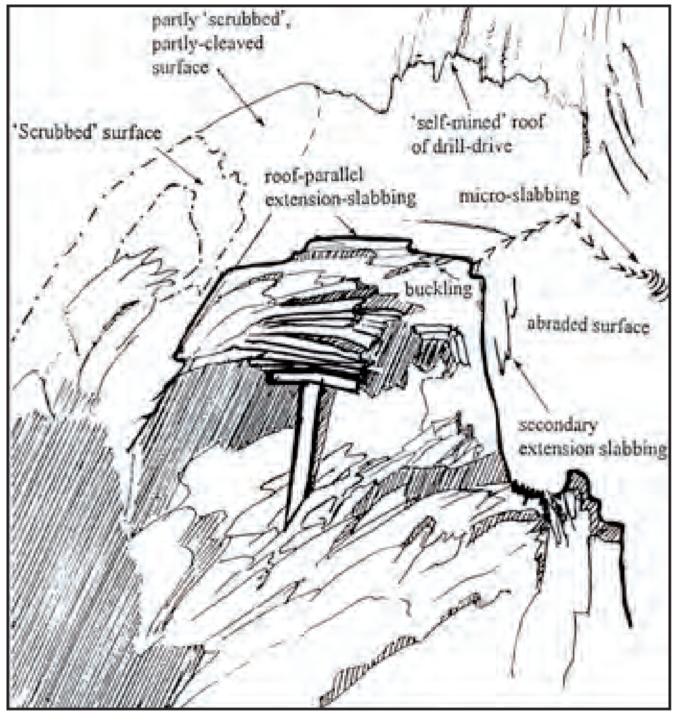
The total stress in the area had been appreciably enhanced by induced stresses resulting from extensive mining to the west and north.

The entire back of the drill-drive had suffered more than 0,9m of 'self-mining' in the form of closely spaced, face-parallel extension fracturing.

From the 'scrubbed' appearance of the hangingwall (see also p 8) and the abraded whitened surface of the right-hand sidewall, it would appear that two sub-parallel surfaces existed along which the micro-slabbing failure-initiation phenomenon proceeded. The frequent linking of the two 'notch tips' produced the laminated appearance of the 'pack of cards' on top of the timber prop. Viewed on a macro-scale the stope deterioration was stable in a quasi-static, time dependant way. In reality the thin slabs spoiled away from the face with violence in a strain-bursting manner (see also page 22).

b) Interpretative tracing of photograph in fig (a).

c) Diagrammatic sketch of the layout of the sub-level open stope.



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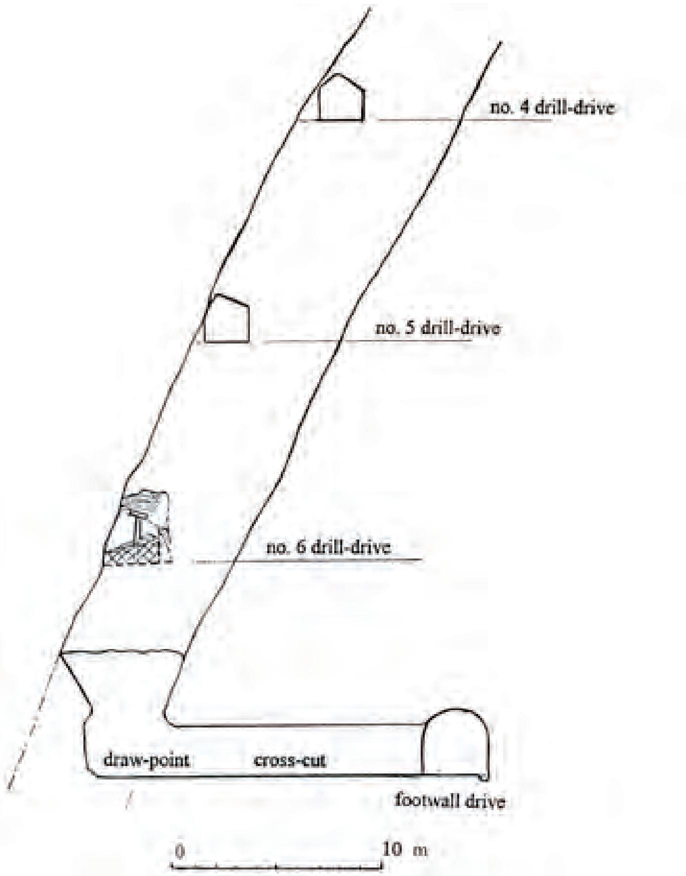


(c)

(a)

2.2.8 Initiation of micro-slabbing at a bedding surface

page 11

Introduction

The East Rand Proprietary Mines Ltd. (ERPM) is a very large mine which forms the eastern limit of the Central Witwatersrand goldfield. Towards the eastern end of the mine the strata below the ore-body become progressively more argillaceous but westward and above the reef, the strata are typically very strong and massive. During the decades of the 60's to the 80's, ERPM was the deepest, and the largest deep mine in the world.

Captions

(a) View northward in 76 level cross-cut on the central section of ERPM gold mine at a depth of 3400 m. The formation of large slabs in the western sidewall appears to be initiated by a complex of curved micro-slabs localized along a smooth bedding plane that dips towards the camera at about 25 @. Between widely-spaced bedding planes the rock is a strong relatively massive quartzite.

Generally the progression of this failure process took place by downward extension of larger indirect tensile fractures which thus formed relatively thin slabs parallel to the side of the cross-cut.

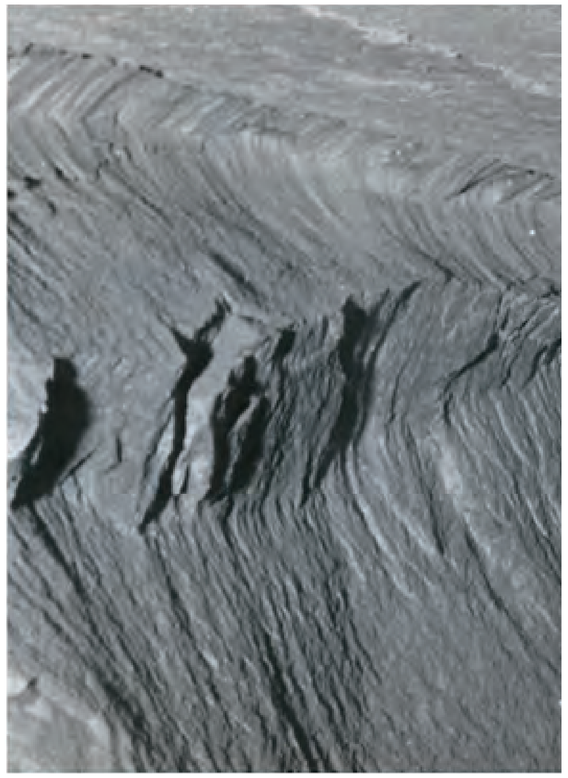
On at least two occasions the major extension fractures grew upwards in the roof to arch back over the original tunnel.

The cross-cut had been stress-relieved by overstoping some 50 m above it several years previously, so the current ambient stresses were low.

(b) Detail of the complexly-curved, primary slabbing in the top centre portion of (a).

(c) Detail of the primary micro-slabs which superficially appear to be buckling. It is more likely that they are echoing the complex process in (b). Interestingly, the outward 'sliding' of the top edge of the micro-slabs against the smooth bedding plane does not leave a 'scrubbed' texture as in fig (e) on page 7.

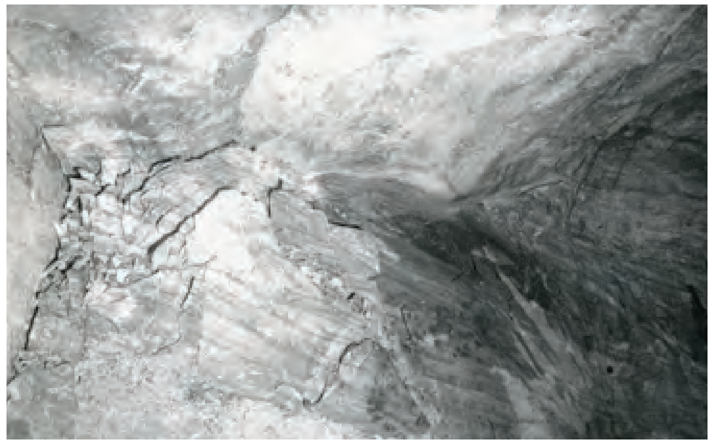
(b)



(c)

(a)

2.2.9 Initiation and development of fracturing in a tunnel at very high stress



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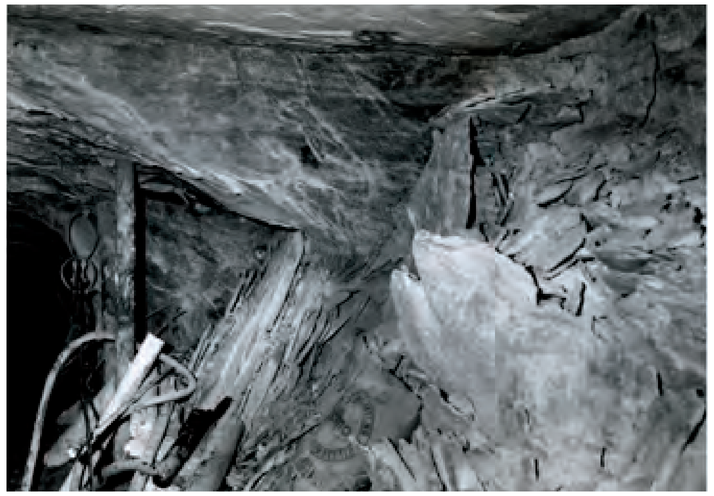


(c)

Introduction

During the period from the early 1960's to the early 1980's, seismological research was being vigorously pursued on ERPM by the Bernard Price Institute for Geophysical Research (BPI). To increase the sensitivity and reliability of location of the system it was necessary to install seismometers ahead of the advancing face of a deep longwall stoping area. The only practicable way of achieving this was to develop a long cross-cut from an old stoped-out longwall two levels above the area of interest.

In order to gain as much new knowledge as possible from a relatively expensive non-producing tunnel, it was decided to use it as a test-site for the comparison of various forms of tunnel support. The Chamber of Mines research organisation (COMRO), which was providing the funding for the BPI activity, agreed to subsidize the support research as well. Very useful insights into the process of brittle rock fracturing under high ambient stresses in high strength rock (350 MPa), were obtained. A comprehensive account of the stress situation and the results were given by Ortlepp and Gay (1984).

During development, the tunnel traversed a stress field whose maximum principal stress value ranged from 60 MPa to 150 MPa (as computed by an elastic analysis - MINSIM). By the time the support was installed the more highly stressed portion was probably subjected to 170 MPa. When final observations were made, the stress field had increased to 220 MPa with only slight further deterioration to the rock and no damage to the support.

Captions

a) View south of tunnel face in stress field of σ_1 = 140 MPa. Acute micro-slabbing break-out commences within 0,4m of face on both sides of tunnel at shoulder height.

b) Detail of east sidewall showing how longer extension fractures extend away from initiating notch to form large slabs. Vertical surface on left is a natural joint which formed a marked stress discontinuity.

c) View north-eastward several days later showing the same portion of east sidewall as in (b). Note complete absence of damage of distant sidewall beyond the transverse joint visible behind the timber poles on the left.

d) View south from same viewpoint as (a), after several metres further advance.

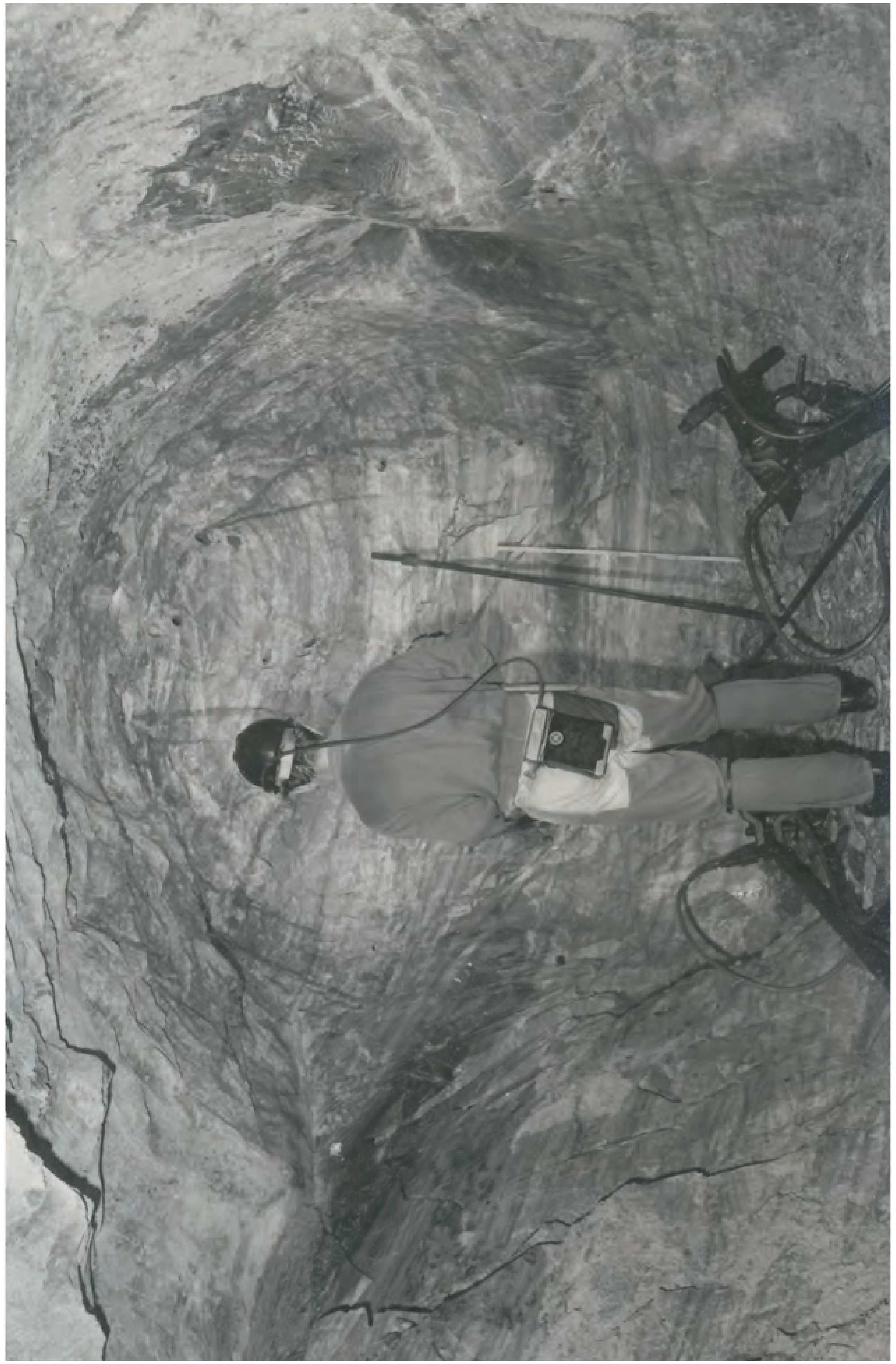
e) View south at approximately the same position 11 months later after tunnel face had advanced a further 60m.

f) View north from same position as (c) five years later when field stress had increased to σ_1 = 220 MPa.

Reference

W D Ortlepp and N C Gay. Performance of an experimental tunnel subjected to stresses ranging from 50 MPa to 230 MPa. *Design and performance of underground excavations*. ISRM Symposium, Cambridge, 1984.

page 12



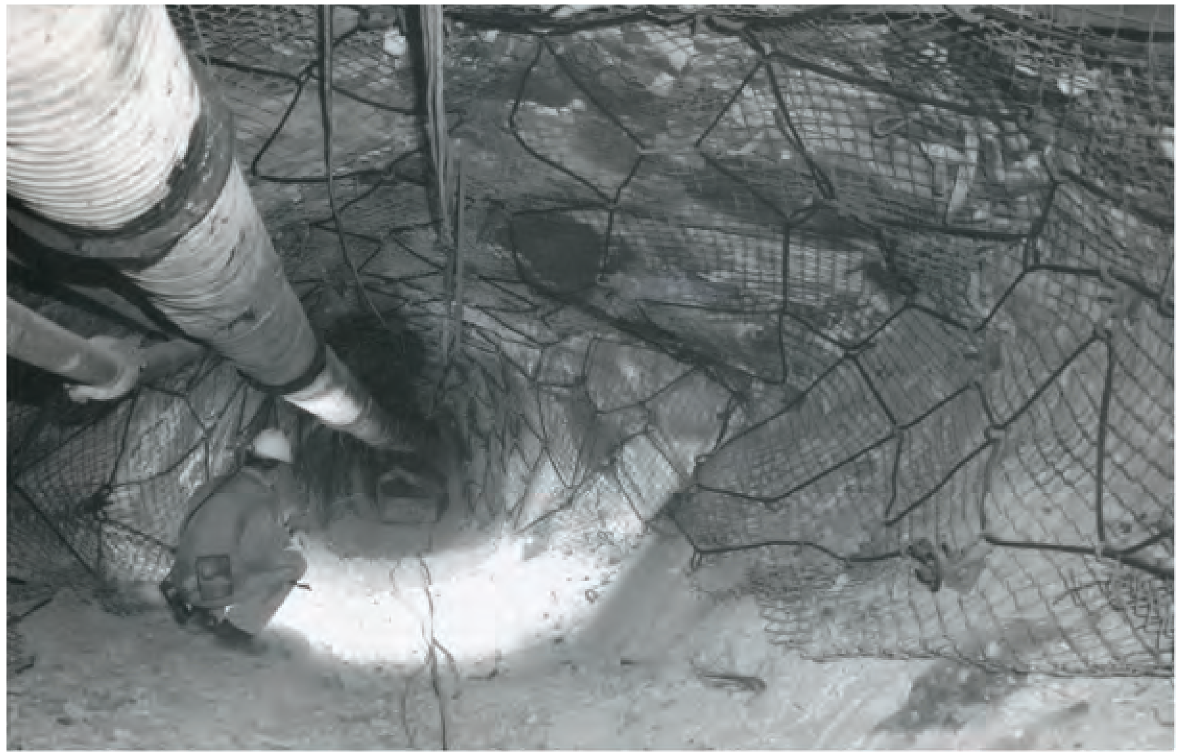
(a)

2.2.9 Initiation and development of fracturing in a tunnel at very high stress

page 13

for captions see p 12

(e)



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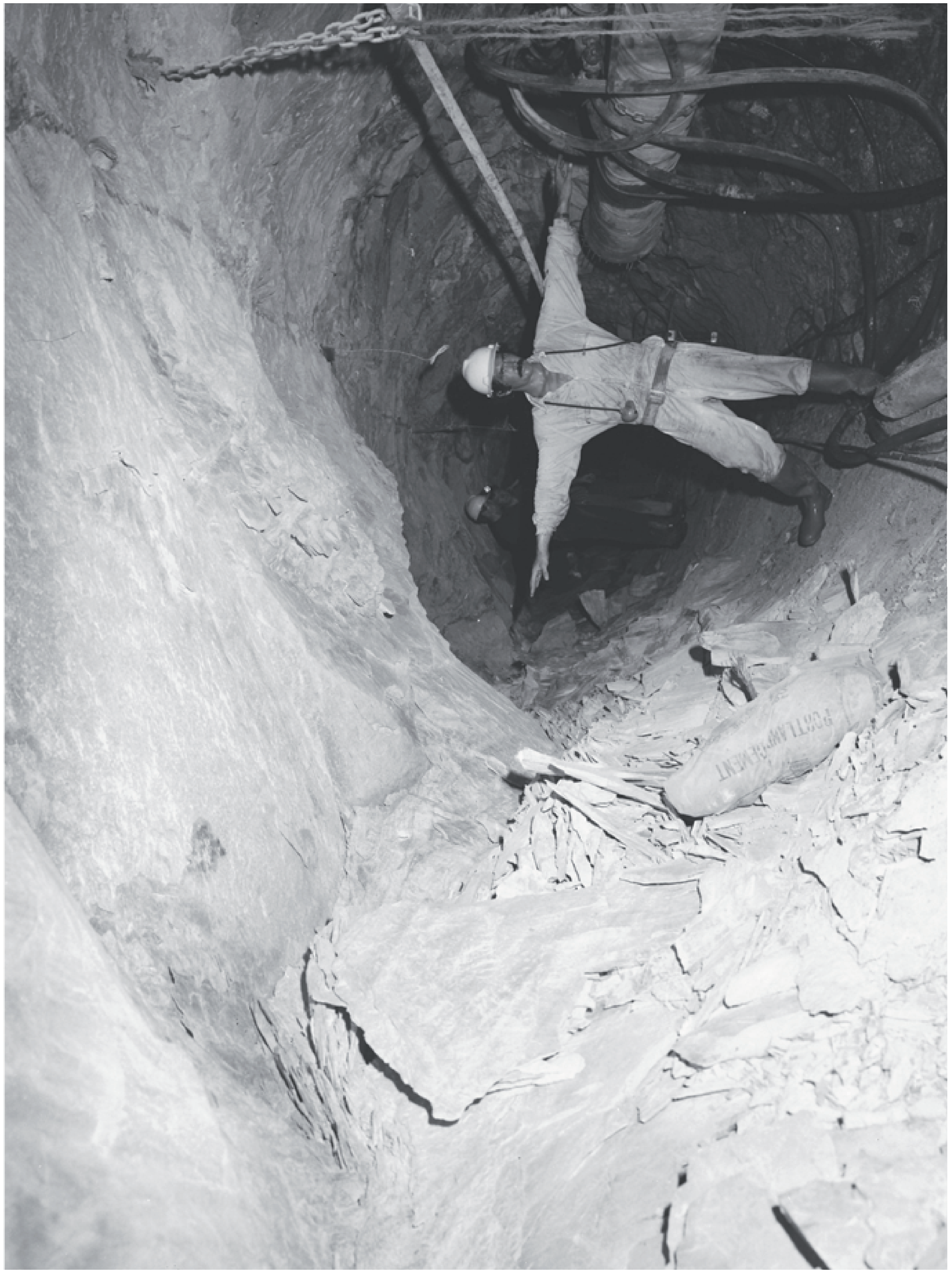


(d)

2.2.10 Initiation of micro-slabbing in a blasthole socket

Captions

(a) Close view of side of traverser bay on 69 level station of H inclined shaft at ERPM - at a depth of 2880 m.

The excavation of the station area on 69 level represented some of the earlier attempts by the mine in 1970 to use controlled peripheral blasting techniques for large excavations.

The ambient stress was moderately low because the longwall sloping some 60m above had been completed several years before.

The micro-slabbing in the upper portion of the photograph is initiated and localized by the stress concentration surrounding the 'socket' end of one of the peripheral blast holes. The grain-size detail of the initiation of this process is shown on page 1.

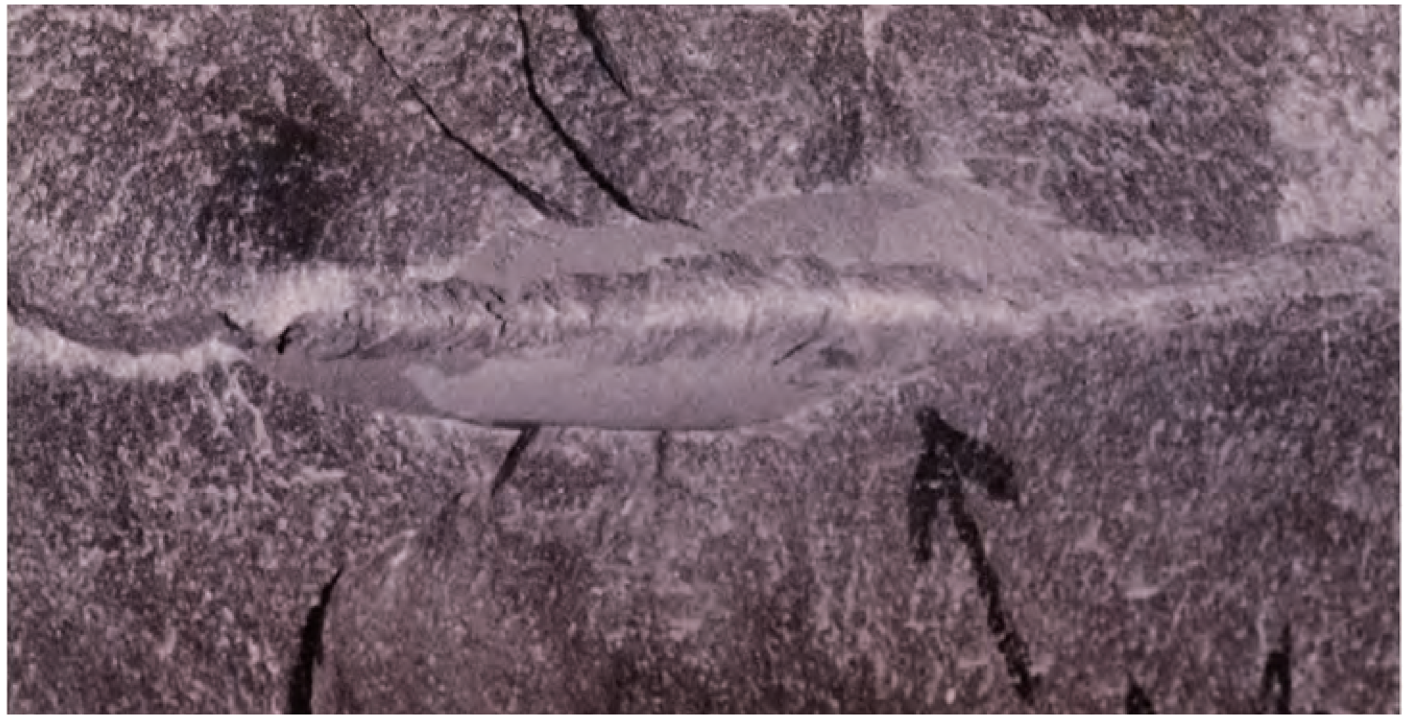
The less well-developed micro-slabbing lower down appears to be localised by a subtle stratigraphic weakness along a bedding-plane.

(b) View eastward along traverser bay showing position of (c).

(c) Detail of micro-slabbing along drill hole.

(d) View of corner at intersection between strike-parallel traverser bay and northern storage bay showing location of (a).

(b)



(c)

page 14

(a)

2.2.11 Stope-induced, face-parallel fractures

page 15

Captions

(a) View westward along strike gulley of 77^E stope on Hercules section of ERPM at a depth of 3300 m. In order to correct the overall longwall configuration, this stope had been mined as a strike-parallel face advancing down-dip for several months. The face-parallel extension fractures induced by the high stresses ahead of tins south-advancing face extended downwards into the footwall in a slightly-curved, remarkably regular manner later revealed by the unusually smooth and strong north sidewall of the gulley.

When this unusual manoeuvre had re-positioned the down-dip abutment of the longwall sufficiently far south, the strike gulley was re-established parallel to the now stationary south face to enable the lowest panel to revert to the normal practice of advancing a slightly underhand face-shape in the direction of strike. The result was a non-typical, markedly-smooth and regular gulley side and a closely-fractured but tightly competent roof.

(b) View southwards of end of cross-raise developed perpendicularly into the hangingwall of 75 ^{E} Hercules stope some 25m behind the face. It shows the persistence of the stope-induced, face-parallel fractures to beyond 12m above the reef plane. Note that there is no displacement along these fracture surfaces or along the bedding planes.

(c) View southwards of south side of 'follow-on' footwall drive developed 12m below, and a similar distance behind, the easterly-advancing face of 67 ^{E} longwall, K shaft, ERPM at a depth of 2770 m. This shows the persistence of slope-parallel extension fractures into the footwall.

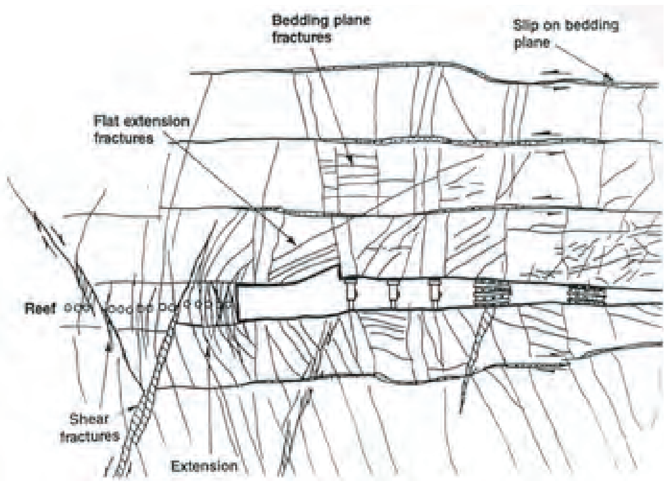
(d) Strike section through the quartzite surround of a typical deep tabular stope about 1m high at the work face after 100m or more strike advance. (courtesy of COMRO 1988 Guide).

Reference

An Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts. *Published by Chamber of Mines Research Organisation 1988.*

(b)

(c)



(d)

(a)

2.2.12 Range of occurrences

Introduction

In attempts to formalize understanding of fracture of brittle and semi-brittle rock, it has been argued that extension fracturing is the most basic and fundamental expression of the onset of failure in such materials.

The ubiquity of the phenomenon through a wide range of stress environs and rock types lends support to this argument.

Captions

(a) Well developed slabbing in a footwall drive pre-developed ahead of stoping at a depth of 2600m on ERPM. The surrounding quartzite is relatively fine-grained, massive and very strong (UCS probably about 300 MPa). The inclination of the strata is about 30°.

The extreme slenderness of the slabs suggests that the extension fractures developed in a stable manner as the ambient stress increased slowly due to the gradual approach of the stoping a few tens of metres above. A subsequent large rockburst which occurred somewhere in the surrounding area caused the 'shake-up' displacement and sliding of the slabs.

(b) Development of slender slabs in weak, un-layered siltstone below the massive Clarens sandstone at an altitude of 2375m in eastern Lesotho. The sandstone cliff is about 50m high and its top forms the plateau above a 150m deep gorge.

(c) Onset and development of breakout in a 5 m diameter machine-bored tunnel at an altitude of 1700m in Clarens sandstone under a cover of 300 m. The sandstone of the Clarens formation is a massive aeolian deposit with a UCS, in this locale, of 30 to 80 MPa (South delivery tunnel of the Lesotho Highlands Water Project).

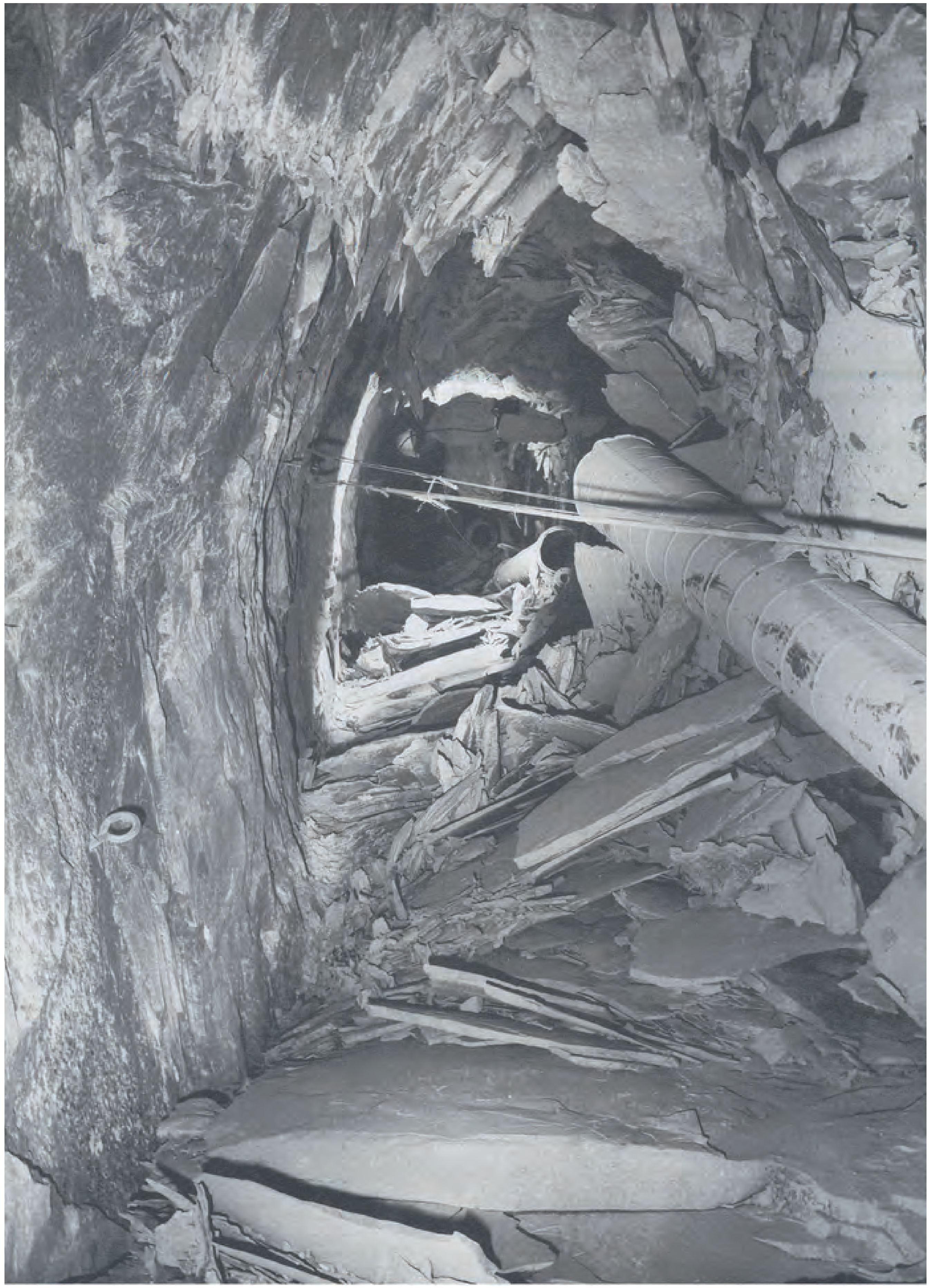
(d) Breakout failure in headrace tunnel through andesite under cover of 1200m in hydro-power project near Taica, Chile. There was sufficient violence associated with this failure for it to have been described as a 'rockburst'.

(b)

(c)

(d)

page 16



(a)

2.3 Direct tensile fractures

2.3.1 Fall of unfractured roof in stope

Introduction

Excavations in hard rock are almost invariably created by drill-and-blast procedures. Moreover the rock mass is usually traversed, to a greater or lesser degree, by pre-existing discontinuities such as joints or bedding planes. Consequently, pure tensile failure through pristine rock resulting from simple gravity forces, is seldom observed.

Caption

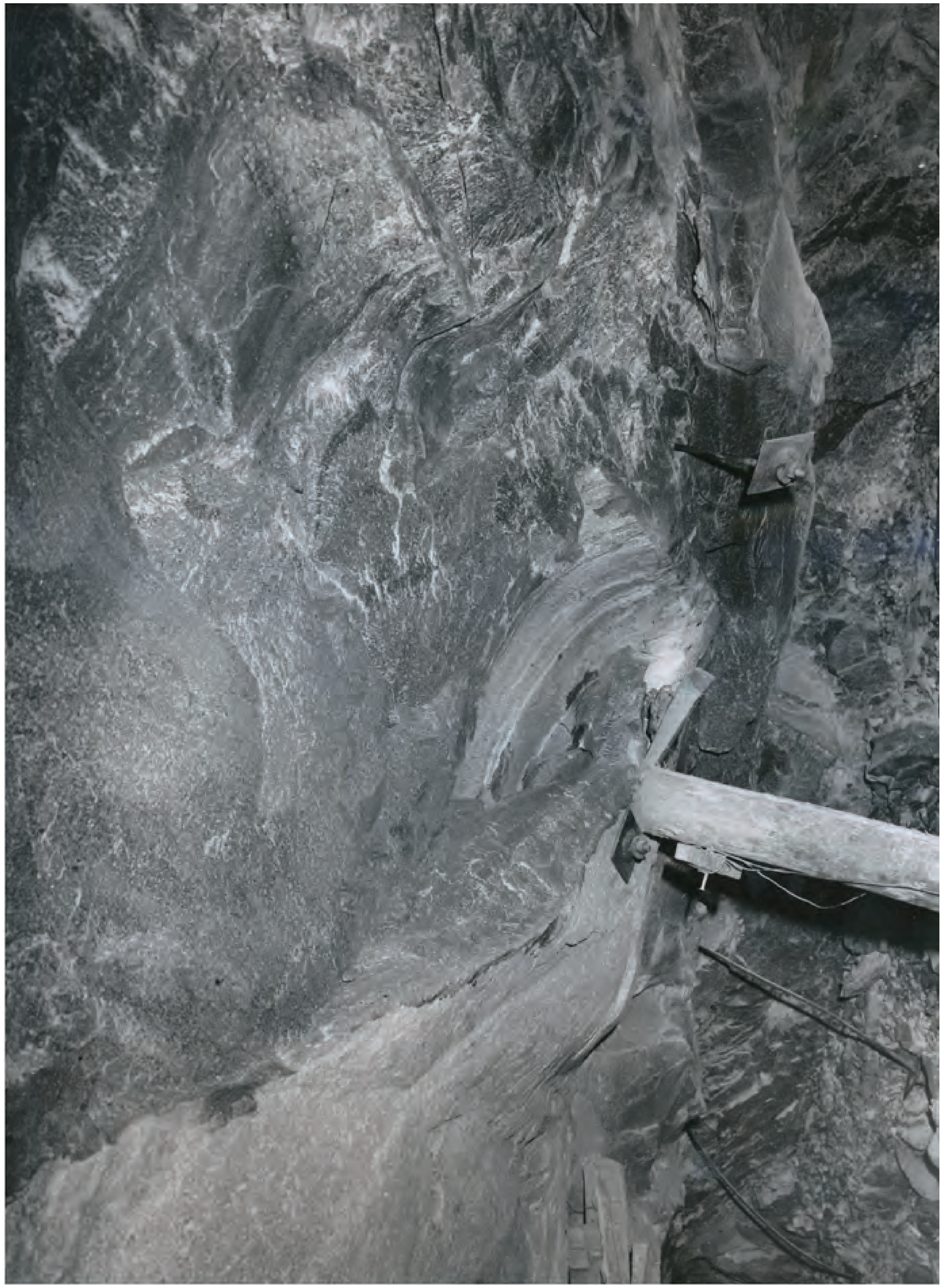
(a) General view of roof of No 10 panel of 27 level 16^{C} sloping line on Harmony gold mine. The 'Khaki shale' which often causes bad roof conditions elsewhere in the OFS goldfields, is virtually entirely absent over the Harmony lease area. In places, however, local aberrations occur in the otherwise generally regular, shallowly-inclined sedimentary succession above the Basal Reef. What appears to be a syngenetic eroslonal feature or 'pot-hole' structure was conspicuous in this view. The top of the mine pole just right of centre in the background. marks the location of the fall.

(b) View along the strike gulley showing the large piece of unfractured roof that fell. No report had been received of any accompanying noise or distant tremor that might have triggered the fall. There is a conspicuous absence of face-induced fractures which normally result from sloping at depth once a span greater than a few tens of metres has been mined out. Close to the top of the timber prop on the right, a portion of strongly-curved cross-bedding is visible.

(c) Close view of surface from which, the fallen piece of hangingwall had torn away. The immediate roof to the left of the timber prop has a smooth surface with a texture characteristic of a sedimentary bedding plane, and similar to that of the roof of (a). Apart from the curved 'cross-bedding' immediately to the right of the top of the prop, the remainder of the roof visible to the right and stretching back over the camera is clean, sharp and conchoidal in appearance. The left-hand edge of the new fracture surface extends steeply for a short distance above the right side of the. prop before it intersects the curved cross-bedding surface beyond which it flattens to become sub-parallel to the original roof. Vestiges of 'hackle' traces and plumose structures can be detected. These features together with the generally conchoidal appearance of the new surface suggest a dominantly tensile mechanism for this fracture.

(a)

(b)



(c)

page 18

2.3.2 Rapid-propagation textures

Introduction

Fractures around excavations at depth sometimes show intrigueing patterns and textures on their exposed surfaces particularly if the rock is fine-grained and brittle and they are viewed under oblique lighting. Inferences as to the manner of propagation of the tensile fracture which produced the surface can sometimes be drawn.

Captions

(a) View along haulage in strong massive quartzites some 90 m below plane of reef ore-body where a large strike stabilising pillar was believed to have suffered 'foundation failure' which generated a large seismic event (M_L = 3,3) - Lenhardt and Hagan (1990). The haulage was located at a depth of 3100 m below surface but the reef-plane had been mined-out several years before the haulage was driven. Small, isolated falls of rock were noticed during examination of tunnels in the vicinity of an extensive area of damage on, and close to, the plane of sloping. The point of origin of one such fall is just above the protruding rock-bolt just left of centre in the illuminated portion of the tunnel roof.

(b) Closer view of roof of tunnel highlighted in (a) showing curved patterns of tensile fracture progression through joint-bounded blocks which remain locked in place in top corner.

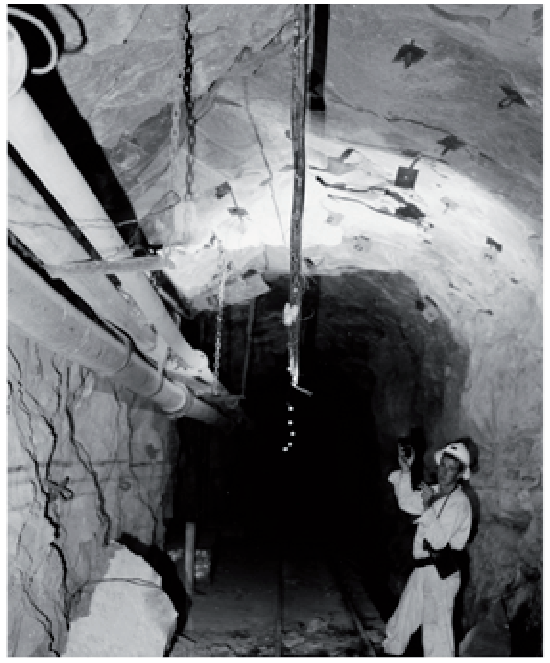
(c) Detail of plumose textures on fractured surface of block of rock lying on track below point (b). The circular arc mid-way down the fracture plane, along which the radial traces become more marked, may delineate the transition from 'mirror' zone to 'hackly' zone – Engelder (1987).

(d) Plumose patterns visible on sidewall of damaged tunnel at similar depth about three kilometres further east on the same mine as (a), after another large seismic event 6 months later.

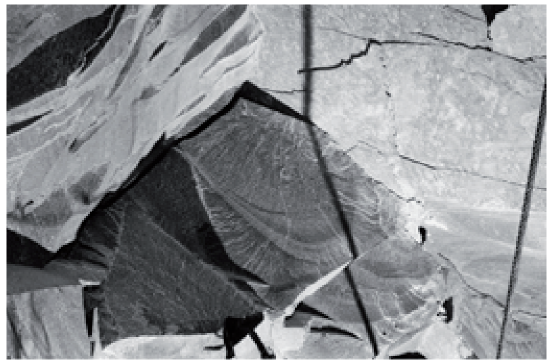
References

W A Lenhardt and T O Hagan. Observations and possible mechanism of pillar-associated seismicity at great depth. *Technical Challenges in Deep Level Mining*. SAIMM. Johannesburg 1990.

T Engelder. Joints and shear fractures in rock, *Fracture Mechanics of Rock*, edited by B K Atkinson, Academic Press, 1987.



(a)



(b)

(d)

(c)

2.3.3 Mirror zones in hard rock

Introduction

Of the many forms of plumose meso-structure that may be seen on fresh fracture surfaces underground the mirror zone is the most striking.

In *Fracture Mechanics of Rocks*, page 35, T Engelder (1987) (ref. page 18) describes the mirror zone as an essentially flat surface adjacent to the point of origin of a rupture, before the slow but accelerating crack tip reaches a critical velocity beyond which the branching or bifurcation, which forms the hackle zone, must occur. Mirror zones are seldom seen on natural joints because the rock is usually too coarse-grained.

The transition from a single crack propagating at sub-critical velocity to the many smaller fractures of hackle zone, takes place, ideally, along a circular arc. This forms the most striking feature of the phenomenon-see page 23.

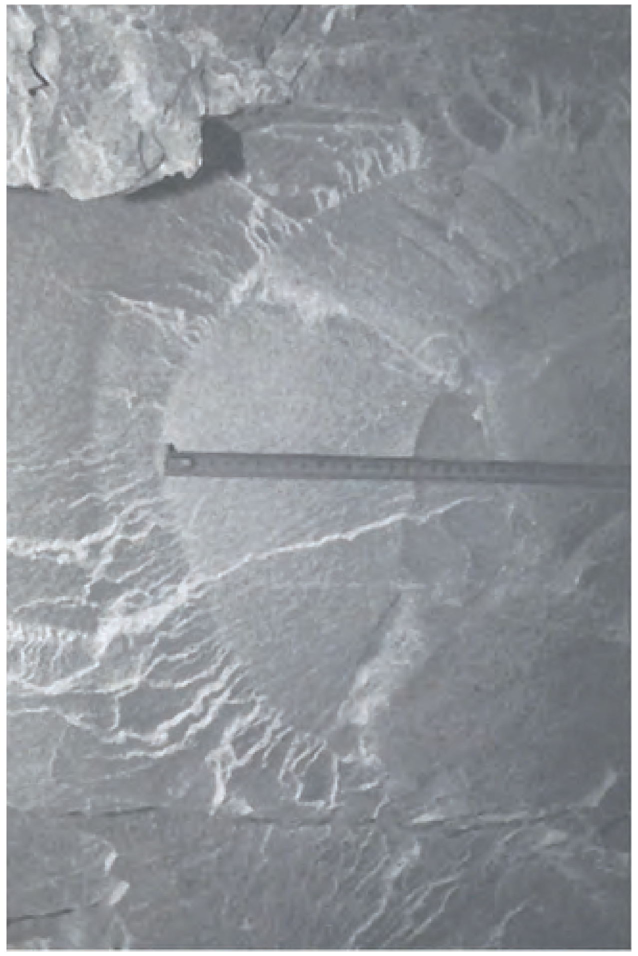
Mirror zones strongly indicate rapid propagation of fracture, therefore violent failure. Such failure occurs as strain-bursting or explosive spalling of a free surface close to the origin of a large rockburst – see pages 38 and 77. Mirror zones are often seen on Vaal Reefs after strain bursts have occurred – B Harris (1994).

Captions

a) Minor rockburst damage in quartzite at ERPM at 2900m depth. Two segments of mirror zones are visible in outlined area of upper sidewall. One is concentric with the circular rockbolt plate and the other is in the shadow of the large suspended rock just below.

b) Spalling in quartzite sidewall of a Vaal Reefs tunnel which was part of wide-spread damage resulting from a very large seismic event on a fault which intersected the cross-cut some tens of metres away.

c) Fresh spall of lightly shotcreted quartzitic sidewall of a tunnel in a deep gold mine in the Carletonville district.



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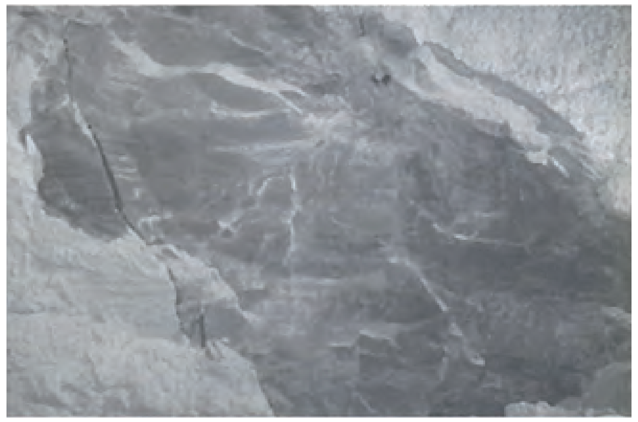


(c)

Reference:

B Harris. *Rock Mech. Dept. Rep. R11-106/94*
Vaal Reefs Exploration and Mining Co Ltd.

page 19

(a)

2.3.4 Blast-induced fracturing

Introduction

The detonation of an explosive charge in a borehole in solid rock generates a rapidly-propagating cylindrical stress pulse of great intensity. The rock immediately surrounding the hole may he pulverized by the shock front of the radial compressive wave. Beyond the crushed zone, the tensile stress in the tangential direction is sufficient to overcome the steady-state compressive stress in the surrounding rock and the tensile strength of the intact rock material. Thus tensile fractures will he created, the altitude and length of which will be determined by the ambient stress state.

If the rock is reasonably isotropic in respect of its strength properties then the relative length of the blast-induced fractures will reflect the anisotropy of the static stress state. The tensile fractures will extend most easily in the plane which is perpendicular to the minimum principal compressive stress while their propagation may be completely suppressed in the plane normal to the maximum principal stress. A nearly axis-symmetrical distribution will indicate that the steady-state stresses are approximately equal in the plane perpendicular to the borehole axis.

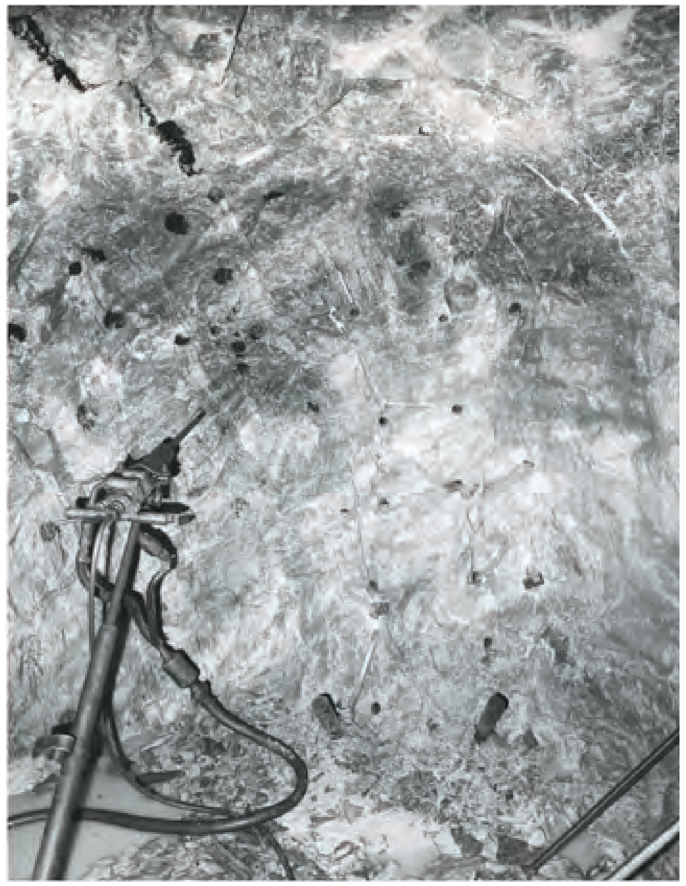
In such a case the length of the fractures produced by equal explosive charges in similar strength rock, will qualitatively reflect the stress intensity-shorter fractures indicating higher stress.

Captions

a) View westward of the face of a tunnel in hangingwall quartzites about 65m above and 35m ahead of a Main Reef Leader stope mining out a shaft pillar at a depth of 1200m below surface in a central Witwatersrand mine. Audible micro-fracturing of the rock was occurring continuously.

b) Close view of central portion of tunnel face showing that the radial fractures extending from the blasthole sockets are strongly developed in the near-vertical direction and total absent in other directions.

c) Detail showing that ‘break-out’ or ‘dog-earing’ in top right hole is perpendicular to radial fracture direction.



(a)

(b)

(c)

2.3.4 Blast-induced fracturing

Captions (continued)

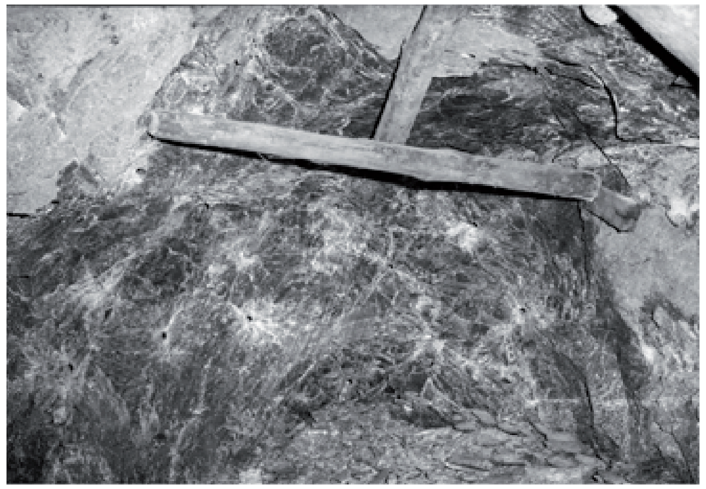
b) Close view of two sockets and three newly-drilled blast-holes in centre of face. Sockets are linked by radial blast fractures dipping at 67 ° towards NE. 'Dog-ear' break-out fracturing in blast holes occurs across a diameter dipping at about 25 ° to SW. Borehole break-out is initiated at the point of tangency with the maximum principal stress direction which thus directly confirms the direction indicated by the radial blast fractures - see pages 1 and 2.

c) Close view of the same tunnel face after 35m advance. As before, both the blast fractures and borehole break-out indicate a maximum principal stress dipping about 60 ° northward which agrees with the stress situation that would be inferred from the mining geometry.

d) View of recently-blasted face of a tunnel in steeply-dipping quartzite at a depth of 2600m below surface at DRD some 24 km west of the mine in which photos (a) to (c) were taken. The tunnel end was same distance below a large unstoped area where the ambient stress was probably some 60% greater than the pro-mining stress at this elevation: ± 110 MPa.

e) Detail of sockets left of centre of fig (d). Radial blast fractures are of approximately the same length and equally distributed around the sockets.

f) View towards the back area from close to the face of a near-horizontal tabular stope at moderate depth. The photograph shows traces of blast-induced fractures emanating from the socket-end of a blast hole which had been slightly over-drilled and so penetrated the smooth plane which formed the footwall contact of the reef body. The traces are strongly curved, sweeping symmetrically away from the axis of the hole both forwards and bachvard. The hole was about one metre long and near-perpendicular to the stope face before the blast. Traces of the face-parallel stope-lnduced extension fractures are clearly visible.



(d)

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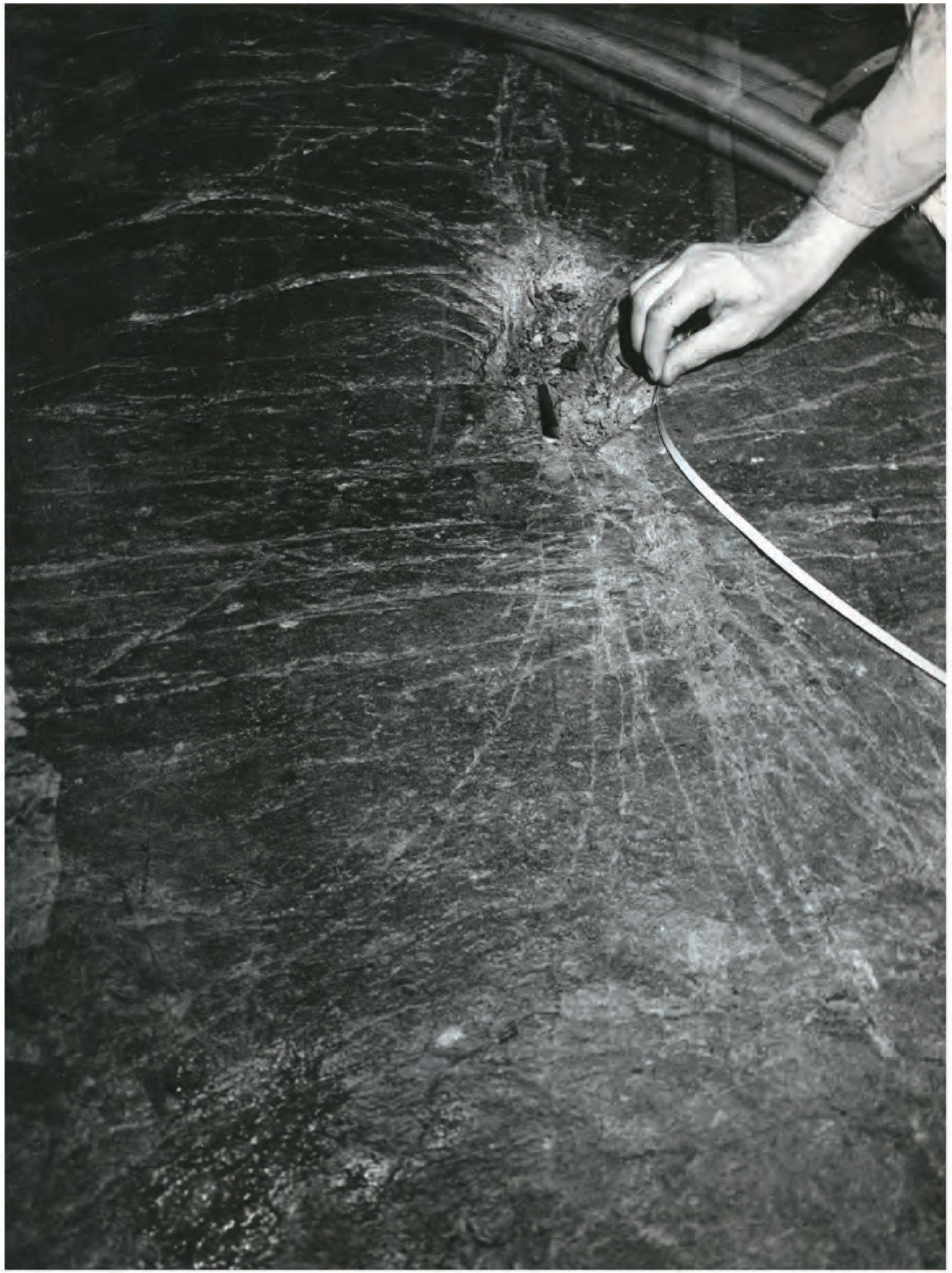
page 21



(f)

2.4 Shear Fractures

As the depth of milling increases and the stress intensity around excavations becomes greater, the study of fractured surfaces becomes more difficult and the interpretation of their mode of origin becomes more ambiguous. Tunnels that are driven in advance of stoping are invariably surrounded by a zone of fracturing usually in the form of more-or-less concentric shells of parallel slabs formed by extension fracturing. These effectively conceal from view the failure process that may be continuing at the interface between the surrounding highly-stressed, but not yet fractured, material and the rock which has just become fractured.

Mining-out of the ore-body, or sloping, in Witwatersrand-type deposits entails the creation, by drilling and blasting, of a tabular excavation in the plane of stratification, usually only 1 - 2m high, but with eventual dimensions in the dip and strike directions of hundreds to thousands of metres. As in a tunnel, the same solid-to-fractured interface exists ahead of an advancing stope and this interface is itself moving, on average, at the rate of advance of the stope. In contrast to the tunnel, however, the final effects of the fracturing process are continuously observable as the face exposes new ground and traces of the fractures are left imprinted on the roof and floor of the stope. More often than not the surfaces of these traces are abraded and striated and strongly suggest that shearing has occurred along them. Their attitude is usually nearly perpendicular to the plane of the stope, and parallel to the face direction, that is they appear to extend in the plane containing the inferred maximum and intermediate principal stress vectors. Often, however, the fractures seen in the roof are inclined at some 30 ° from the perpendicular, usually tilted towards the face but sometimes tilted away from the face. In either case the attitude is more in keeping with conventional notions of shear failure surfaces deviating from the σ_1/σ_2 plane by an oblique angle which is a function of the internal friction of the rock.

Careful studies by R Brummer (1987) have shown that shear displacement along these planes was necessary to accommodate the compressive shortening or convergence ahead of the face which results from the very high intensity of stress along the edges of the extensive stoping excavation. Similar shortening accompanied by strong dilatation occurs in over-stressed slender pillars as they acquire the familiar ‘hour-glass’ shape. The same effects are also found, although less obviously, in long strip pillars between adjoining slopes.

Considerable evidence exists in the body of the literature to suggest that these ‘shear fractures’ are surfaces of intense arrays or alignments of small extension fractures. The ‘shearing’ is really the result of geometric constraints that force the final fracture to form in such a way as to accommodate convergence and to have the conjugate arrangement or appearance which is expected in the classical theoretical analyses of failure of solids.

The discussion concerning the origin of these fractures can become somewhat academic and pedantic. Ultimately, however, it leads to the question as to whether brittle rock material can ever, under naturally-occurring conditions, experience true shear fracturing with the plane of the fracture not being pre-determined by the prior existence of arrays of extension fractures.

The answer to this question will have very important implications for the eventual adequate understanding of the problem of rockbursts. At this stage in the development of knowledge, I believe that violent shear fracturing of the shear rupture type does occur without ‘pre-conditioning’ of the rock mass. A brief argument for this conviction follows towards the end of this discussion.

Steeply-inclined fractures extending for considerable distances parallel or sub-parallel to a stope face, are sometimes found to have several millimetres of finely comminuted rock-flour or fresh ‘gouge’ material filling them. Usually these features have small closely-spaced pinnate joints or micro-cracks of limited length forming an acute angle to the shear surface. According to T Engelder in Chapter 2 of *Fracture Mechanics of Rock* (1987), these inclined micro-cracks are one of the surest signs of a shear origin for the fracture. The apex of the shear angle between the smaller features and the shear surface points in the direction of the shear movement along the ‘fault’.

The thicker the filling of fresh rock flour and the more pronounced the inclined micro-cracks the stronger is the probability that such features are burst fractures - ‘fossil imprints’ of the source of the shear rupture type of seismic event that is comprehensively documented in section 3.2.4. Features fitting this description were observed in 1978 on Doornfontein gold mine in an area of experimental drag-bit rock-cutting which was consequently being closely monitored by a dense seismic network. One of these features is depicted in the photographs below. The network recorded no significantly large seismic events that could be associated with these shear zones. How relatively large shear fractures such as these could have formed without release of substantial seismic energy is extremely puzzling. The bulk of the evidence presented in section 3.2.4 argues against the possibility that significant shear fractures such as these can occur in an aseismic manner.

Whether or not large shear ruptures can erupt in, and propagate through, a pristine rock mass which is not ‘pre-conditioned’ by an extensive planar array of intense localised extensional micro-cracks, is an obvious and important question which unfortunately cannot be answered definitively by the study in this book. An attempt had been made (sec page 53) to see whether there was a strong planar concentration of microscopic pre-fracturing along the rupture surface which would indicate that its propagation path had been pre-determined. Samples were taken at distances ranging from

50mm to 1,5m away from the plane of rupture, and thin sections and photo micrographs were prepared. Unfortunately the photo micrographs and the samples were lost before a proper analysis could be undertaken. A preliminary assessment had indicated, however, that there was no conspicuous enhancement of the intensity of micro-cracking beyond that of the more-or-less uniformly-sparse background density.

This absence of a pre-weakened zone supported the impression formed by the author during the three years that the rupture was being explored, that it had erupted spontaneously from some original flaw at some distance below and ahead of the stope face. Here the stress regime was characterized by large deviatoric stress which had not yet caused any discernible pattern of macro or micro-fracturing. The rupture then propagated explosively through a pristine rock space which, although at the point of being almost critically-stressed, had not failed but on which a strong directional tendency was imprinted by the prevailing static stress field. The attitude of the plane of rupture, and the direction of propagation of the fracture front within this plane, would be determined by the superposition of the transient stress generated by the rapidly-advancing 'crack-tip' on the existing static stress field.

The resulting effect would be that the rupture would drive upwards, metaphorically like an inverted bolt of lightning following its ionized but invisible pre-determined path, towards the intensely stressed but strongly confined zone ahead of the stope face.

The large difference between the transient σ_{max} and σ_{min} neccessary to propogate the rupture as a surface of shear failure would be lost in the strongly-confined static high stress zone immediately ahead of the stope. The fracture front would then lose momentum and die at, or just beyond, the plane of the stope as suggested in photo (d) on page 50. Enigmatically, like the damage causd by the lightning bolt, the rupture front would sometimes be deflected away from the stope towards the solid where it would die out harmlessly. At other times it might deflect towards the mined-out area and 'daylight' into the stope at the face to cause intense damage, as indicated on page 37.

References:

T Engelder. Joints and shear fractures in rock, *Fracture Mechanics of Rock*. Edited by B K Atkinson. Published by Academic Press, London 1987.

R K Brummer. Fracturing and deformation at edges of tabular excavations : development of a numerical model describing such phenomena. *Thesis. Rand Afrikaans University*, 1987.

3 ROCKBURSTS

During the several decades that rockbursting has been a major concern in modern deep-level mining, an extensive library of literature on the subject has accumulated and some considerable research effort has been devoted to the understanding of the phenomenon. Three international symposia on rockbursts and mining-induced seismicity have been hosted by South Africa, by the United States of America and by Canada since 1982. A working commission on rockbursts has existed within the International Society for Rock Mechanics for some years.

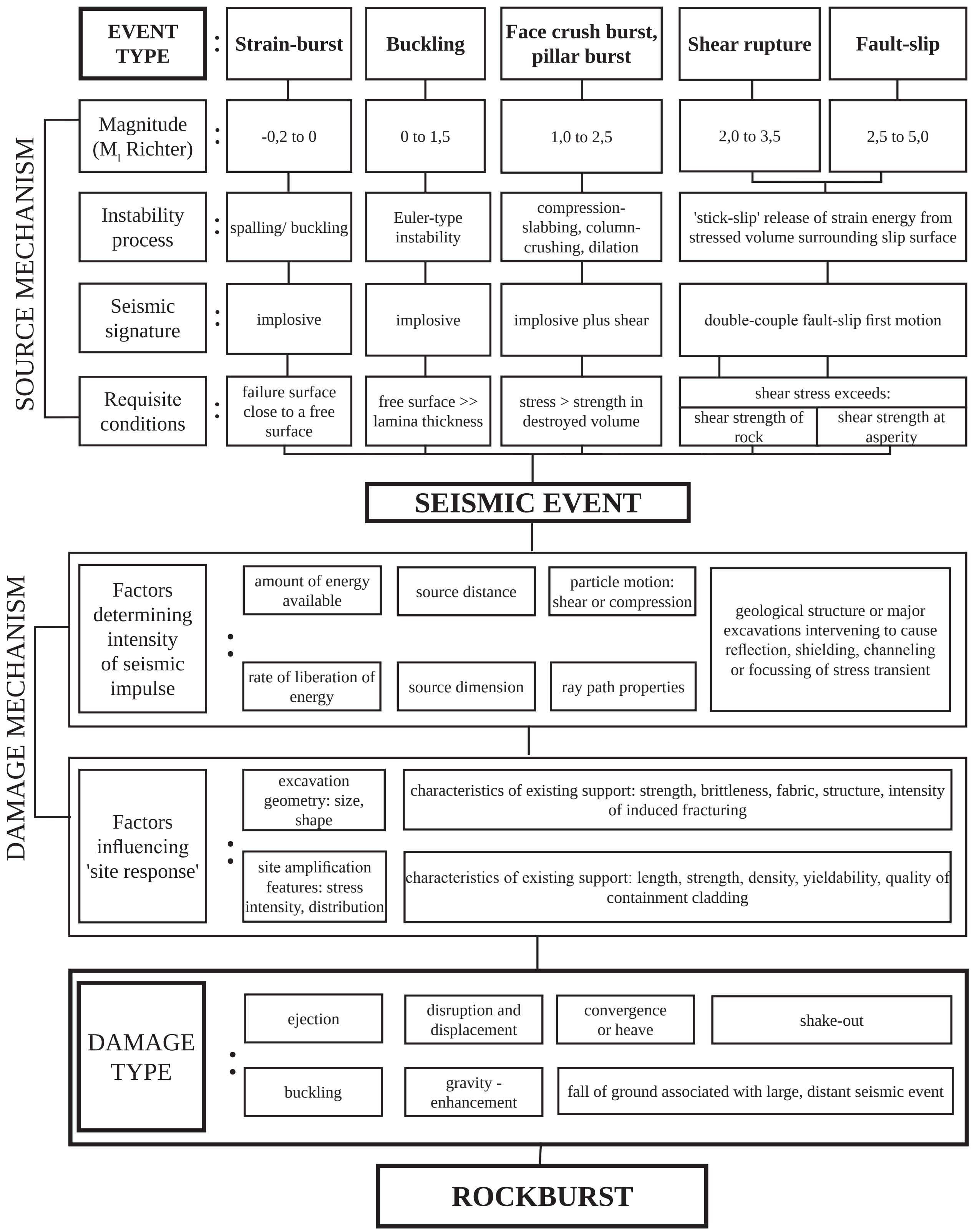
In view of this, it is disappointing and somewhat surprising to find that no widely-recognised definition of the term ***rockburst*** has yet been adopted. It appears that few attempts have been made even to categorize the range of phenomena in a simple manner, and few comprehensive descriptions of specific incidents have been published.

The essential purpose of this book will be adequately served if the reader should understand a ***rockburst*** to be, simply .... ***a seismic event which causes violent and significant damage to the tunnel or the excavations of a mine.*** Such a definition poses no constraints on the magnitude or nature of the seismic event and is broad enough to encompass the notion of a dichotomy that recognizes the possibility of distinctly separate and different, but necessarily related, mechanisms for the seismic source and for the damage phenomenon.

A very simplified classification of seismic event types recently suggested by Ortlepp and Stacey (1994) is tabulated below. Although the magnitudes of the smaller events are essentially guesses, it should be noted that the energy range possibly extends over ten orders of magnitude. It would seem most unlikely that one simple mechanism could cover this entire range.

Seismic event	**Postulated source mechanism**	**First motion from seismic records**	**Richter magnitude M_L**
Strain-burst	Superficial spalling with violent ejection of fragments	Usually undetected, could be implosive	- 0,2 to 0
Buckling	Outward expulsion of large slabs pre-existing parallel to surface of opening	Implosive	0 to 1,5
Face crush / pillar burst	Violent expulsion of rock from stope face or pillar sides	Mostly implosive, complex	1,0 to 2,5
Shear rupture	Violent propagation of shear fracture through intact rock mass	Double - couple shear	2,0 to 3,5
Fault-slip	Violent renewed movement on existing fault or dyke contact	Double - couple shear	2,5 to 5,0

ROCKBURST FLOW-CHART



The essential natures of the first two source mechanisms are different from the last two. The difference is that, for the first two, the source and damage locations are probably coincident – the rock involved at the source is also involved in the damage. For example, strain bursting occurs right at the surface of the opening and is strongly influenced by the local shape of, and stress concentration on, that surface. The unstable failures represented by buckling and face crushing are also importantly affected by the opening in their immediate vicinity - that is, they cannot occur in the absence of the opening.

In contrast, the last two mechanisms represent shear failure along a surface existing, or incipient, deep within the rock space and this shear failure zone could be hundreds of metres in extent. Such conditions are only likely to occur in association with large scale mining operations at considerable depths. The surface of slip may, or may not, daylight into an excavation. If it does, the damage is likely to be catastrophic in intensity.

The ‘pillar-foundation failure’ associated peculiarly with the strike-aligned stabilizing pillars systematically deployed to limit the length of longwall faces on a few very deep mines, is believed to be a special case of the shear rupture mechanism occurring along a static abutment.

The third category of event is more ambiguous and is probably best seen as an intermediate case where smaller surfaces of slipping, perhaps along alignments of induced extension fracturing, form shear surfaces which intersect in a somewhat conjugate manner ahead of a stope face or traverse, in hourglass fashion, right through a pillar.

In the shear rupture or fault-slip mechanisms, the energy is released from the instantaneous relaxation of elastic strain from a very large volume of stressed rock surrounding the surface of slip and the magnitude of the event will be correspondingly very large. In addition, multiple sub-sources of energy may result from impacts at minor steps or jogs or from shearing of smaller asperities along the shear surface during the progression of the movement front. An alternative possibility is that shear (and impacts) occur not only along single shear surfaces, but also along sympathetic features as a result of stress transfer to these neighbouring structures. On the seismic record, the time of occurrence, magnitude and characteristics of these sub-sources may be hidden in the much greater energy release and coda from the main event.

However, it is possible that, because of much closer proximity to a vulnerable mine opening, the smaller sub-source may be much more important in determining the location and intensity of damage than the main event. A notable example of this ‘stress transfer’ causing the secondary event to become the main agent for damage, is the multiple source episode described on pages 96 to 98.

The proposal that a dichotomy linking source mechanism and damage mechanism should be adopted, is intended to develop a more methodical approach towards the understanding of what is believed to be the most complex phenomenon encountered in any mining activity anywhere. A graphic attempt to encapsulate the vast complex of factors involved in each of its aspects and, at the same time, illustrate the dichotomy in a more visual manner, is given on the facing page.

A perusal of this flow-chart or event-tree will show something of the extent to which the application and development of quantitative seismological techniques and procedures has provided understanding and insight into the physics and mechanics of the phenomenon.

It is hoped that the chart will also identify other areas where seismology has yet to be used in a focussed way to provide illumination of aspects of the problem which still remain obscure. This emphasis on seismology as a key contribution to the development of the present level of knowledge is, in a way, a tribute to the crucial roles played by pioneers such as Neville Cook, Rod Green, Art McGarr, Steve Spottiswoode and, more recently, Aleksander Mendecki. The influence which they have had as co-workers, mentors and friends on my own personal development is hereby gratefully acknowledged.

The respect which must be accorded to seismology and seismologists, however, is not one-sided and it should not be allowed to diminish the importance of certain vital contributions which have come from more humble workers through simple but determined application of fundamental engineering precepts together with the use of basic observational skills.

Perhaps foremost amongst this type of contribution has been the crucially important disclosure and elucidation of the ***shear rupture*** as one of the most important source mechanisms for major rockbursts. It may also be seen as providing a small but unique insight into the origin of the pristine earthquake - a part of the mystery of shallow crustal earthquakes which has so far been totally unexplored in a direct, phenomenological way and is likely to remain so in the future.

The observations referred to above are dealt with in sections 3.2.4.1 to 3.2.4.5 and the way in which they have made a contribution to the study of earthquakes is indicated in papers by A McGarr et al (1979), P Segall and D D Pollard (1980), and R Sibson (1985).

A perusal of the South African literature does not reveal when the close association between burst fractures and rockbursts was first recognised. From personal acquaintance, it is known to the author that P G D Pretorius, a well-known mine manager of the early 1960's, had been interested in these features for a long time before he described the typical burst fracture in 1972. However, the first irrefutable proof of the cause and effect relationship of *burst fractures* to rockbursts and the first detailed definition of its shear mechanism came from the studies referred to above. These were carried out on East Rand Proprietary Mines between 1974 and 1980 under the patronage of K E Steele, the general manager at that time. Without the patience and understanding of all those on the mine who were involved in what might have seemed to them to be a pointless and unproductive exercise, our understanding of rockburst mechanisms would now be much poorer.

Acknowledgement must also be made and gratitude expressed to Blyvooruitzicht mine which, at the author's request, drove a short exploratory raise on a burst fracture on 24 level and to Hartebeesfontein mine for the freedom of access they provided to an exposure on 34 level which made it possible to show that the shear rupture source mechanism was not confined to the central Witwatersrand - see pages 58 to 62. The exposure at ERPM, however, remains the original type example of the shear rupture process. It made possible a unique study that has opened a whole window of insight into the mystery of major rockbursts and also, it may be argued, allowed a glimpse of what is probably the essential mechanism of a pristine shallow earthquake - an insight which is believed to be a 'first' in the world of crustal seismology.

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W D Ortlepp and T R Stacey. Rockburst mechanisms in tunnels and shafts. *Tunnelling and Underground Space Technology.* Vol. 9, Number 1, pages 357 - 362, 1994.

A McGarr, D D Pollard, N C Gay and W D Ortlepp. Observations and analysis of structures in exhumed mine-induced faults - *U.S. Geol. Surv. Open File Rep. 79 - 1239*, pages 101 - 120, 1979.

P Segall and D D Pollard. The mechanics of discontinuous faults. *J. Geoph. Res., 85* pages 4337 - 4350, 1980.

R H Sibson. Stopping of earthquake ruptures at dilational fault jogs. *Nature Vol. 316* pages 248 - 250, July 1985.

P G D Pretorius. Strata control and rockburst problems on Central Witwatersrand gold mines. *Symposium on strata control and rockburst problems on the South African gold mines*. Assoc. of Mine Managers of South Africa, Johannesburg, page 513, 1972 - 1973.

3.2 Source mechanism

3.2.1 Strain burst

3.2.1 Strain burst

Introduction

Before extension fracturing has penetrated to any depth into the walls of a highly-stressed opening in brittle hard rock, the stress in the immediate 'skin' of the rock surface is at a maximum. Violent 'exfoliation' or spalling of the surface which can then spontaneously occur is termed strainbursting. The source mechanism and the damage mechanism of this small seismic event are inextricably one and the same phenomenon. An on-going instance of this process in a stope is recorded on page 10. The mirror zone, as described on page 19, can also be an indicator of strain bursting.

Captions

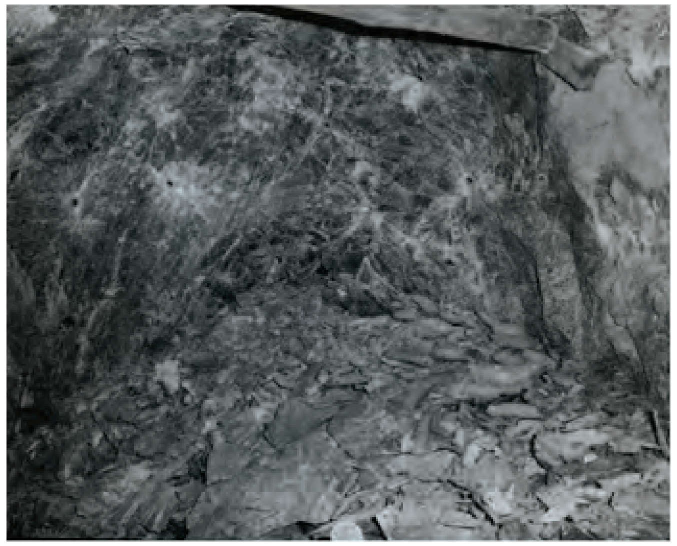
a) Detailed view of eastern sidewall of tunnel shown in (b). The surrounding rock was massive, strong quartzite with a UCS value estimated at greater than 280 MPa.

Although no stratification was visible, the dip of the strata was steeply towards the camera.

The locus of the 'notch'-driven fracture initiation was clearly not influenced by stratification or other geological structure. Spalling-off of 'wafer'-thin slabs to form the smooth surfaces extending away from the notch, occurred violently with the noise of a pistol-shot - typical of the strain-burst phenomenon.

b) View towards the recently-blasted advancing face of a cross-cut driven in a north-westerly direction into footwall strata 2700 m below surface on DRD mine. The reef in the immediate area had not been sloped and the ambient stress was significantly increased by extensive stoping in the surrounding region.

c) Detail of micro-slabbing 'locus' from near the tunnel face back towards the start of the micro-slabbing shown in (a). Note 'wafer'-thin small slab 'nipped-in' and retained by the confinement of the micro-slabbing.



(b)

(c)

(a)

3.2.2 Buckling

3.2.2.1 Buckling of roof in a shallow coal mine

Introduction

Rockbursts, in the sense normally conveyed by the term, do not occur in coal mines in South Africa. One isolated incident however, could appropriately be described as a rockburst, although it occurred at a depth of only 25m. Since its mechanism appeared to be clearly displayed and the main history easily ascertained, a brief description of the attendant circumstances and their interpretation warrant inclusion here. A more complete account has been published in the reference cited below.

The incident occurred in the shallowest portion of the mine where the roof of the 4m thick horizontal seam comes close to the floor of a gentle valley above.

The roof rock consisted of a very fine-grained carbonaceous shale which outwardly appeared massive and homogenous but had a fissile and strongly anisotropic nature. The UCS perpendicular to the stratification was 65 MPa and the Brazilian tensile strength was about 2 MPa and 4 MPa, perpendicular and parallel to the strata, respectively.

The rockburst occurred during 'top-coaling' where the primary bord and pillar extraction had been completed some months before. A loud noise was reported to have accompanied the collapse.

Captions

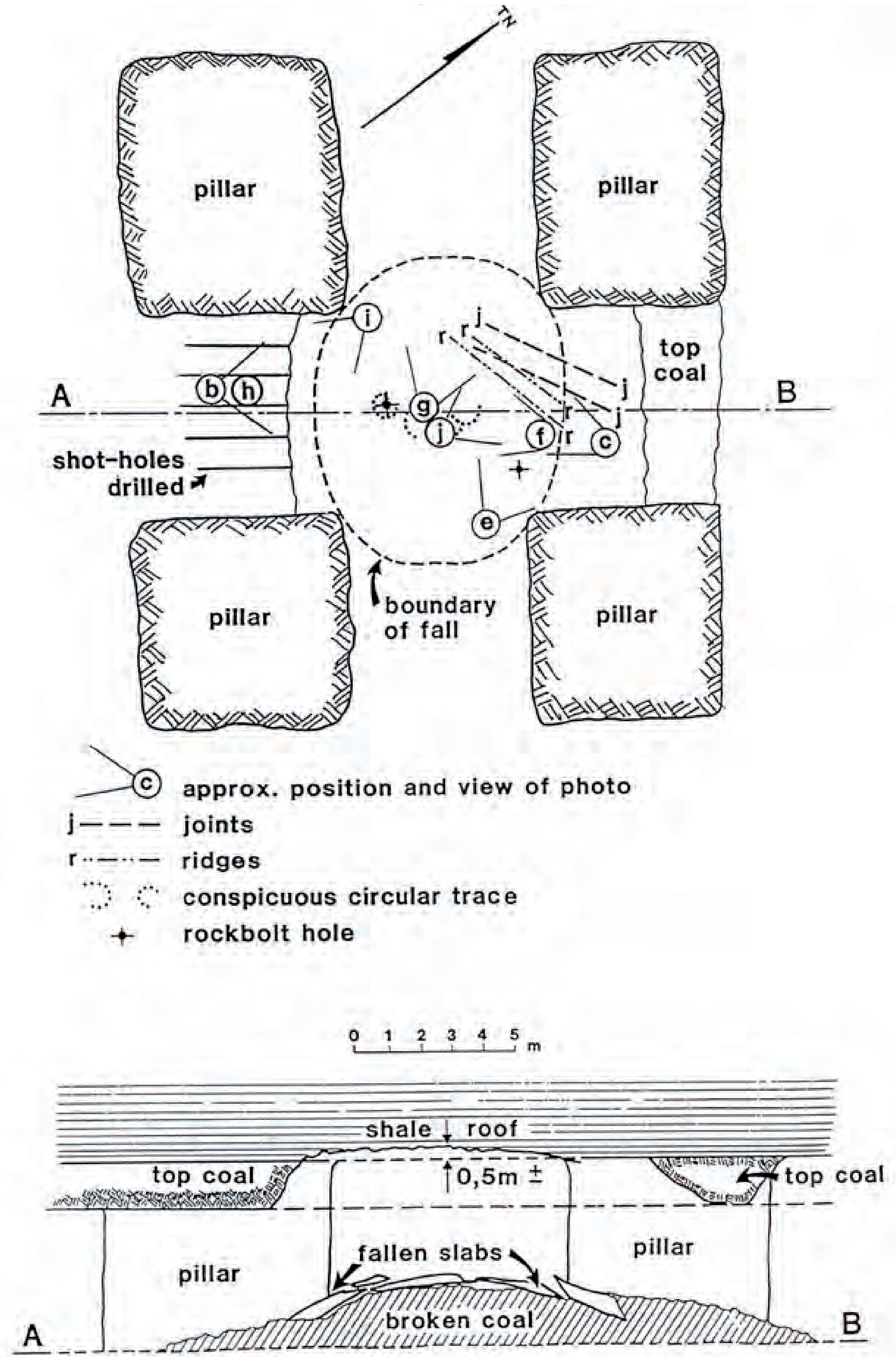
a) Plan and section of affected opening showing outline of collapse and position of photographs.
b) General view from floor elevation towards north-east showing slender/less of fallen shale slabs and shallowness of roof cavity.

Reference

W D Ortlepp and M A Moore. Underground observation of high propagation-rate extension fractures. *6th Int. Congress of Int. Soc.of Rock Mechanics*. Montreal 1987.

(b)

page 23



(a)

Captions (continued)

c) View westward parallel to joint direction showing wide expanse of variously textured fresh failure surfaces. All roof support was installed subsequent to collapse.

d) Section through collapse showing:

(i) the postulated stress situation

(ii) gravity failure mechanism which might normally have been expected.

(iii) plate-buckling failure mode which is believed to be the more likely mechanism of collapse.

e) View northward across the ridges and joints shown end-on in (c).

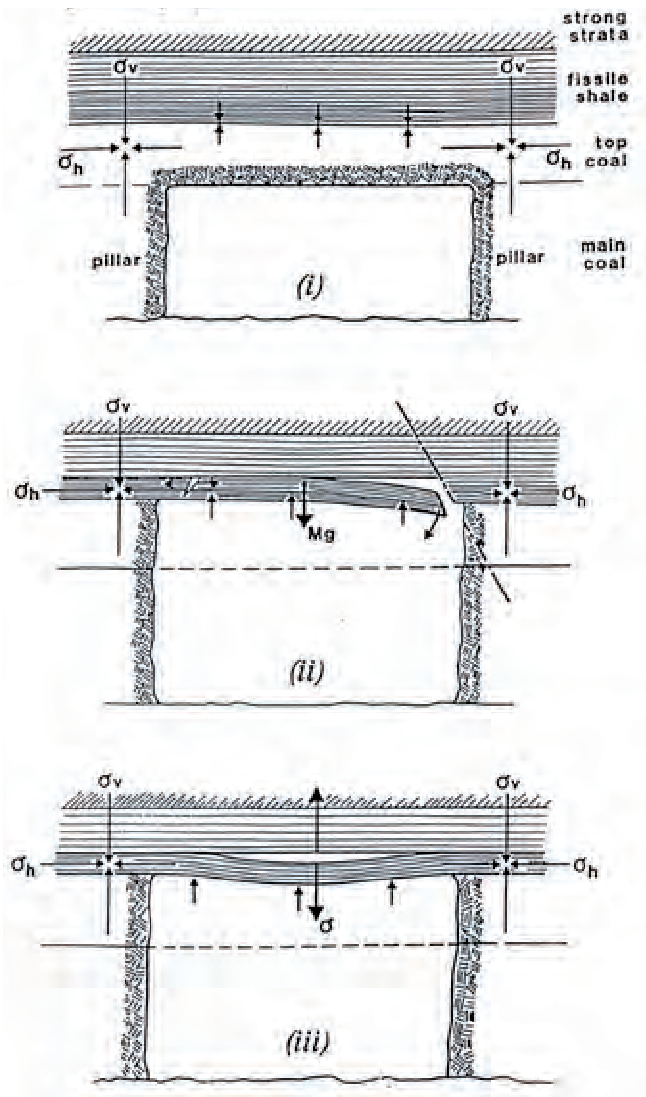
f) Close view north-westward of plumose structures in fan-like array along roof surface left of centre in middle-ground of figure (c).

(g) Close view northward of arcuate 'gouges' where spreading plumose fans appear to interact with pre-existing vertical joint weaknesses. These are sub-perpendicular to main joint direction identified in (c). Note loose particles adhering to roof fracture surface in centre right, possibly by electrostatic forces resulting from a 'charge-separation' effect.

(h) Enlargement of upper central portion of figure (b) showing array of mirror zones and hackled surfaces. Roojbolt hole in top left was being drilled at the time of the collapse. Dashed line encloses area shown in close view in fig (f).

(i) Close view of north showing top coal tending carbonaceous shale above - incipient buckling perhaps?

(j) Detail of near-perfect arc which shows the transition from an extension fracture spreading smoothly at increasing propagation velocity (mirror zone) to fracturing of a 'hackly'nature. Here excess energy is available above that which can be absorbed by growth of a single fracture. The energy absorbed is limited by the terminal velocity of crack growth which is about 60% of seismic shear wave velocity. Beyond this transition, multiple fracturing must develop to accommodate the excess energy. This occurs in the form of radial traces along which two or more fractures develop out of the plane of the original single fracture.



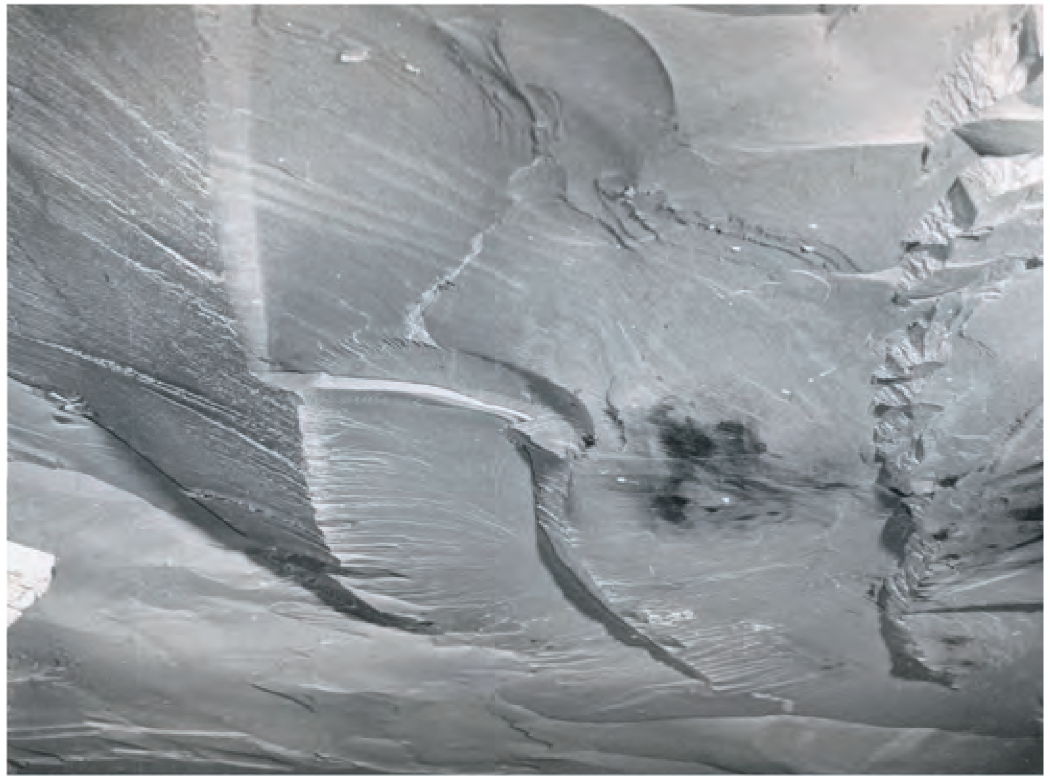
(d)

(a)

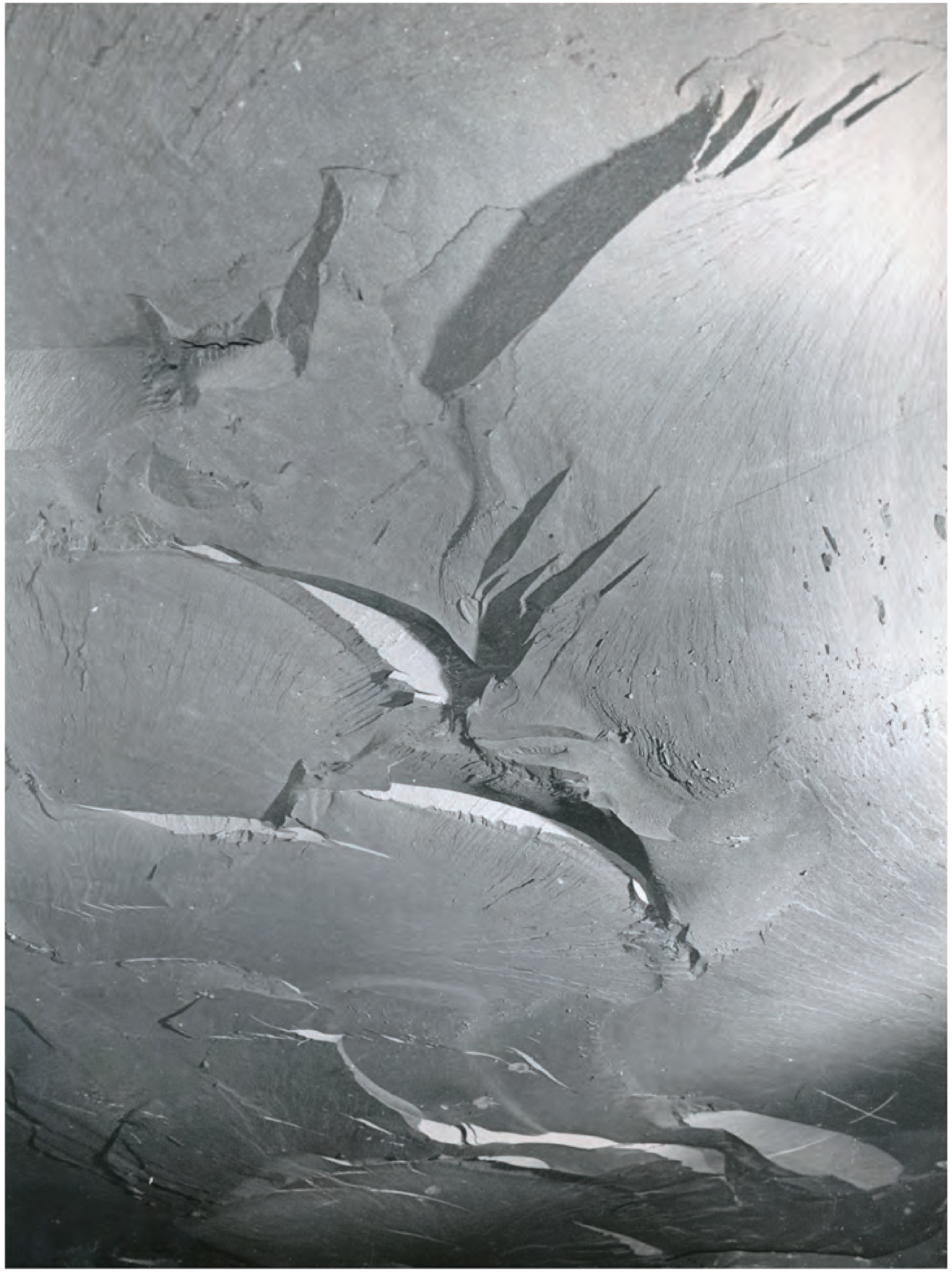
page 25

for captions see p 24

(e)



(f)



(g)

3.2.2.1 Buckling of roof in a shallow coal mine

for captions see p 24

(h)

(i)

(i)

3.2.2.2 Buckling of roof in a shallow coal mine

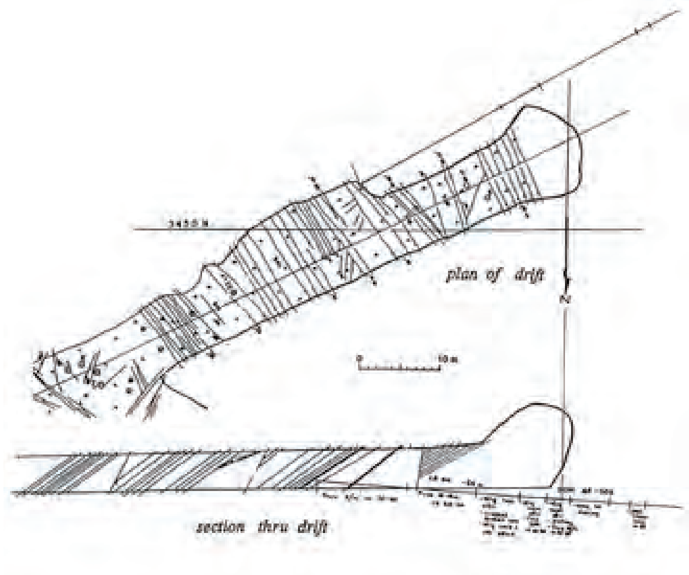
Introduction

Understanding of most instances of violent failure of rock which damage mine workings and which are broadly encompassed by the term rockburst, is based on the assumption that there is a strong element of induced stress caused by extensive mining in the vicinity. Where this element is lacking and explanations are forced to postulate the existence of 'locked-in' residual tectonic stress, such explanations may seem somewhat facile and evasive and are therefore viewed with understandable suspicion by sceptics.

However, careful study of properly documented cases show that a small proportion of rockbursts in mines and perhaps a majority of the phenomena described as rockbursting in shallower civil engineering tunnels, must belong to this category where inherent stress plays a major role.

Perhaps one of the best studied of such incidents is the **Craig drift rockburst** which occurred in February 1990 in the Strathcona mine of Falconbridge Ltd in Ontario. A special investigative group, which included the author, was called together to study the occurrence. A comprehensive report was compiled in the form of inter-office memorandum 91-2a by T Semadeni.

The nearest stoping was a narrow cut-and-fill operation 500m away, so mining-induced stress was negligible at the drift face. Extrapolation from stress measurements made elsewhere (the nearest some 400m away) suggested that the undisturbed pre-mining stress should have had a maximum value of 56 MPa close to horizontal E-W in attitude. The intact rock strength was of the order of 300 MPa and, as would have been expected, there were no signs of unusual spalling or other indications of 'weight' in the drift. The tunnel dimension was 8m x 5m.
After the first burst of magnitude M_N 1,8 which produced 300 t of debris, diamond drilling was done to probe for the Fraser No. 2 fault which was not expected to be intersected for another 150m. The core was disked in the footwall of the fault which indicated higher stresses than normal. The second M_N 2,3 rockburst occurred 10 days later, after rehabilitation of the end but before any further advance of the face. 600t of debris resulted from the second event. A special investigation was convened to consider the two incidents. While it was considered that the fault was the prime causative agent driving the event, the investigating team felt that there were other special features which played an important role in determining its relatively severe magnitude and the very considerable enlargement of tunnel dimension represented by the burst cavity. The existence of a very prominent joint set parallel to the fault formed an array of slender slabs sub-parallel to the tunnel face which presented a significantly large free surface for potential outward buckling. As creep-slip occurred on the fault in response to a local residual tectonic stress, a lack of any transverse structure to weaken these slender but strong slabs allowed them to accumulate super-critical in-plane stress (with correspondingly large elastic strain energy). Failure then occurred with the violent instability characteristic of brittle buckling.



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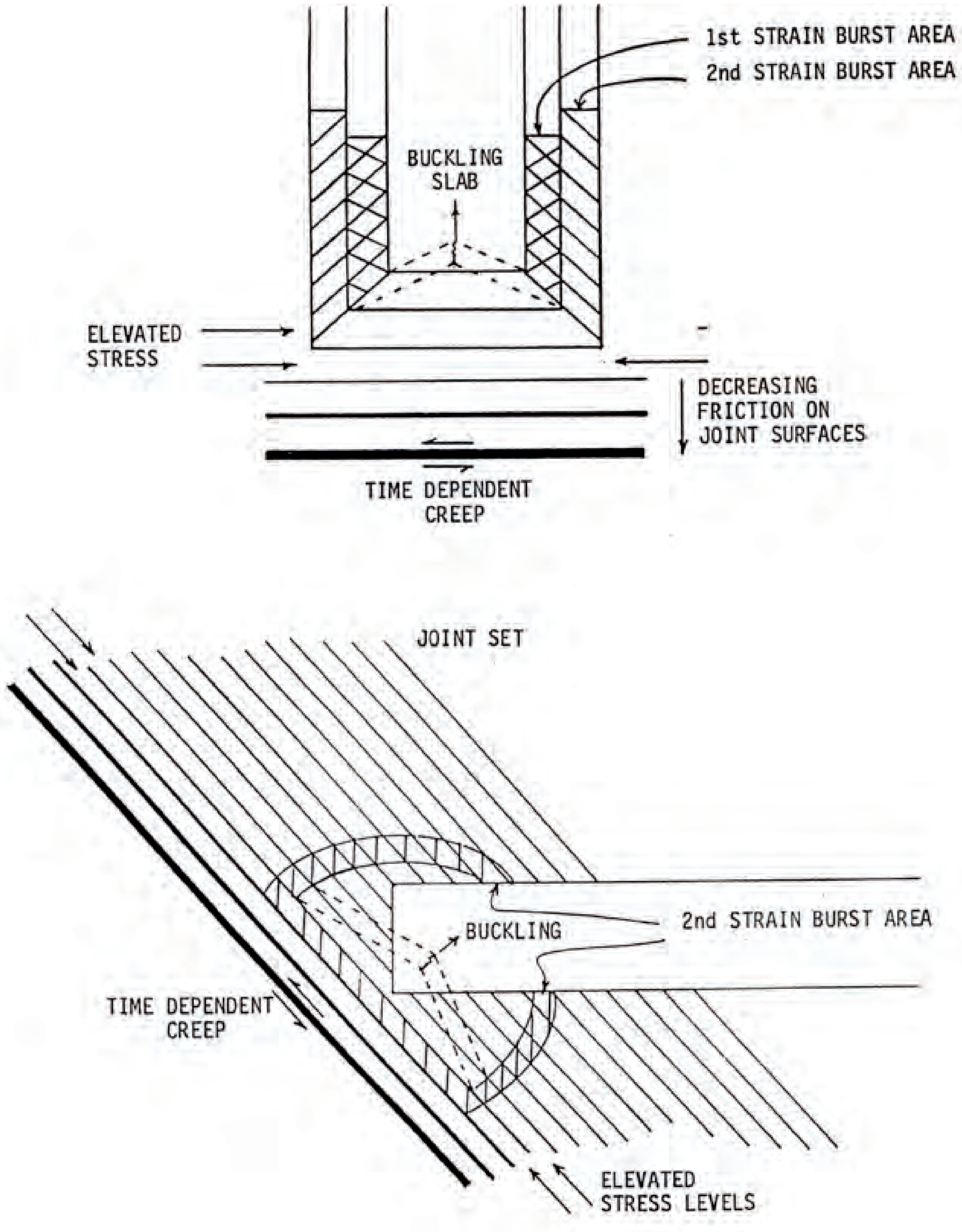

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(b)

3.2.2.2 Tunnel face near fault - the Craig drift

Captions

a) Plan and section showing the mapped distribution of joints in the drift.

b) Schematic plan and section view showing the basic elements of the proposed buckling rockburst mechanism. An analysis using state-of-the-art numerical modelling techniques subsequently confirmed that this mechanism was feasible.

c) View westward of drift end after first rockburst $M_N = 1{,}8$

d) View westward of drift end after second rockburst M_N*, = 2,3.*

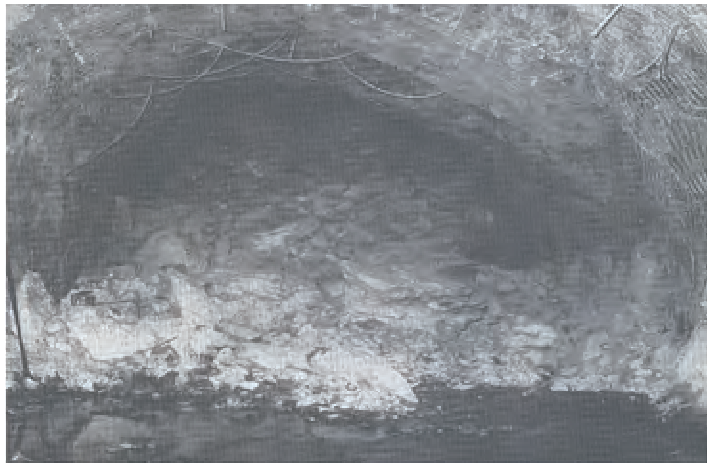
e) View north-eastward from near the toe of the debris pile showing broken Swellex, end-anchored tube bolts and grouted cable anchors that had been installed during rehabilitation operations after first burst.

f) View north-eastward from near the top of the rock-debris pile showing the high point of the burst cavity - 12m above the floor of the drift. Closely-spaced jointing sub-parallel to fault creates a laminated or layered structure. The pipes lying on the debris pile and supported on the trestles are for supply of back-fill slurry to fill the void of the abandoned heading.

Acknowledgement

Figures (a) and (b) and photographs (c) and (d) are taken from the report by T Semadeni. Gratitude is expressed to the management of Strathcona Mine.

(c)



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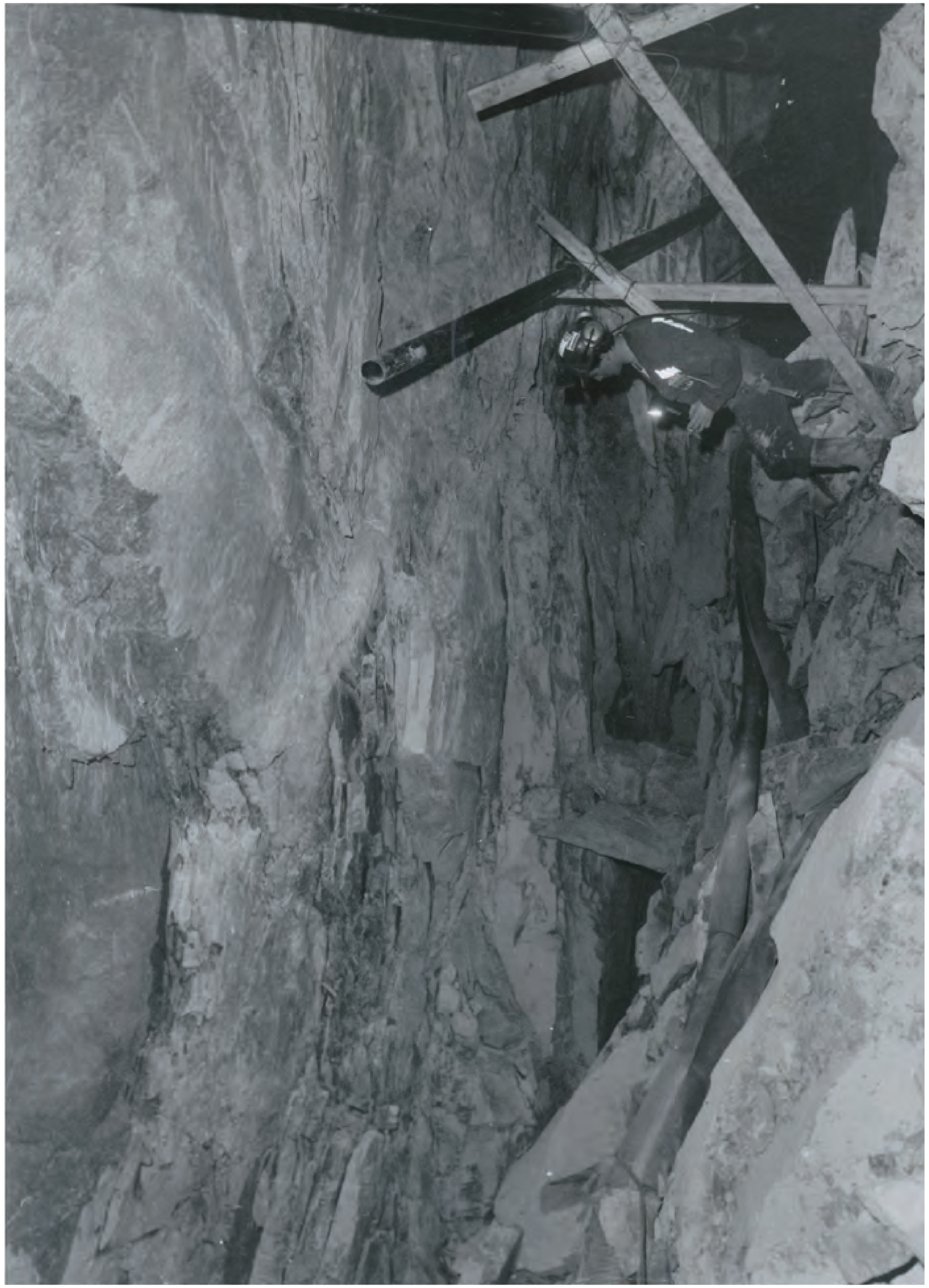

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Introduction

One type of damage associated with rockbursts in tabular slopes which, when viewed at a simple level, might be thought to have an obvious explanation, is the face-burst. Historically, this might be the classic prototype 'pressure-burst' of early Witwatersrand gold-mining - broken rock erupting from the face due to pressure exceeding the strength of the material.

When a more profound study is made it soon becomes apparent that the mechanism of damage, as is usually the case, is not at all simple.

A clear illustration of some of the complexities that are likely to be encountered during closer study was afforded by the following example.

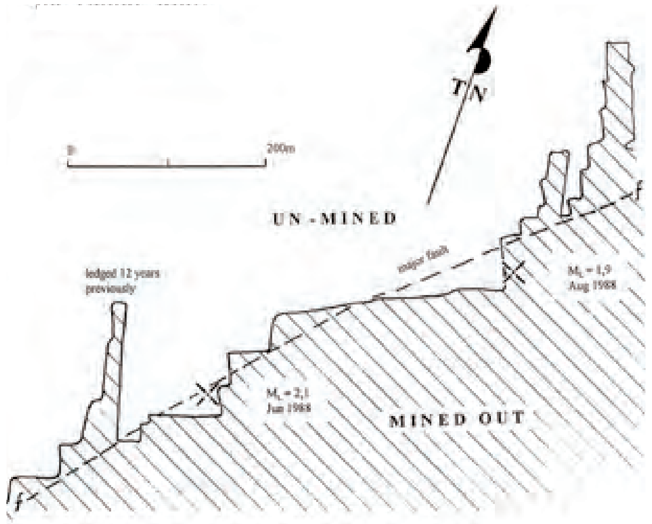
On a deep mine, a section working the Ventersdorp Contact Reef (VCR) experienced two rockbursts separated by about 3 months in time and 400m geographically. The plan in fig (a) shows considerable similarities in respect of stope configuration, proximity to the major fault and magnitude of the associated seismic events. Probably because of a three-fold difference in stoping width (working height), there was a major difference in the severity of the damage suffered. In the later event in the easterly stope, where the stope width was 1,3m, damage was limited to scattered falls and no serious injuries were suffered by the workers. The earlier event in the west-most stope caused damage to the stope face that was quite unprecedented in the experience of the author. The details of the mechanism are obscure and mind-boggling.

Captions

a) Regional plan of extensive VCR sloping, isolated by more than 1000m from other sloping on tlie mine, slwwing location of seismic events.

b) View down face of 5^W panel showing working height of over 3m - typical of appearance of 4^W panel before the burst. The trace of the major fault appears as a vertical ridge down centre-right of photo. The absence of damage on the face or obvious comminution on the fault trace strongly suggests that fault-slip was not the source mechanism of this event.

c) Up-dip view of area of severest damage in 4^W panel. The near-vertical, rubble 'wall' on the left, parallel to the line of packs, was formed by the rescue operation that removed several hundred tons of burst rock that virtually completely filled the space between the wall and the packs. The packs were actually buckled and displaced back\vards by 0,5 to 1,0m by the hulking of the burst debris. The depth of the remaining rubble behind the wall is believed to be more than 2,5m. The relatively smooth curved roof opposite the two observers in the background was measured to extend for 2,7m beyond the edge of the rubble wall.



(a)

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Captions (continued)

d) Plan and section of the worst affected area of 4^W panel and plan of the north-face up-dip sloping that was mined beyond it to re-establish mining of 4^W.

e) View towards the face from behind the first row of packs about one third of the way down from the top of 4^W panel. This shows the complete choking of the working area by the broken rock expelled back from the face. Note the lack of any sign of convergence on the packs.

f) View north ward some 9 weeks later near top of 'north facing' re-establishment stope. The vertical solid wall behind the observer is a prominent dip-aligned joint which forms the western edge of the crush pillar bet\veen the old abandoned stope and the new. The charging stick in top right corner has been thrust into an opening at the top of the wall which appears to be continuous with the original stope roof described in (c). The observer's hand is indicating the only significant induced fracture seen anywhere in the new stope. This feature has some comminuted material on its surface suggestive of shearing along it, but it is not like the 'burst fracture' described in section 3.

g) View west along north face showing reasonably good hangingwall conditions. A careful search along the 7m of roof exposed behind the face showed no sign of induced fracturing parallel to the old 4^W face.

Speculation

The prominent dip-aligned joint exposed by the subsequent re-establishing north-face proved to be a strongly-developed discontinuity parallel to the 4^W panel face. It appears to have prevented the normal development of the face-induced extension fractures which characteristically (at moderate to great depths) exist some 2 to 10m ahead of longwall stope faces. The resulting concentration of stress between this feature and the advancing 4m high face allowed a state of quasi-stable 'super-stress' to develop in the incipient vertical plates ahead of the face. With additional extension fractures forced to grow here (because they could not migrate beyond the joint), the Euler slenderness of the slabs would increase until, with characteristic buckling instability, violent disruption of the slabs would suddenly occur. The disruptive energy needed to break the slabs into rubble and to thrust the fragmented buckling mass into the working area of the stope would be drawn from the elastic strain energy in the disrupted volume and its stressed surrounds. In this case the source mechanism and the damage mechanism are indistinguishably parts of the same complicated process.

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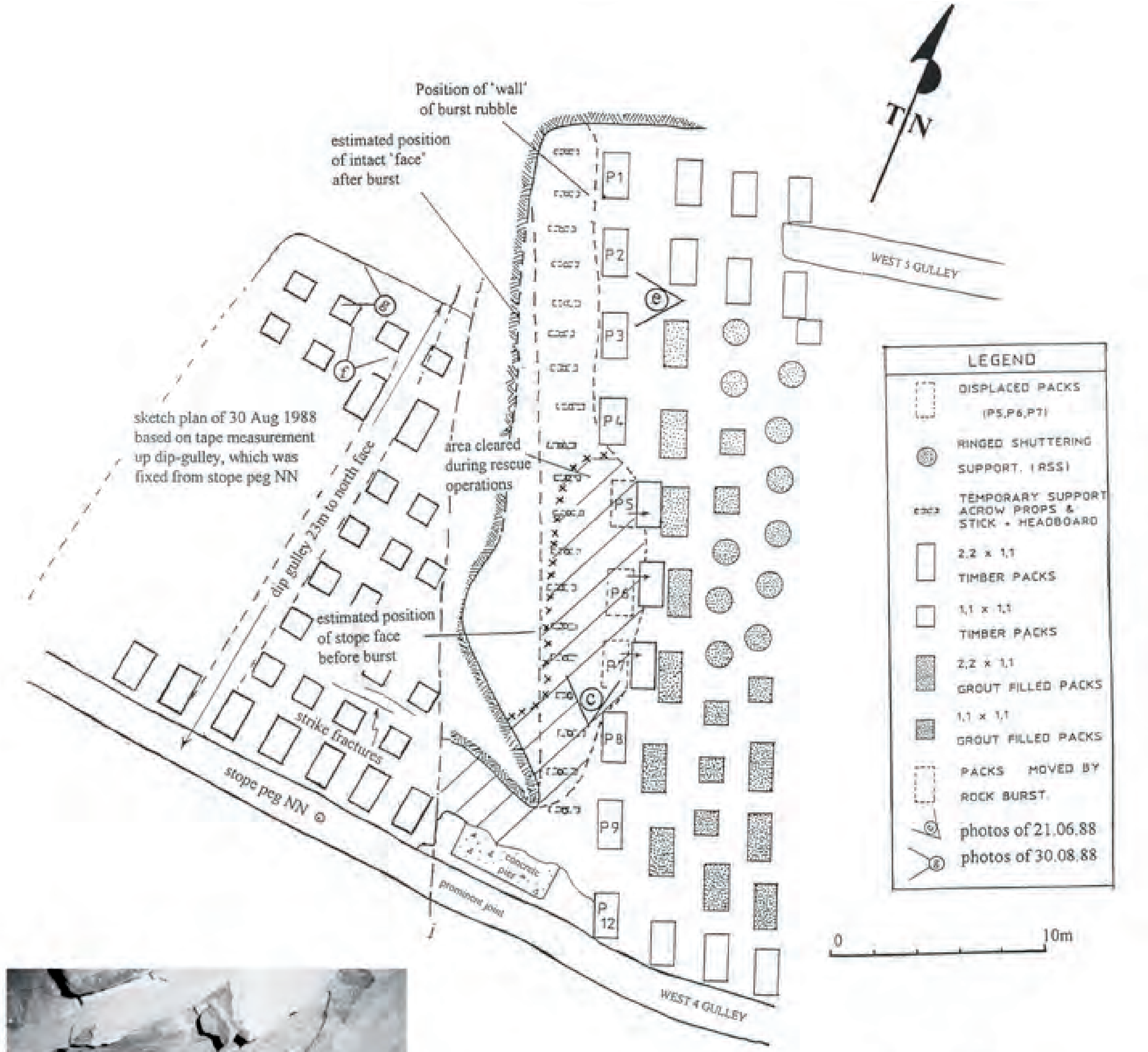

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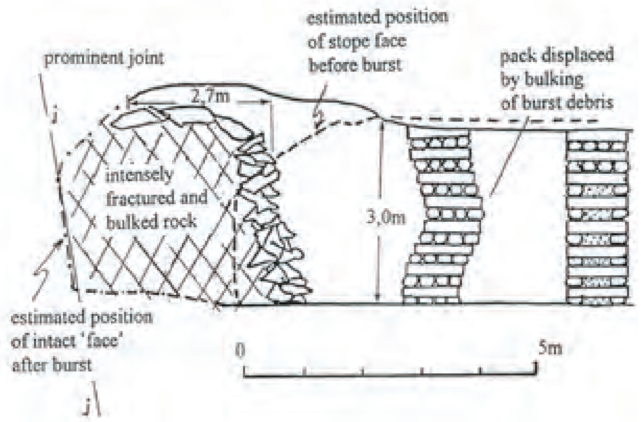

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3.2.3.2 Pillar burst in shaft

Durban Roodepoort Deep 5^ sub-vertical

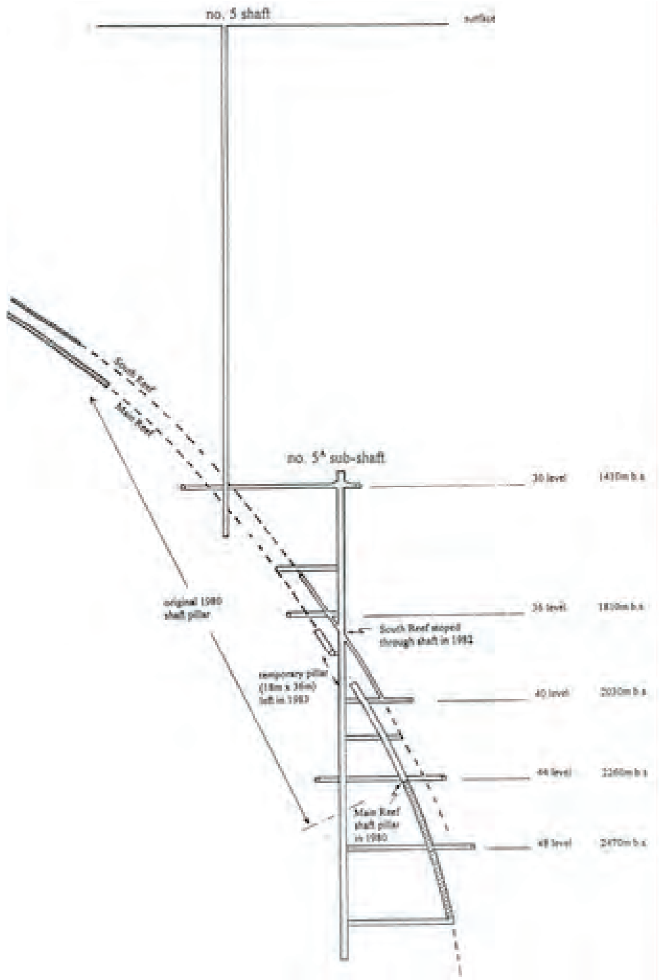
Introduction

Damage to deep vertical shafts that can be directly attributed to rockbursts are fortunately extremely rare events. The dislodgement of a relatively small block of rock or piece of concrete from the lining, which would result in negligible damage in a horizontal tunnel, could easily cause a major disaster by seriously damaging the guides or winding equipment in a shaft.

Isaacson (1962) makes several references to the problem as it affected operations in the Kolar goldfields in India. Despite the high level of seismicity and the very large number of shafts in South African gold mines, only very few instances of damage occurring during the operating life of mine shafts have been recorded.

The worst of these occurred in the Orange Free State goldfields in 1973, apparently as a result of slip movement on a major fault which intersected the shaft 200m above the sloping horizon - Williams 1976. The movement on the Wesselia fault nine years later which is described on page 75, is believed to have resulted in considerable delay to normal operations in the same shaft, but no account has been published in the technical literature.

It is worth noting that the protective shaft pillar was intact in each case at the time of the event. When a shaft pillar is being removed, usually at the end of the productive mining life of the area, large rockbursts are common occurrences and serious damage to the shaft occurs much more frequently. This is not surprising in view of the fact that the shaft pillar area is usually a very highly stressed remnant and the stress levels become even higher as the size of the remnant is reduced.



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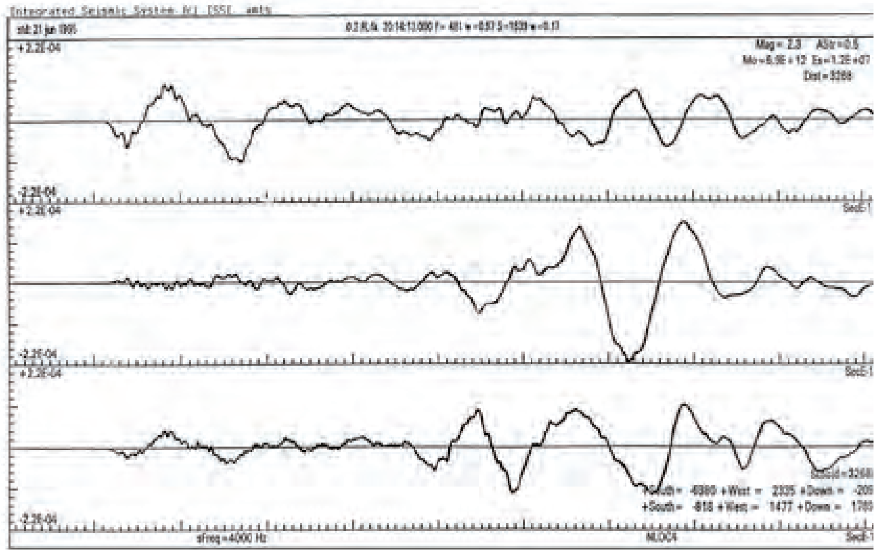

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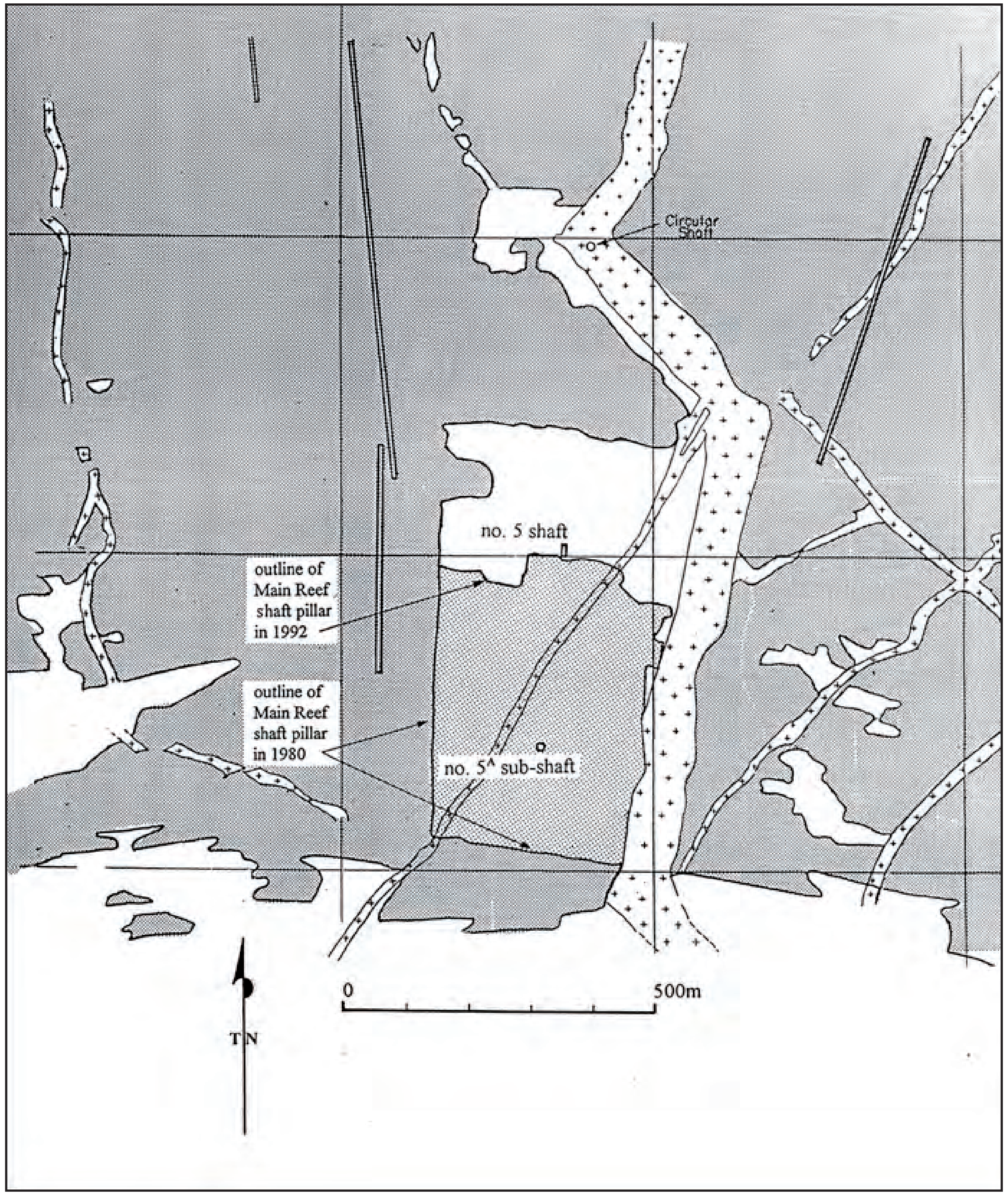

(a)

3.2.3.2 Pillar burst in shaft

Durban Roodepoort Deep 5^ sub-vertical

Introduction (continued)

A particularly interesting event of this kind occurred on 21 June 1995 on the Durban Roodepoort Deep gold mine. The following features made it an occurrence of unique value for phenomenological study of the seismic source mechanism and rockburst damage mechanism:

- the seismic characteristics were properly captured by a high-fidelity digital system albeit limited to a single 3-component station about 4km away on a neighbouring mine.
- the source area was well constrained.
- the total extent of damage was easily determined and well documented.
- it had all the characteristics of what might perhaps be termed a 'soft' rockburst, the crustal counterpart of which would be the 'slow' earthquake.
- it dramatically illustrated the potential danger inherent in even a small 'remnant' left close to an important excavation.

Briefly the historical background was as follows:

Extensive sloping, during several decades, of large areas of Main Reef and South Reef had left No. 5 shaft and 5^ sub-vertical shaft surrounded by a large pillar of some 400m on strike and 1400m on dip - fig (a). Over a period of about 10 years the pillar was carefully extracted from the deeper levels upward with the South Reef faces leading, until the configuration shown in fig(a) was achieved in 1989.

In accordance with correct rock mechanics design, the inner pillar area on South Reef was the first portion of the shaft pillar to be mined after proper provision had been made to the shaft steelwork to accommodate the (pre-calculated) unavoidable convergence and ride displacements that would occur. The 20m x 45m pre-stoped area was filled with unclassified, uncemented mine tailings to limit the displacements of the rock-mass and to effect a ventilation seal.

(e)

(f)

page 32

(d)

3.2.3.2 Pillar burst in shaft

Durban Roodepoort Deep 5^ sub-vertical

Introduction (continued)

Because of delays in modifying the steelwork across the Main Reef intersection 70m below timeously, a small temporary inner pillar of 18m on strike and 36m on dip was left from 38 level downwards when the Main Reef stoping continued towards its final position on 30 level. Due to successive changes in management and the moving-on of all the personnel involved in the pillar removal operation, the temporary inner Main Reef pillar was not removed. Hoisting through the converging South Reef intersection continued without any problems during the following 12 years and there were no premonitory signs of the impending disaster contained within the now-forgotten 'temporary' pillar. Fortunately the rock hoisting duties of the sub-vertical had also ceased and the shaft was kept open solely for the vital operation of maintaining pumping for the entire mine.

The seismic event that occurred at 20:15 on 21 June 1995 was felt by mine officials living nearby as a long duration tremor preceded, a few seconds before, by a 'rushing' noise that came from one quarter and receded in the opposite direction (this is a subjective phenomenon often perceived by people after a very large seismic event has occurred at a great distance).

It was recorded by a 'stand-alone' ISS Int. Ltd seismological station on the adjoining mine some 3,5 km to the east and attributed the following basic parameters:

Moment (M_o) 6,9 x 10^{12} Nm
Radiated energy 1,2 x 10^7 J
Magnitude M(M_o) 2,3

The most significant feature of the seismogram is the low frequency content of the event - fig (c). For both P and S arrivals the velocity peaks occurred at about 7,7 Hz. Such an extremely low frequency for such magnitude suggests two things. Firstly the source size radius (Brunes model) would be large, 182m, and the stress drop correspondingly low at about 3,6 x 105 Pa. These parameters would suggest slip along a pre-existing fracture plane involving low rupture velocities and a large volume of relaxation.

Mine officials were soon alerted to the reality that damage had occurred not far away but close by. Alarm calls received were from the two attendants on 44 level pump station at 5^shaft. Their rescue involved long and tortuous journeys along 36 level and 40 levels to old travelling ways through the old stopes east of the main dyke - fig (a). The fact that these were still open and that there had been no significant fresh tails along the unsupported tunnels through the dyke, proved that slip along the dyke contacts was not a possible source mechanism and that the source region was therefore confined to the area immediately around the shaft.

During subsequent visits the main impression gained was that much crushing had occurred in the small Main Reef pillar with considerable downwards extension of the shaft-parallel 'wrap-around' fractures. Signs of slippage were restricted to very slight indications of 'rock-flour' gouge on an E-W steeply-dipping joint (perhaps a minor fault) shown in fig (h), but no off-set was visible. In the cross-cut from 38 level Main Reef drive southward to the South Reef drive some 12m west of the shaft, what was thought to be the westward extension of this fault/joint was observed. There was no sign of movement along this discontinuity and no damage at all in the totally unsupported cross-cut. The Main Reef drive to the east of 38 station was inaccessible due to a local collapse but westward it was completely undamaged.

The South Reef drive was also open for about 50m eastward from the cross-cut apart from old spills of waste-fill from waste-filled paddocks above.

The lack of damage in the two reef drives and the linking cross-cut, which together virtually circumscribe the small pillar, confirms the 'softness' of the rockburst. It also supports the suggestion that the source mechanism was probably the near-total crushing of the 'temporary' pillar, perhaps initiated and localized by a small amount of slip along the prominent E-W joint/fault surface in (h).

page 33

(g)

3.2.3.2 Pillar burst in shaft

Durban Roodepoort Deep 5^ sub-vertical

Captions

a) Plan of the lower portion of the eastern section of Durban Roodepoort Deep Ltd.

b) Dip section showing the extent of the shaft pillar in 1995 and the position of the 'temporary' Main Reef inner pillar.

c) Seismogram of the event.

d) View almost vertically downwards in north-easterly direction of initial damage to the concrete brick-lined sidewall adjacent to the north east rock hoisting compartement. Photographed 5 days after the rockburst.

e) View vertically downwards towards the west in the man-hoisting compartements.

f) View eastward along 38 South Reef drive showing about 50% convergence in the initially-stoped inner pillar area and no sign of recent closure or ride movement. Photographed 21 days after the rockburst.

g) View of final expression of damage in main compartements.

h) View vertically downward from suspended temporaray station floor on 38 level showing main burst cavity as it appeared about month after the rockburst. Enlargement of the damaged zone occurred in the form of two or three further collapses during the clean-up and make-safe operations. There was no further seismicity and explosives were not used. The more-or-less plane surface extending down the top (north) edge of photograph is the joint/fault.

References

E Isaacson. Rock Pressure in Mines. *Mining Publications Ltd*, Salisbury House, London, 1962.

A W Williams. Technical notes on the recovery operations in a vertical shaft damaged by ground movement. *Papers and Discussions of the Assoc. Mine Managers of S. Africa.* 1976/77 pages 11 - 21.

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(h)

3.2.4.1 Introductory note : the type example

xviii

Inasmuch as more than one-quarter of this book has been devoted to the phenomenon of shear rupture or ‘burst fracture’ and most of this to one particular instance, it might appear to many readers that a disproportionate amount of attention has been given to this single topic. It may be that such a point of view is well founded and the author is guilty of self-indulgently riding an obsessive hobby horse. However, the strong belief has to be expressed that the emphasis given to this matter and particularly to the special occurrence in the West Claims area of ERPM is indeed justified. Even at the risk of appearing only to want to create a further opportunity for discourse on the topic, it is felt that a fairly comprehensive explanation should be offered to the reader who can then make his own well-informed judgement on the relative importance of the shear rupture phenomenon in the etiology of rockbursts.

It should perhaps be conceded at the outset that it has been a matter of compulsive interest for a very long time for the author to want to know, in the most simple and physical terms, just what happens when a very large amount of energy is suddenly and violently emitted from somewhere in the semi-infinite rock-space surrounding a mine, to express itself as a large rockburst. It is just not possible to accept that the primal source of the energy could have been contained within the limited volume of rock that has ‘burst’ out into the mine openings.

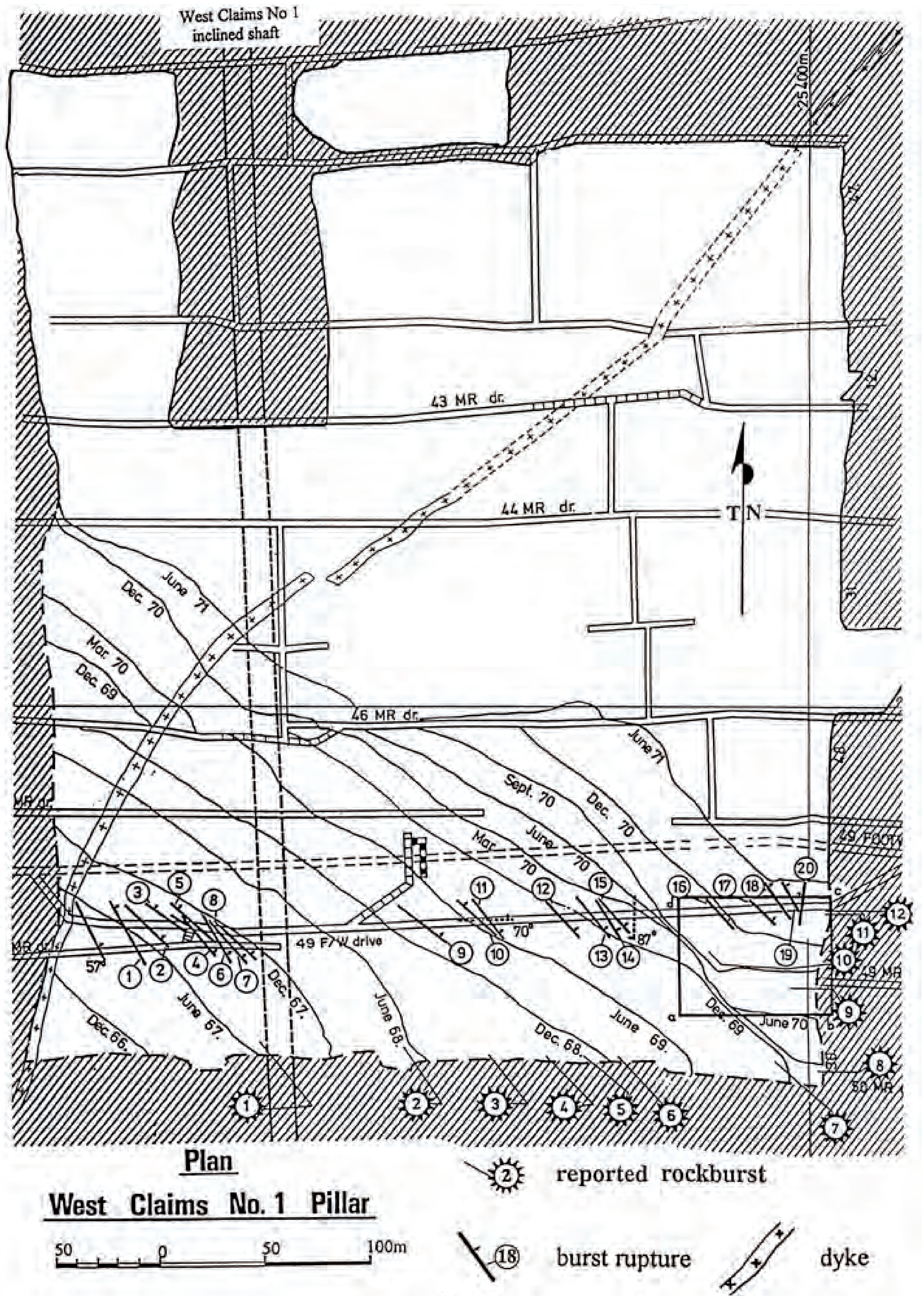
It was also not possible to accept that the energy release or seismic event was an ephemeral, transient happening that would have no visible effect or leave no ‘fossil imprint’ somewhere in the rock mass. It simply required that the ‘footprint’ had to be discovered and then definitively identified! This is essentially what happened at ERPM.

Although intriguing glimpses had been seen before on other deep mines of the central Witwatersrand (also belonging to the Rand Mines Group), the essential and definitive proof that the ‘burst fracture’ or ‘shear rupture’ was the origin and source mechanism of a major form of rockburst, was provided by the West Claims remnant. Here a remarkable sequence of at least twenty ‘footprints’ was revealed by the replacement footwall drive and later, somewhat serendipitously, two of them were convincingly associated with recorded rockbursts.

There were several reasons why it was on ERPM that the definitive link was made between the shear rupture mechanism in the solid rock mass on the one hand and the burst fracture and rockburst damage manifestations in the stope excavations on the other. Some of these reasons were largely fortuitous while others were entirely due to mining circumstances and to the intrinsic physical and geological nature of the rock mass surrounding the study area.

The mining geometry of the West Claims No. 1 shaft pillar was very simple in outline and strictly ‘bounded’ in the sense that it was totally surrounded by relatively extensive mining on two stratigraphically-close reef horizons. Because of the double-layer nature of the stoping and its isolation from any abutments, the stresses in the remnant were considerably higher than usual for the moderate prevailing depth of 2030m. Importantly, because of the remoteness of the other abutments, any seismic event that occurred during the mining of the pillar had to be the consequence of something that happened right there, within the volume confines of the remnant.

The geology of the area was particularly simple. There was only one dyke in the entire pillar with only a small amount of associated fault-throw. The strike of the structure was perpendicular to the direction of the mining face - see Figure (a) - and any resultant non-uniformity of the stress-field would have limited extent along the mining face. The rock mass comprised typically uniform and strong quartzite, relatively massive and almost free of jointing.



(a)

The total absence of faulting enabled mining to proceed more or less without interruption along a relatively straight longwall face. The 'follow-behind' replacement footwall drive on 49 level encountered repeated traces of induced shear fractures all of which possessed a very consistent strike direction parallel to the mining face, and all of which dipped at similar inclinations in roughly the same direction. The fact that these features were so similar in attitude and all shared other attributes of freshness of gouge material and texture, made it certain that they were manifestations of the same physical process. Their similarity is quite simply attributable to the uncomplicated mining geometry and the single direction efface advance of the longwall.

In the light of these rather special circumstances it is not easy to challenge the claim that the particular 'burst fracture' that was explored was not unique but indeed representative of a suite of similar phenomena. The repetitive and cyclic nature of these fractures argues strongly for a process whereby mining-induced stress increases in a zone ahead of, and below, the longwall face to a critical level at which failure occurs violently. This failure drives a new rupture* along a more-or-less plane surface whose attitude and extent is determined by the prevailing stress field. The occurrence of the fracture results in a partial relaxation of the formerly intense stress in the region beyond the new fracture surface. This relatively relaxed state then persists for some time before continuing face advance causes a further stress build-up which progressively increases to the critical intensity when the next unstable rupture is initiated. This cycle was repeated again and again, probably more than twenty times, each new fracture creating a fresh 'footprint'.

After some 10m of development in the exploratory raise, the fracture that was being opened up was found to intersect another rupture of identical character and morphology which was not exposed anywhere in the footwall drive. It was entirely fortuitous that it was this particular rupture (no. 18) that had first been revealed in such a vivid manner that it had virtually demanded further exploration because, in the light of present understanding, it is most unlikely that any one of the twenty other fractures would have intersected another similar feature higher up. The fact that the intersected fracture had a markedly different strike direction, was parallel to a deliberately-changed stope face direction and that it pre-dated the 'typical' burst fracture was later shown to be not fortuitous but the direct consequence of a change in the pattern of mining. This cause-and-effect association enabled important conclusions to be deduced that served to confirm the plausibility of the entire hypothesis regarding the source mechanism of these events.

There were two further fortuitous, but vitally important, links in the chain of circumstance that led to the West Claims area becoming the 'type area' which yielded the unique proof of existence of this type of rockburst source mechanism. At this time Dr Art McGarr of the USGS Office of Earthquake Studies was involved in a long period of study carried out on the mine into the seismological characteristics of rockbursts. A special working relationship had developed between Art and the author which resulted in him being closely drawn into the enthralling pursuit of trying to trace the origin of the 'footprints'.

Most importantly, the mine manager allowed himself to be persuaded, by purely scientific argument, to start a long-sustained, non-productive tunnelling exercise to satisfy the whim of his enthusiastic rock mechanics engineer. The development, totalling some 90m, was guided in its direction and to some extent in its rate of advance, purely by the wishes of the author!

Later, some 12m of raising was done on Blyvooruitzicht gold mine, again at the request of the author, to confirm the persistence of a burst fracture observed there beneath one of their longwall slopes. Apart from this, it is almost certain that no similar endeavour has ever been done on any other mine in any other country.

* see also page xiv

Art McGarr's involvement in the exploration of the type example on ERPM resulted also in a further important confirmation of the close similarity between the shear-type rockburst source mechanism and the source mechanism of shallow crustal earthquakes. The distinctive and relatively simple geometry of the overlapping, echelon segments of the rupture where it was first exposed - photo (c) page 42 - persuaded Art to subject it to a numerical elastic analysis - Mc Garr et al 1979.

A similar approach was adopted and extended, by Segall and Pollard (1980) in a paper in which some of their conclusions were reinforced by reference to the ERPM occurrence analysed by McGarr. They concluded that the way in which a fault segment 'stepped' at an echelon break, in relation to the sense of movement on the fault, would determine whether the ongoing seismic history in that region would be in the form of low energy earthquake 'swarms' or fewer, much larger, single earthquakes. Further extension of these ideas by Sibson (1985) suggested that dilational steps or 'jogs' could act as kinetic barriers that opposed propagation of the earthquake rupture. A notable instance was the 1966 earthquake at Parkfield which is possibly the most closely studied portion of the San Andreas fault in California.

Even a superficial perusal of these papers will show that these scientists, along with many others, have no difficulty in recognising, and then using as a foundation for further hypotheses, the very close physical similarity between earthquake source mechanism and the shear rupture or fault-slip origins of the large rockburst-causing seismic events in mines.

It takes but a small conceptual extension of this widely-accepted physical identity to allow one to make the suggestion that the explored rupture (no. 18) is also the 'type example' of the *pristine earthquake* and the only instance where the anatomy of an earthquake source, albeit a very small one, has been exposed and explored.

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P Segall and D Pollard. The mechanics of discontinuous faults. J. Geoph. Res., no. 85 pp 4337-4350, 1980.

R H Sibson. Stopping of earthquake ruptures at dilational fault jogs. Nature, vol. 316 pp 248-250, July 1985.

3.2.4.2 Seismic source: shear rupture

Introduction

There are indications in the early literature on the rockburst problem in South African gold mines that “shearing of rock” appeared to be associated with violent manifestations of rock failure.

P G D Pretorius gave a detailed description of ‘burst fractures’ in 1972 (for reference see page xviii), but provided no illustrations as far as the author is aware. The first photographs purposefully taken of such features were made several years before at the suggestion of Pretorius, then manager of City Deep gold mine. The resulting rather dramatic photograph was used by Art McGarr in one of his early papers but the negative was subsequently lost.

Over the following several years, evidence gathered from underground study reinforced our conviction that shear ruptures (Pretorius’ burst fractures) were frequently the primary cause of rockburst damage.

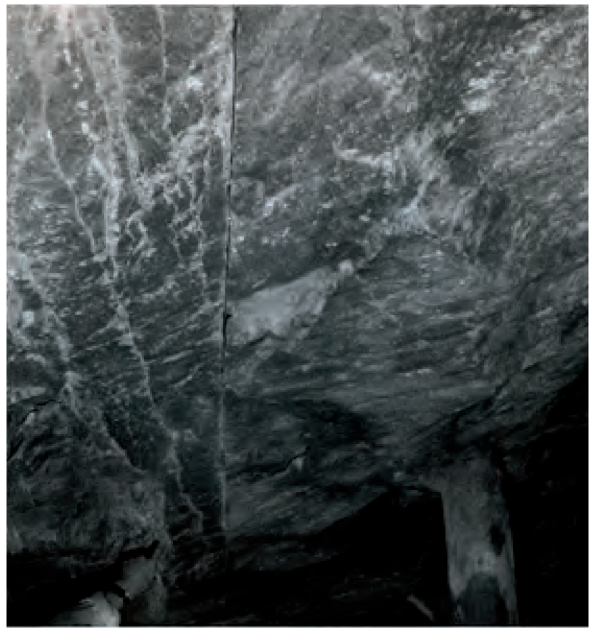
Captions

(a) View south westward parallel to the face direction of 72E panel on L shaft longwall stope at ERPM Ltd. The longwall face at this position was very underhand i.e. on a minor dip about mid-way between true dip (22 ° SW) and strike. The trace of a minor ‘burst fracture’ is being pointed out, to the west of which the hangingwall was conspicuously free of any induced fractures for a distance of 1,5m. Normal frequency of extension fractures is about 0,15m as visible in left foreground. Two parallel, straight joints are visible crossing the face fractures and the parallel burst fracture at about 15 °. There is a pronounced step of about 70mm downward to the east along the burst fracture.

(b) Close view of the western of the two joints referred to in (a).

(c) Sketch plan of tlie portion of 72E panel showing the unusually acute angle between the toe of the face and the scraper gulley. The scraper gulley is parallel to an E-W fault with a 5m downthrow towards the south. The depth of the stope is some 3060 m below surface.

(a)



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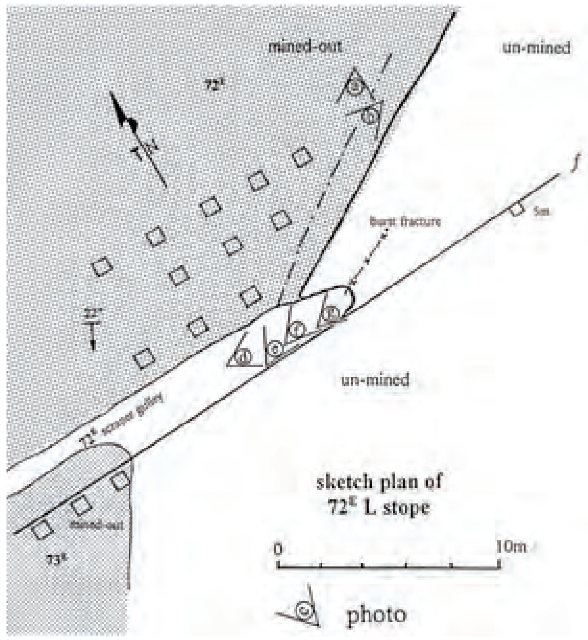

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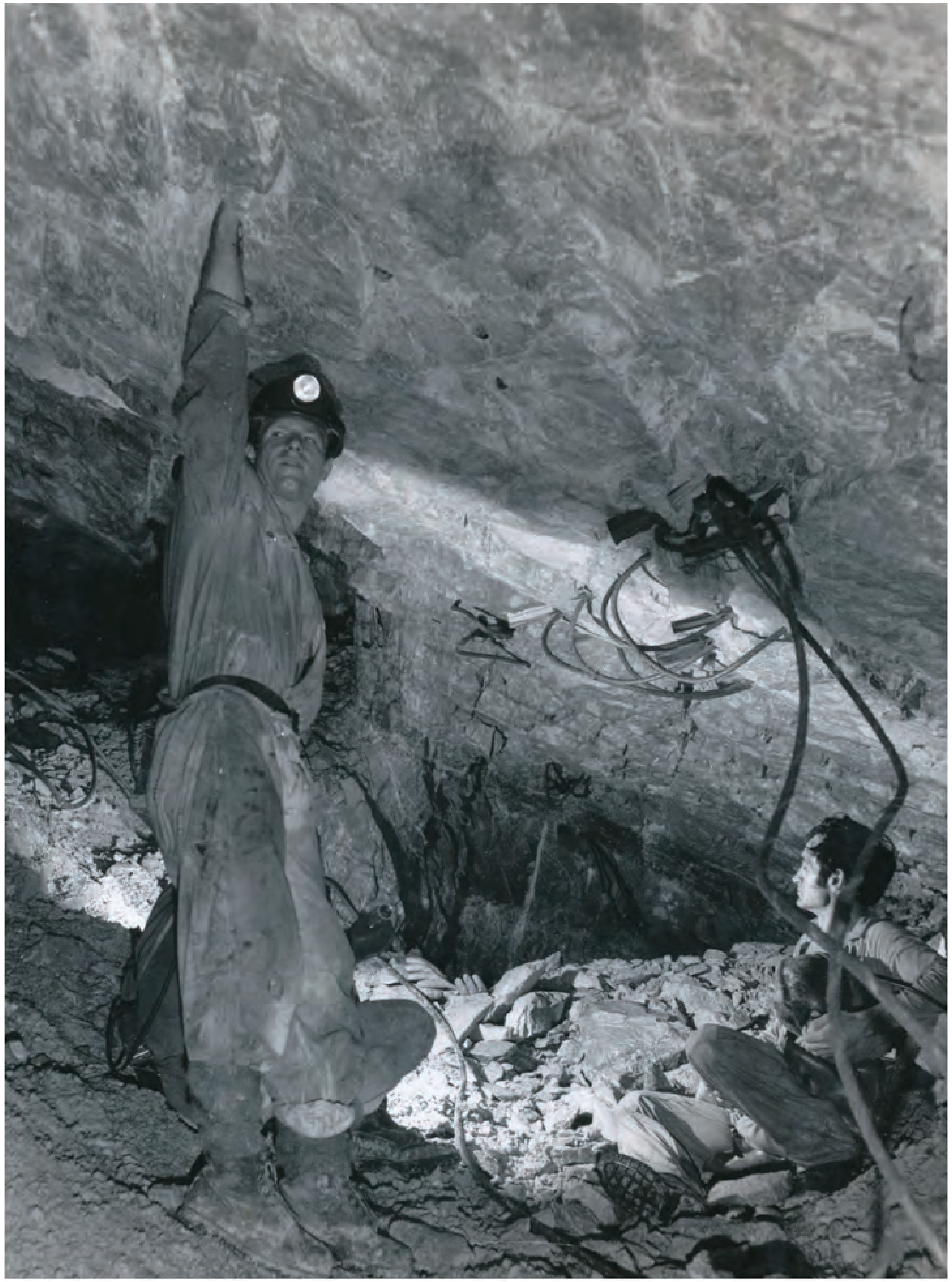


(d)

page 36

Captions (continued)

(d) View towards the gulley end. McGarr's hand shows a cavity along the extension of the minor burst fracture of fig (a). A conspicuous, whitened, comminuted fracture, apparently terminating at the bottom contact of the reef, is visible in the centre background.

(e) View north-eastward from gulley upwards along the stope face of 72^E panel.

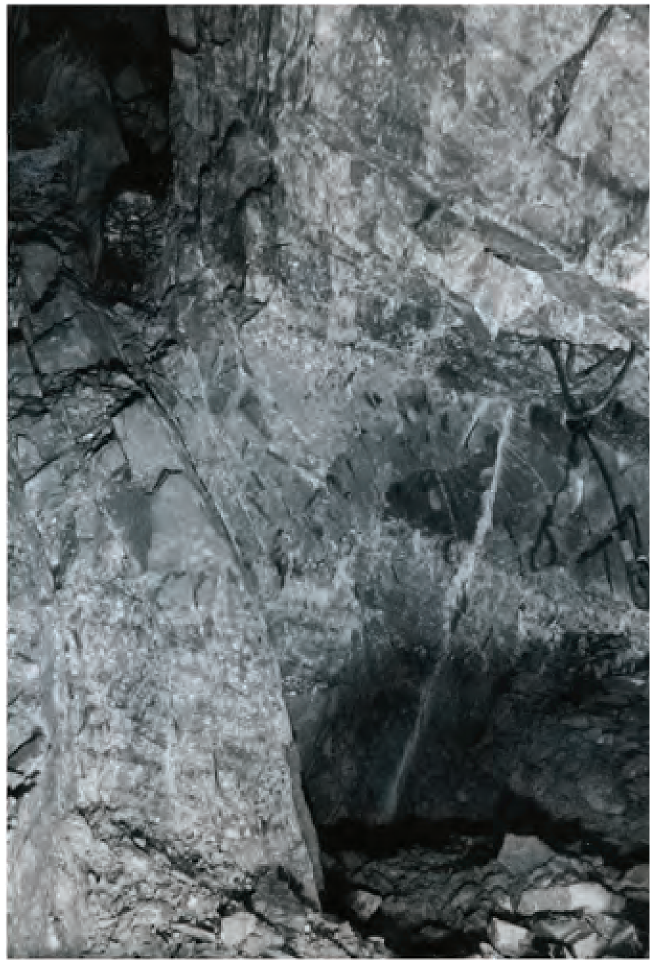
The burst-fracture cavity of (c) is visible in upper left of photograph pointing towards the mine prop at the toe of the panel face.

(f) Closer view of end of gulley and toe of stope face. The slightly-curved prominent discontinuities dipping at about 80 ˚ just left of centre are probably joints of the set visible in (a). The face-induced extension fractures which normally would be expected to dip from right to left in the footwall appear to be modified to become sub-parallel to the joints.

(g) Close view of the new, prominent burst fracture which appears to terminate against the reef about 2m ahead of the stope face. It is not possible to determine where the face was when the fracture occurred.

The slip movement along the burst fracture appears to be about 30mm downward towards the west, thus normal in type. The secondary extensional fractures form an acute angle with the shear surface such that the angle points in the direction of the relative movement. This feature and the right-stepping 'en-echelon' overlapping of the shear fracture itself appear to be consistent characteristics of burst fractures.

(e)



(f)

(g)

3.2.4.3 'Daylighting' burst fracture

Introduction

Over a period of several years, observations made in the West Claims area of ERPM provided several important pieces of evidence which would eventually be linked together to identify the burst fracture (shear rupture) as the ultimate source of one type of rockburst.

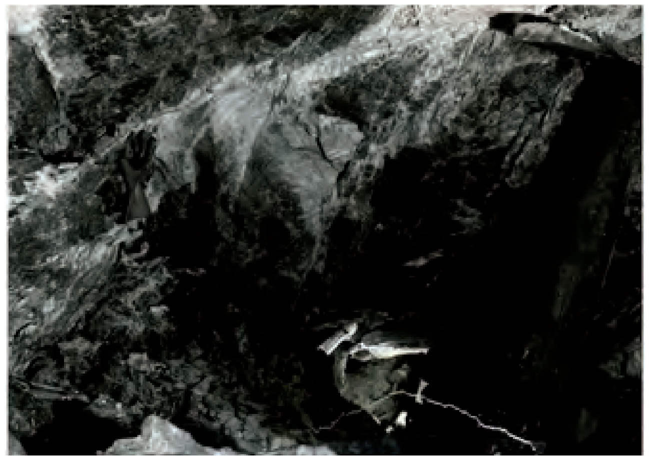
Captions

(a) View down minor dip, parallel to face of the 46^E Main Reef stope of West Claims shaft east longwall on ERPM Ltd. This stope was visited soon after the faces were re-opened after a very severe rockburst had caused extensive damage to the reef drives and stope accessways nearly 3 months before on 21 January 1974.

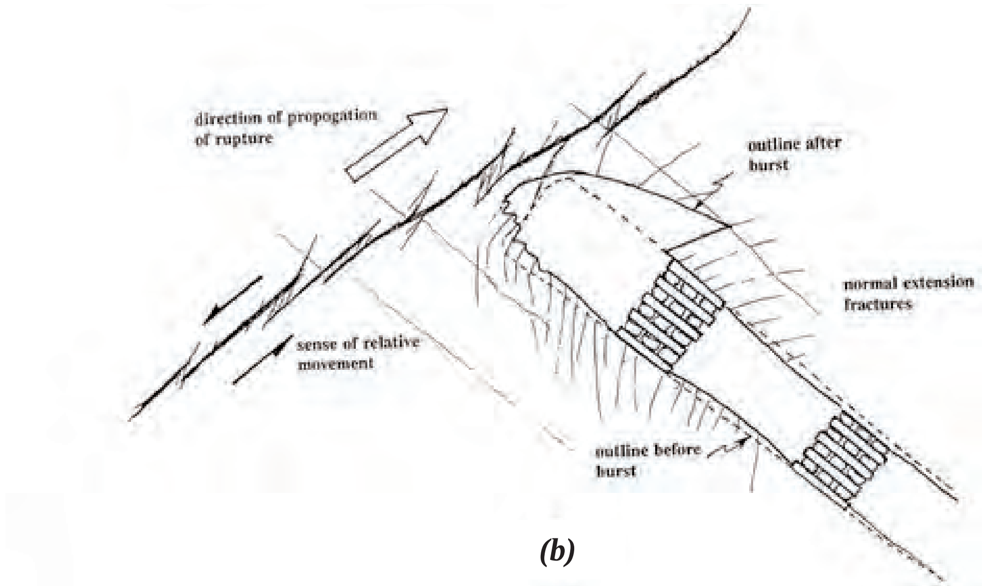
The working area is still choked with burst debris just beyond the illuminated portion about 8m away further down the stope. The support visible along the face was installed during the re-opening operation. The jagged, comminuted surface which extends from the face (marked by glove) across the hangingwall over the timber pole, is the trace of a major burst fracture whose rupturing probably caused the damage, of the rockburst of 21 January.

(b) Vertical section perpendicular to the line of the stope face showing present profile of the opening and how it would have appeared before the rockburst. The conjectural representation of the burst fracture as originating below the stope and extending upward through the stope face into the roof, is based on the strong expectation that the source mechanism was the same as had frequently occurred before in the West Claims pillar remnant - see page 41.

c) Detail of 'daylighted' portion of burst fracture. The intensely comminuted 'rock-flour' is particularly strongly developed on the main shear surface which extends upwards at 60° from the glove into the hangingwall. Some comminution is also visible along the oblique, secondary fracture surfaces which would, usually be expected to be of a pure extensional nature.



(a)



(b)

page 37

(c)

3.2.4.4 Shear rupture source mechanism - West Claims

Background and location

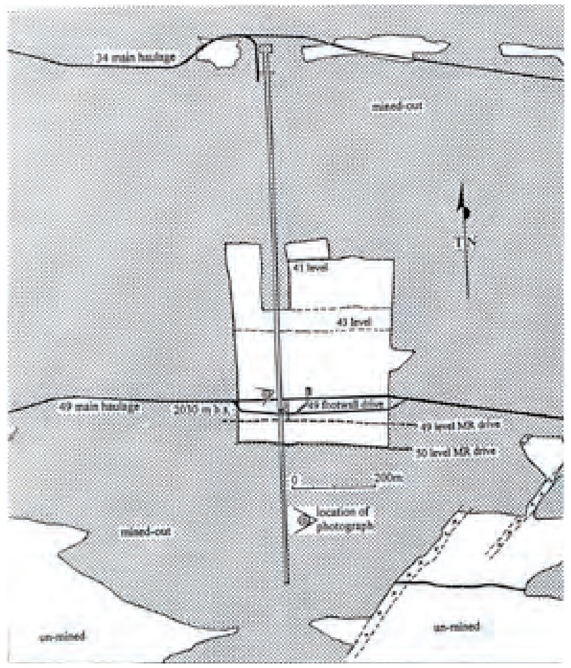
Introduction

The situation and circumstances which provided the opportunity to exhaustively explore the source mechanism of a type of rockburst characteristic of the mines of the Central Witwatersrand, are described below.

Captions

(a) Outline of lease area of ERPM showing extent of mining and location of West Claims No 1 inclined shaft and pillar remnant.

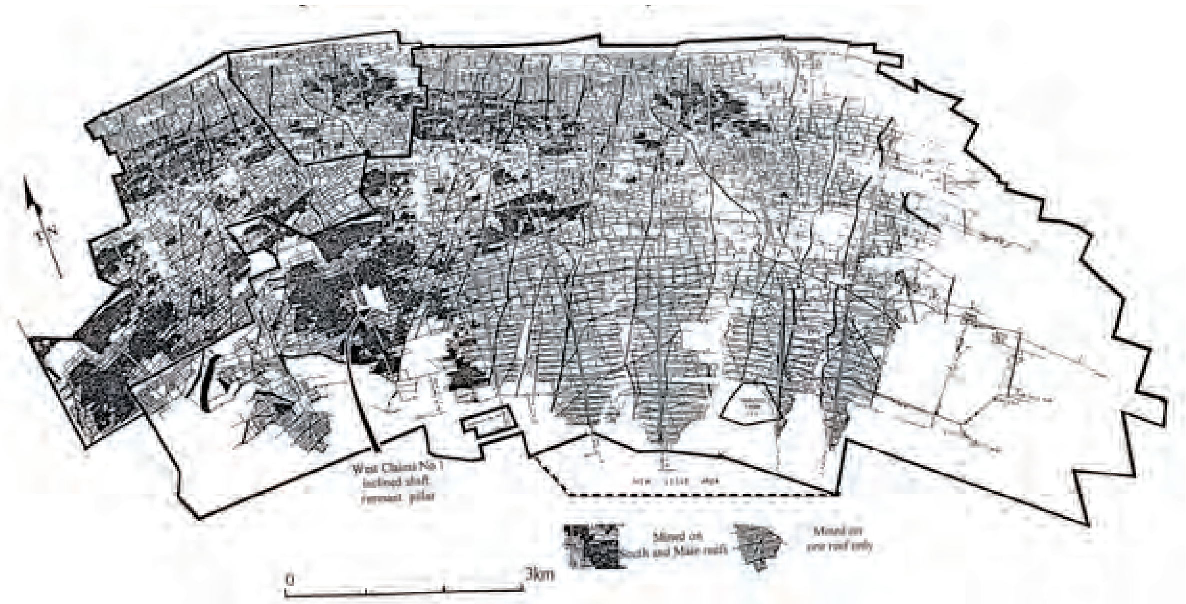
(b) Plan view of No. 1 shaft pillar showing extent of mined-out area as at end of 1965. During 1965 some internal development, mainly raising, was underway to prepare for further overstoping of No 7 shaft below 43 level. No stoping was in progress anywhere within the pillar remnant area. On September 17, a seismic event of magnitude M_L = 3,7 of unknown location and source mechanism, caused major damage within the pillar area. The highly-stressed portion of the shaft, from 43 level to 50 level was destroyed and the main haulage on 49 level was almost completely choked for the full 360m length between the eastern and western edges of the pillar. Since all the infrastructure that it was designed to protect had been destroyed, the pillar no longer served any purpose. Removal of the pillar by means of an overhand longwall stope commenced at the south western corner of the remnant in 1966.



(b)

(c) View westward in 49 main haulage showing extent of choking by large slabs ejected from roof and north sidewall.

Timber poles and pack were installed during rescue operations. The mirror zone in the roof suggests that the fracture that separated the slab from the remaining solid roof propagated at terminal velocity (close to 2000 m/s). *See p 40 for another view of damage to 49 haulage east of shaft probably caused by the same seismic event.*



(a)

page 38

(c)

3.2.4.4 Shear rupture source mechanism

Background and location (continued)

Captions (continued)

(d) Detailed plan view of intersection of new ore-pass crosscut and old 49 main haulage at position about 60m east of no 1 inclined shaft.

Commencing in mid-1969, the cross-cut was driven northwards from 49 replacement footwall drive to establish an ore-pass to handle ore from the upper panels of the longwall. It coincidentally followed one of the few significant joints that existed in the pillar area, through the point of intersection with the old main haulage. The traces of all pre-existing fractures around the old haulage were particularly clearly exposed on this joint surface.

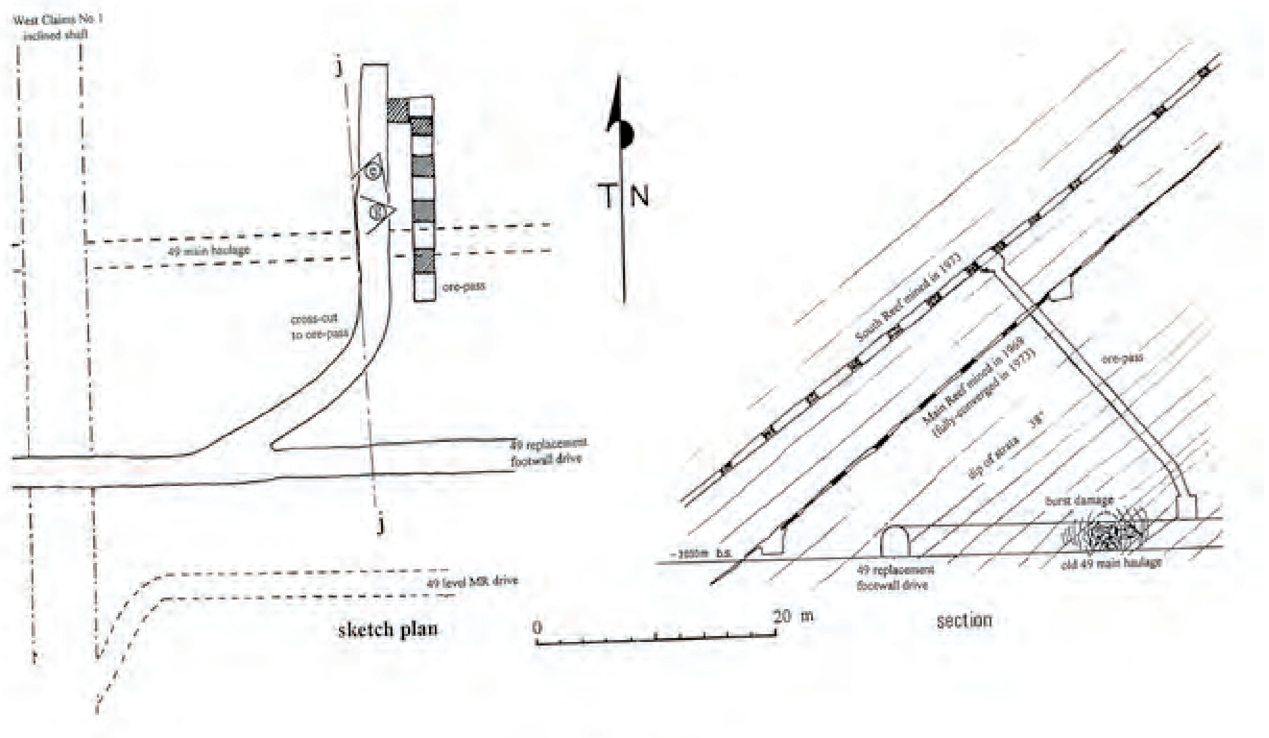
(e) View south-westward along the ore-pass cross-cut towards intersection with haulage. The haulage, centered at left third of photograph is choked by thick slabs of rock which appear to have heeled over or rotated into it mainly from the north. In the right foreground a 'spider web' tracery of fractures intersecting the joint plane gives an indication of the complexity of damage resulting from the rockburst event of September 1965 - superimposed over previously existing 'static' stress fracturing.

(f) Partly conjectural interpretation of fracturing around the rockburst-damaged old 49 main haulage. The left half of the diagram is intended to represent the fracture condition typical of a quartzite tunnel in a high-stress environment where the maximum principal stress is somewhere between the normal to strata and vertical and the k-ratio is 0,5. The right half of the diagram is carefully traced from a photograph viewed normal to the joint surface - (g). The damage mechanism is probably best described as implosive - see Ortlepp 1992.

(g) Detailed view of western side-wall of ore-pass crosscut.

Reference

W D Ortlepp. The design of support for the containment of rockburst damage in tunnels - an engineering approach. *Int. Symp. on Rock Support in Mining and Underground construction*: Laurentian Univ., Sudbury, Ont. June 1992.



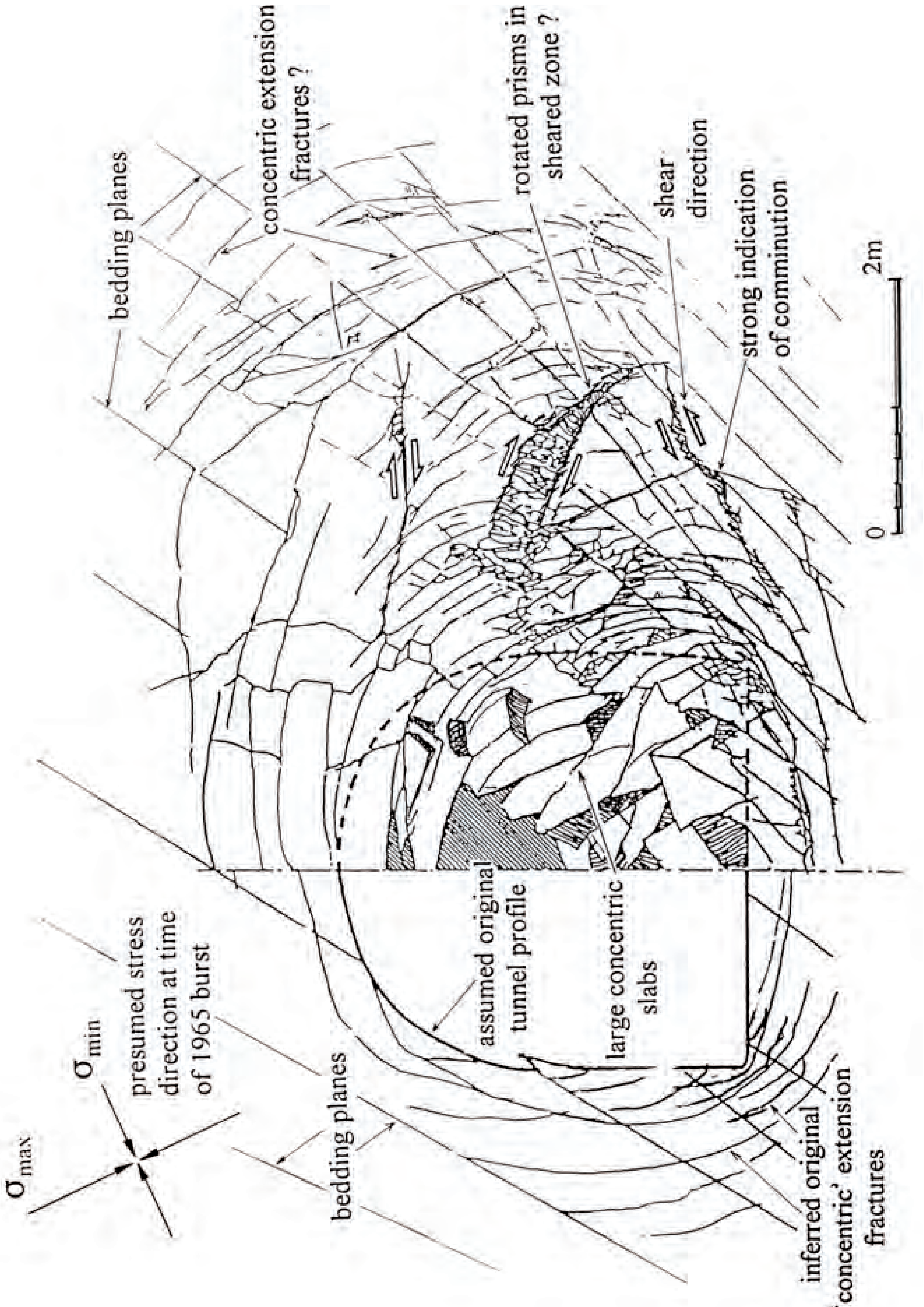
(d)

(e)

3.2.4.4 Shear rupture source mechanism

page 40

for captions see page 39



(f)

(g)

3.2.4.4 Shear rupture source mechanism - West Claims

Shear ruptures in 49 replacement footwall drive

Captions

(a) View north-westward at extreme west end of 49 level replacement footwall drive showing a prominent rockburst fracture. This was the dominant fracture of a group of four old rupture traces freshly exposed by a recent 'shake-out' fall which affected some 20m of the north side of the drive. All four traces were stepped, planar fractures dipping at about 60 ° to the north-east. In fig (b) these traces are represented by the western-most, un-numbered shear rupture symbol near the dyke intersection at the western edge of the remnant.

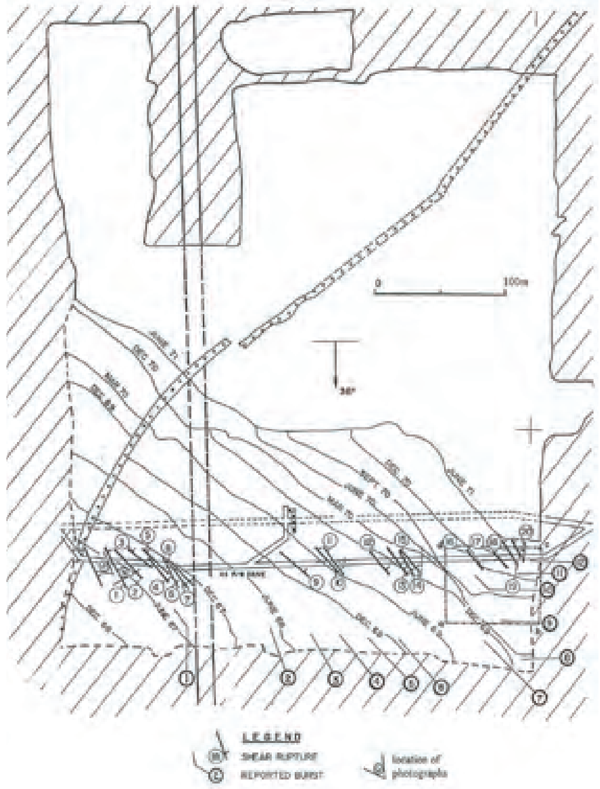
(b) Plan view of the remnant block which originally constituted the shaft pillar protecting West Claims No 1 inclined shaft.

The fall which was bounded by the four fractures referred to in (a) above, occurred on 23 May 1971, possibly as a result of shaking transmitted along the dyke from a major seismic event along the 44 level portion of the longwall slope face some 200m away towards the north-east.

Of the many severe seismic events that occurred during the stoping of this remnant, twelve caused sufficient damage to have been reported as rockbursts. The approximate positions of the longwall at the times of these reports is indicated. Fracture traces, representing the 'fossil' imprint of the more severe of these seismic events, were intersected periodically during the development of the footwall drive. The most dramatic of these fractures was numbered 18 after a subsequent search carried out along the 360m length of tunnel disclosed 20 traces that revealed the diagnostic features of a burst rupture. Because support by steel arches with timber lagging totally obscured one-quarter of the length of the tunnel and partly obscured half of the remainder, it is virtually certain that the 'fossil' records of at least a few more large seismic events were not discovered.

(c) Close view of the fracture visible in (a) which
clearly shows the left-stepping nature of the overlapping segments of the rupture surface.

(a)



(b)

page 41

(c)

3.2.4.4 Shear rupture source mechanism - West Claims

Rupture No. 18

Captions

(a) View south-eastward of a very pronounced shear surface on south sidewall of 49 level replacement footwall drive. This feature is shown as no. 18 in figure (b). The apparent 'doubling-up' of the main surface of shearing is actually an extended overlap (see also figure (c) on page 53).

The prominent bedding plane represented by the pronounced 'step' in the sidewall at the level of the right elbow of the observer (A McGarr) showed a distinct shear displacement of 45mm in a normal sense. The fracture trace extended clearly across the roof of the tunnel and down the north sidewall where the dip of the rupture plane was measured at 63° north-eastward.

This portion of the tunnel was developed in August 1972 and widened out to house an auxiliary ventilation fan in October 1973. The burst fracture was first detected and photographed on 10 April 1974 by the author and Dr A McGarr during one of their frequent visits to rockburst sites. The first description was given by Gay and Ortlepp (1979).

(b) View north-westward of lower portion of burst fracture on north sidewall of tunnel. The apparent increase in thickness of the lower half of the rupture is due to the fact that the camera is not in the plane of the fracture but is obliquely viewing a projecting 'ledge' of shear surface on which the clinometer-rule is resting.

(c) Close view of 'en-echelon' over-lap or leftward 'jog' of upper portion of burst fracture trace on the north sidewall of the tunnel. The magnitude of the jog or step is 260mm. Without exception the jogs are left-stepping (when the fault is observed from the right-lateral perspective). This particular overlap proved to be the best developed of many similar examples that were subsequently exposed. It served as the type example for analyses subsequently carried out in earthquake studies.

Reference

N C Gay and W D Ortlepp. Anatomy of a mining-induced fault zone. Geol. Soc. of Am. Bull. Part 1, 90, pages 47-58. 1979.

(a)

(b)

page 42

(c)

3.2.4.4 Shear rupture source mechanism - West Claims

Exploration of rupture no. 18

Introduction

Drawing on limited material resources and on the unlimited goodwill and patience of mine management, a raise was developed with the sole purpose of exploring the extent and characteristics of this remarkable feature.

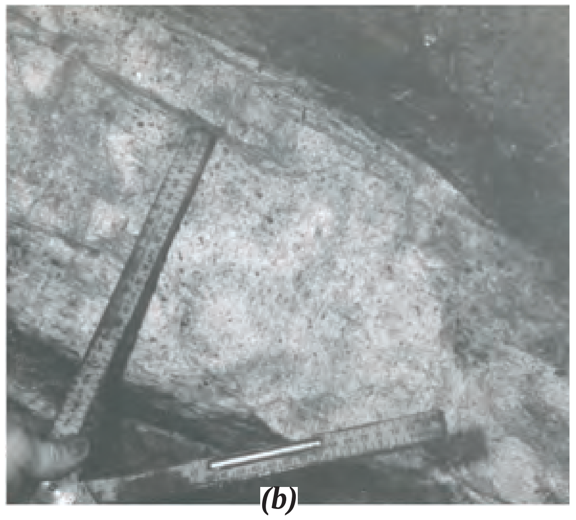
Captions

(a) View of face of raise driven 5,5m up at 40 ˚ from the north top corner of footwall drive about 3m west of the trace of fracture no. 18 on north sidewall. Several 'jogs' occur in 1,5m of exposure, all stepping leftward. The small black specks scattered over the top left corner of the raise face are droplets of oil from the compressed air rockdrill used for drilling the blast holes.

(b) Close view of a small 'fault-scarp' brow in the roof of the raise (just visible as a step on top edge of fig (a). Faint traces oflineations are visible parallel to the inclined arm of the clino-rule. These are mainly in the form of gouge striations with occasional blackish lines suggestive of pyrite particles that have been finely comminuted and dragged along the shear rupture. Like slickensiding on a geological fault, these indicate the direction of the shear displacement.

(c) View of face of exploratory raise on 12 June 1974, now 10,8m up from 49 footwall drive. All exposures until this date had shown one simple planar rupture. This view shows the start of a duplication or 'twin' fracture which appears to branch away from the main rupture surface about 2m back from the face.

(d) Close view of an abraded surface from a similar exposure some 18m further along the exploration raise. Some smoothed and well-rounded particles, several millimetres in diameter, appear to have been 'fused' into the gouge material on the shear surface. Shiny appearance is due to free water running over part of the surface.



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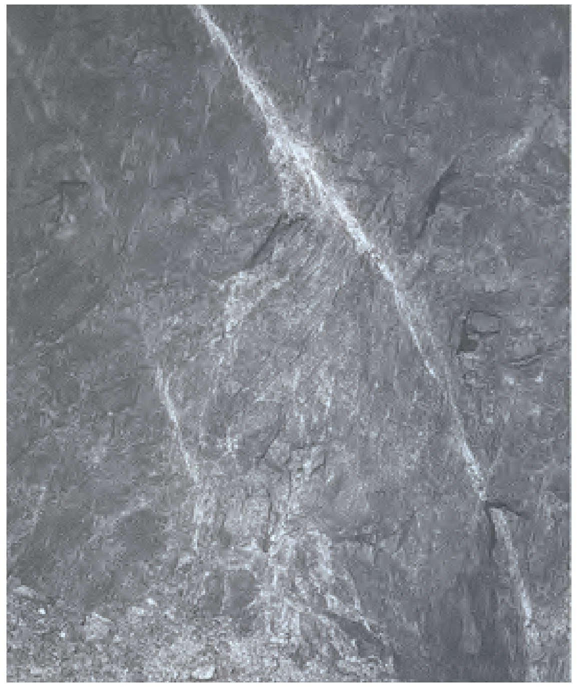
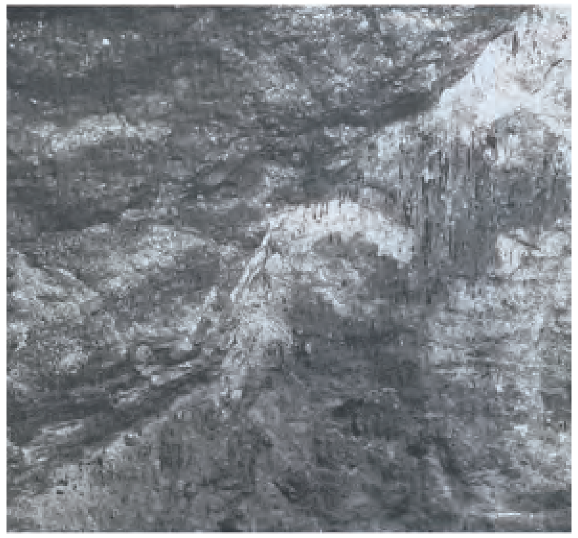
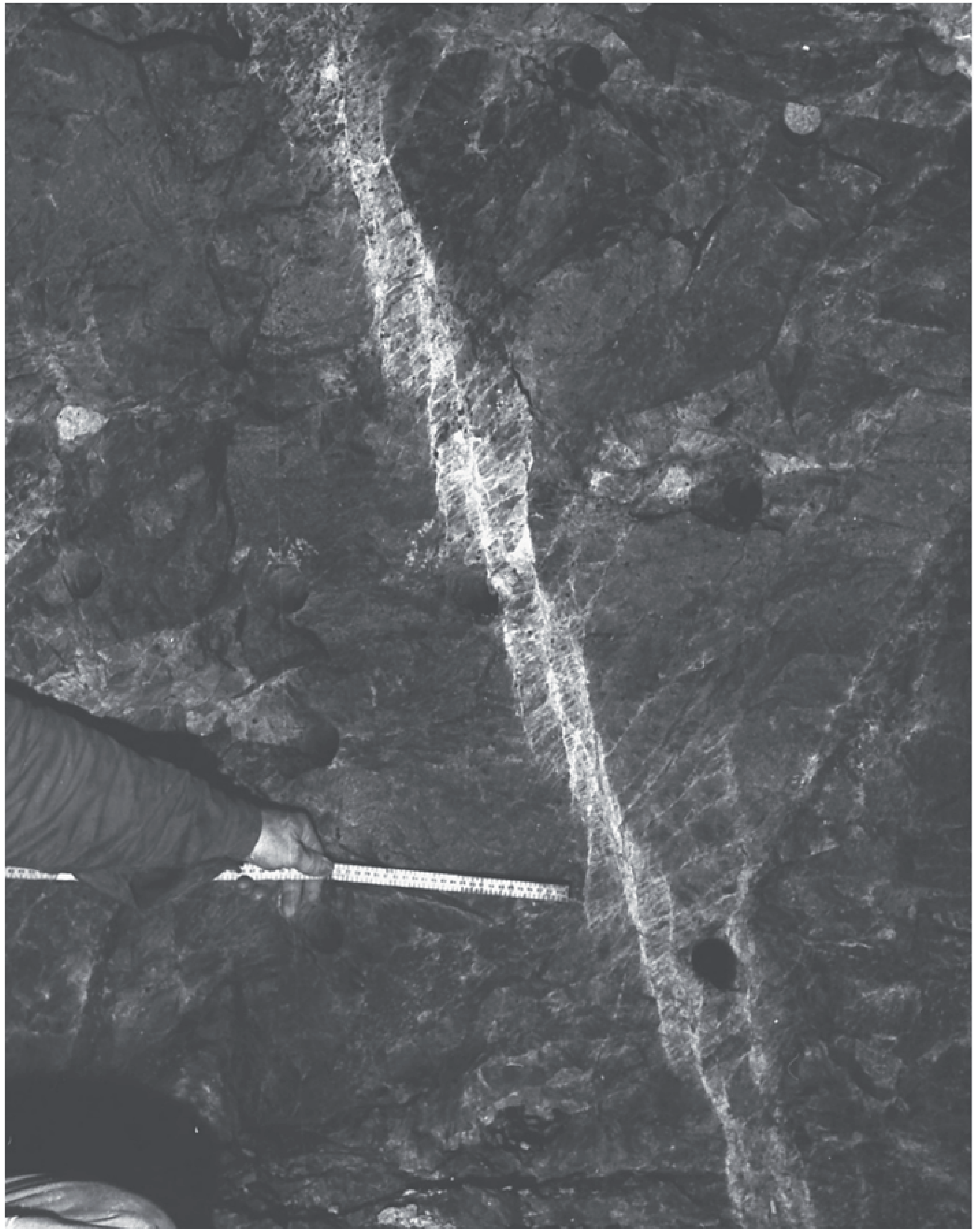


(c)



(d)

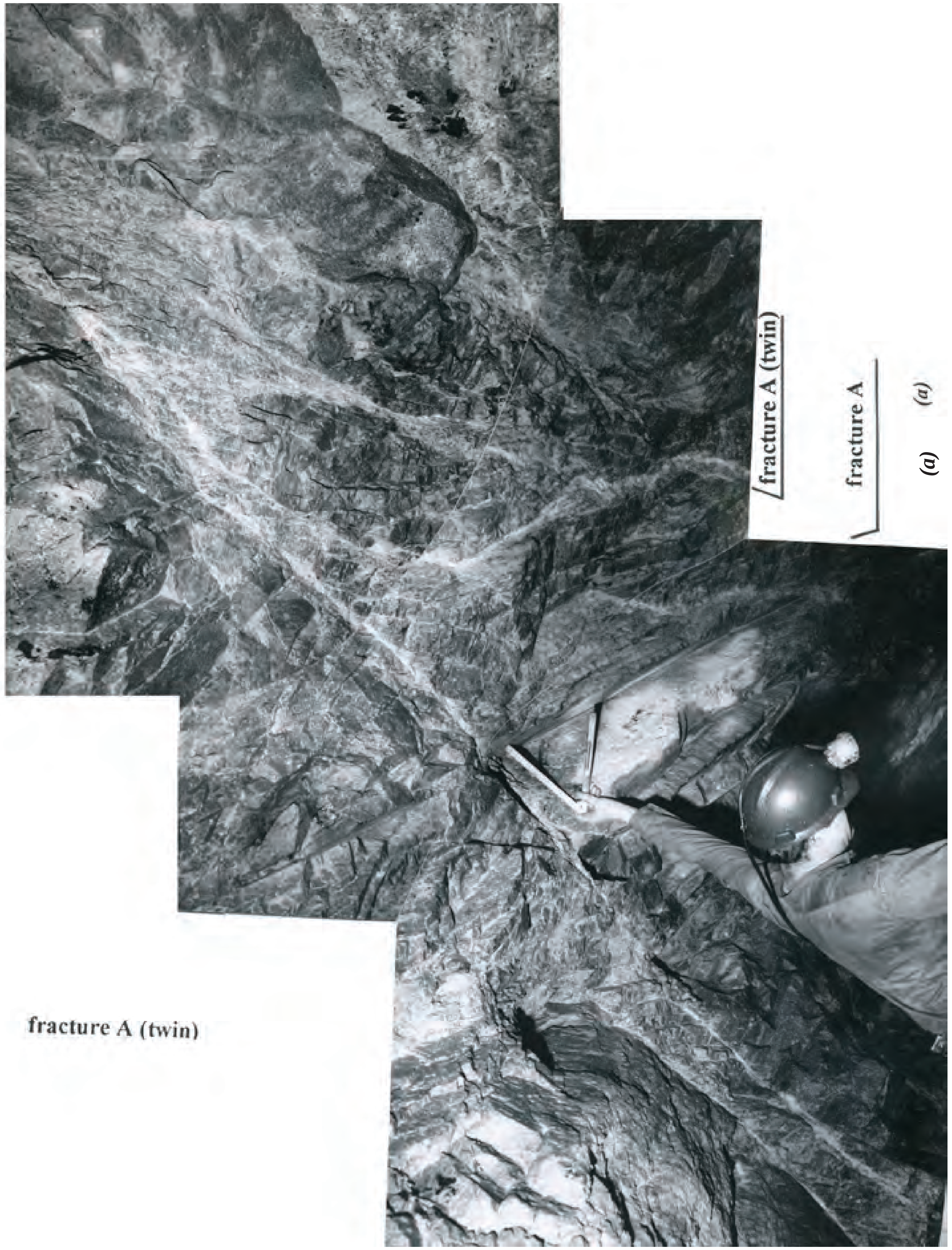


(a)

3.2.4.4 Shear rupture source mechanism - West Claims

page 44

Intersection with second shear rupture



Introduction

On 20 June when the raise was next visited three additional blasts had advanced the face about 4m to a position about 15m up from 49 footwall drive. Considerable complexity of shear fracture traces were now revealed. Composite photographs of the side and roof (a) and of the roof only (b) were assembled and studied. The captions of these two composites are given on page 45.

page 45

3.2.4.4 Shear rupture source mechanism - West Claims

Intersection of rupture 18A and 18B

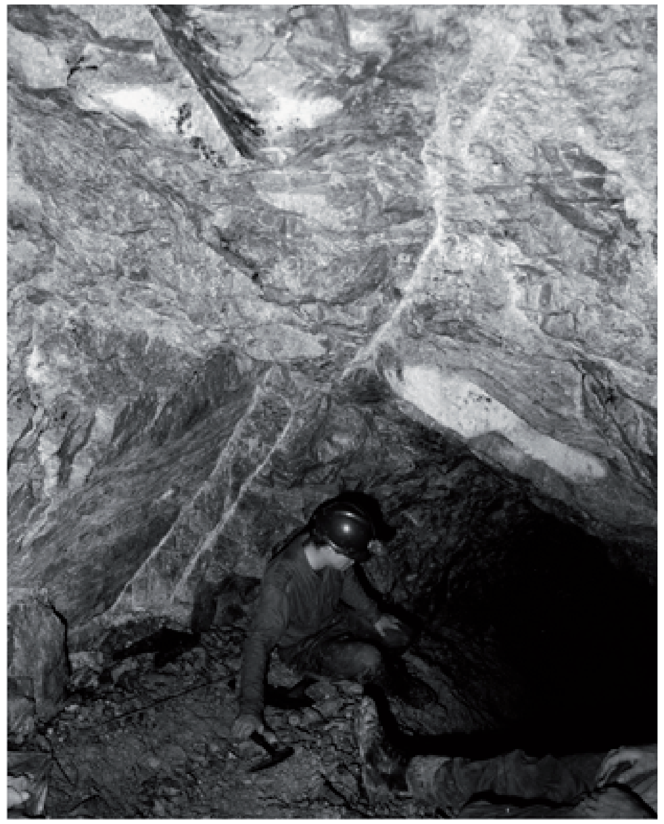
Captions

(a) View eastward to south-eastward down the north sidewall and across the roof of the raise showing the emergence of a new dominant rupture surface from the east (bottom left corner of composite). After about 1m of overlap the rupture continued as a single plane surface towards the top right comer. From centre onwards it is joined by a succession of curved shears coalescing with it from the original rupture trace no. 18 and its twin.

From this point onwards no. 18 rupture was identified as fracture A and the new dominant surface was called fracture B. A distinct bedding plane was displaced across fracture B by about 60mm in the normal sense, as was invariably the case.

(b) On 28 June 1974, after a further advance of 1,4m, the pattern of fracture traces in the raise was recorded by means of a downward succession of four photographs each viewed from close to the floor perpendicularly upward toward the roof. The uppermost of these photographs was close to the face of the raise just above where survey peg no 4525 had been installed. (Painted numbers on the roof are just discernable). This peg was subsequently blasted out and replaced with no. 5349 close, by - see fig (a) on page 46.

There is a distinct single fracture trace stretching across from the left edge of the upper photograph to abut with, but not cross, the more complex shear surface extending downwards through the composite. This is believed to be the abrupt continuance of fracture A which had coalesced with B for a distance of about one metre. This merging of A and A twin with fracture B continues through the second and third photograph. In the lowermost photograph the twin traces of fracture A are clearly separate and more than one metre away from B. The angle of intersection of the two main rupture zones appears to be about 45˚. The nature of the intersection is the only means of distinguishing the relative ages of the two features and it is also believed that it defines the direction of fracture propagation.



(b)

This is an important deduction that will become clearer and more plausible after examination of photographs of pages 47 and 48.

(c) View eastward down the raise showing where the new fracture B first emerged. The 'fault scarp' formed by the upper part of the overlap shows the characteristic 'hackled' surface of fig (d) on page 54.

(d) View of the full face of the raise on 28 June showing the very flat planar nature of shear rupture B stretching across the face from corner to comer. A parallel, less pronounced fracture about 1m below B proved to be very persistent and was labelled B twin. The apparently shallowly-dipping trace across the top of the photograph is the continuation of rupture A (the original no. 18).

(d)

3.2.4.4 Shear rupture source mechanism - West Claims

Location and spatial relationships of fractures A and B

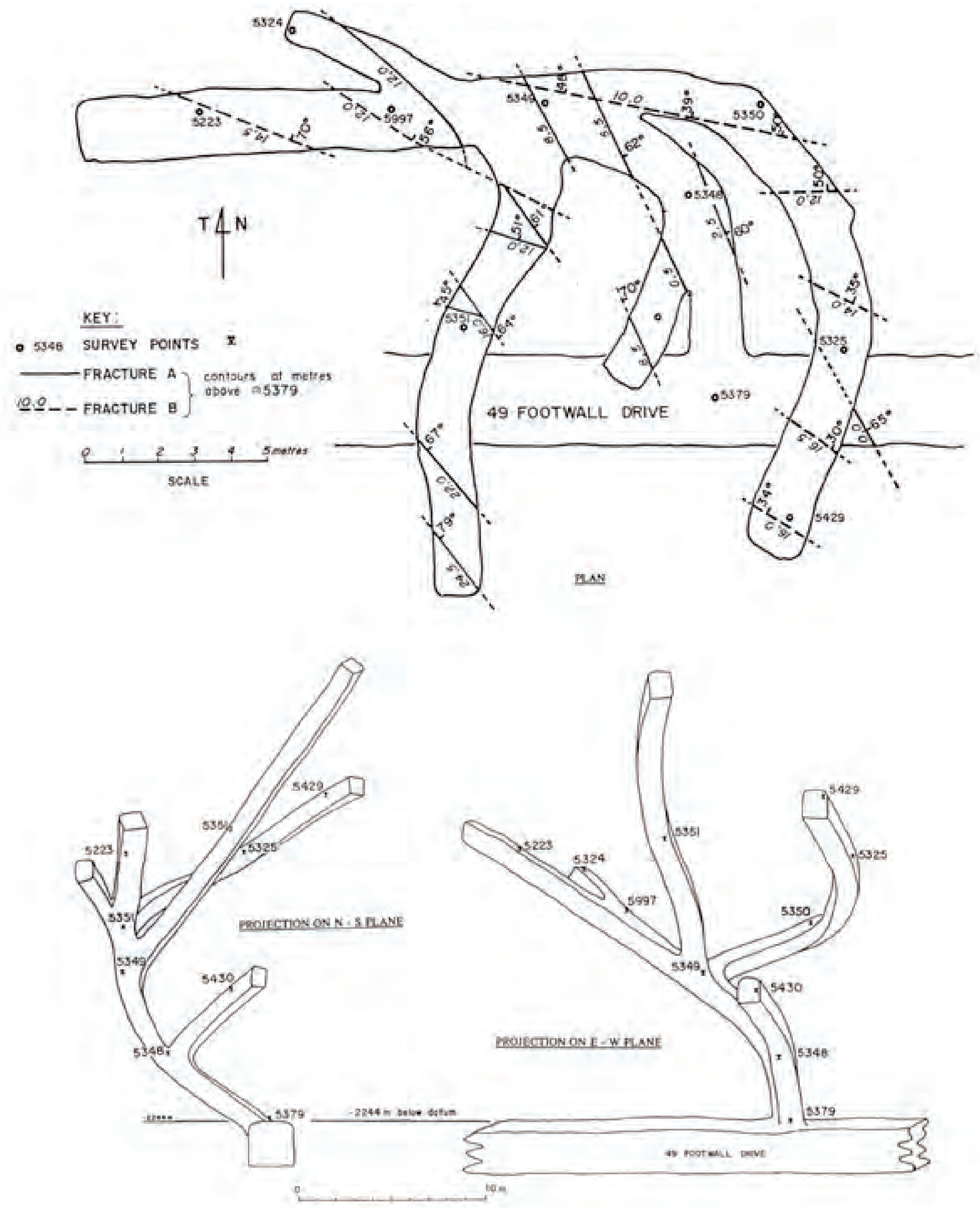
Captions

a) The surveyed plan of the exploration raise and two projections on vertical planes parallel to the dip (N-S) and to the strike (E-W) of the orebody. Although they are represented slightly pictorially, the projections are dimensionally accurate and undistorted. Note that the scale of the vertical views is one-half that of the plan.

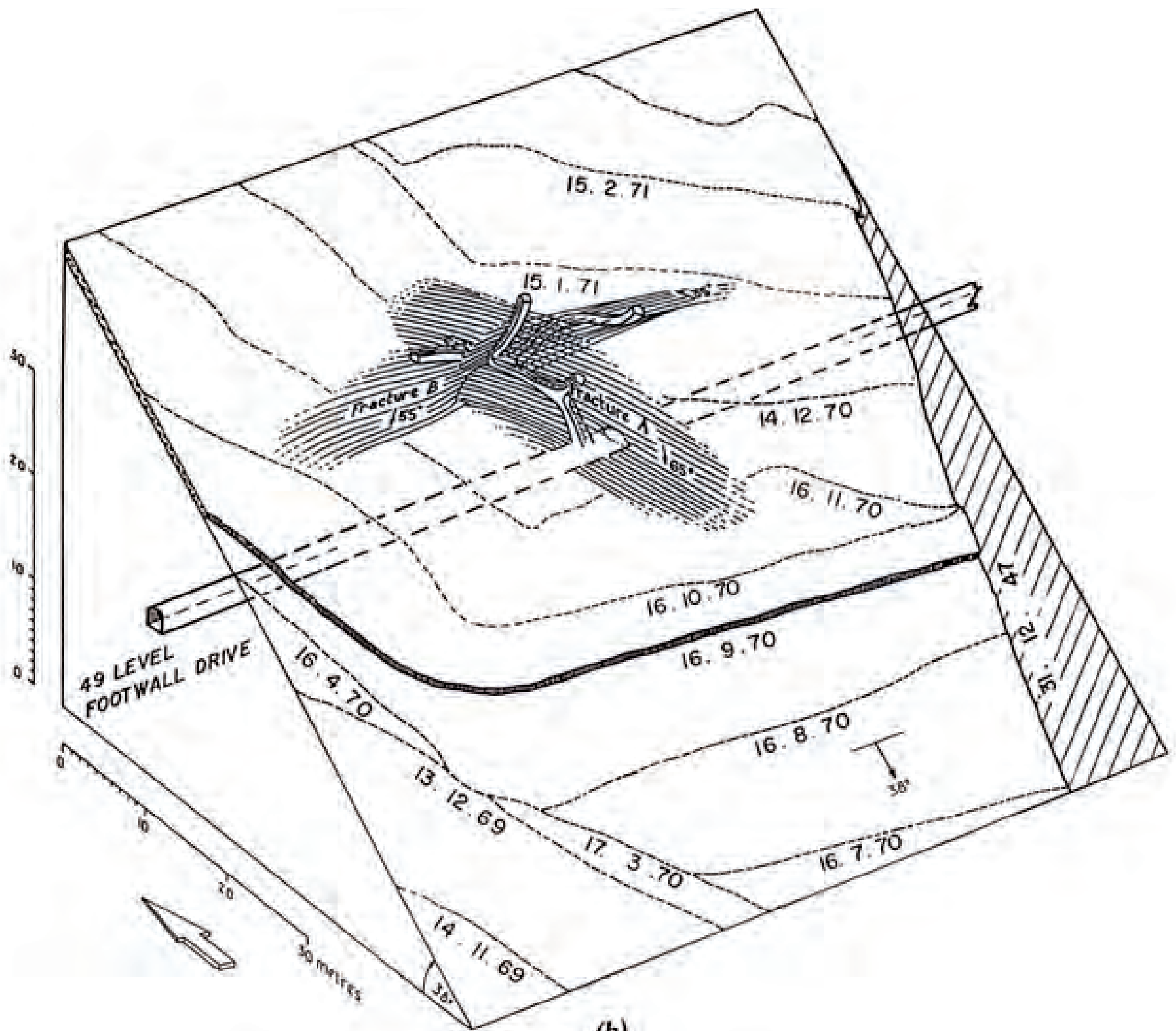
b) Isometric projection of fractures A and B beneath the plane of the ore body. The monthly stope face positions are shown by the broken lines on the stope plane.

c) Vertical minor dip section through fracture A showing position of nearest stope face and enlarged view of a typical off-set of a bedding-plane marker.

page 46



(b)



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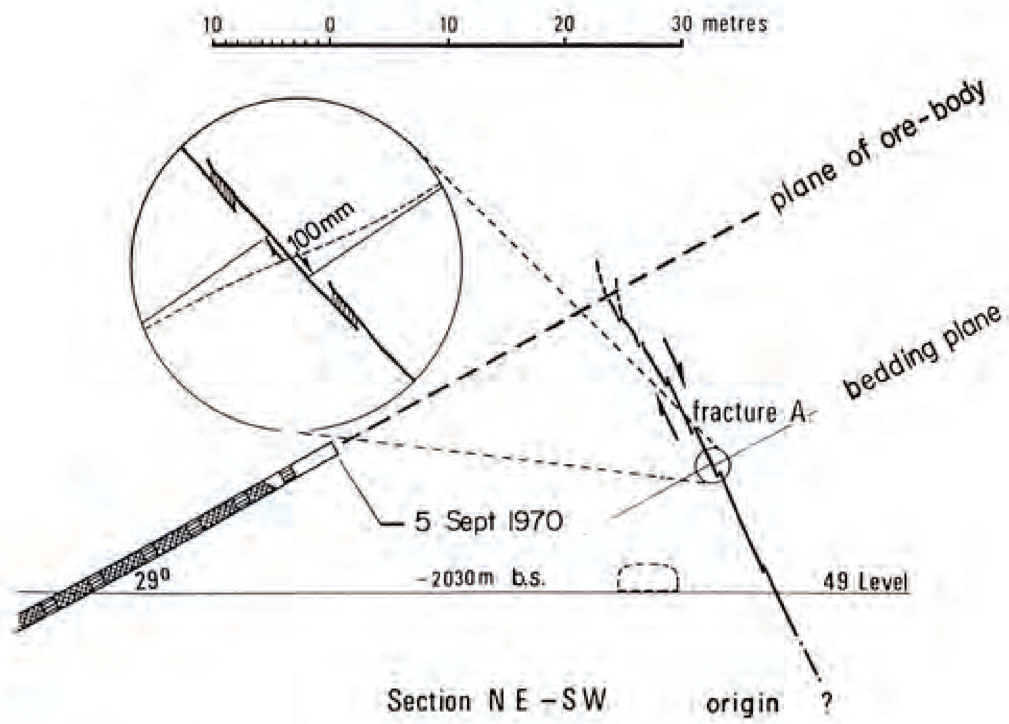


(c)

3.2.4.4 Shear rupture source mechanism - West Claims

Continued exploration of fracture B and intersection with A

Captions

(a) View of face of raise on 12 July 1974 after three more blasts had advanced its position to 20,5m above 49 level drive. The new fracture B appeared to be less intensely sheared than before. Importantly, a minor fall of roof had revealed rupture surface A (former no. 18 trace) to be strongly curved. The nature of its emergence from fracture B (outside the top left corner of the frame) is detailed in (d).

(b) Close view of lower portion of the face of the raise showing the more diffuse nature of the shear displacement across the plane of dislocation, particularly along its upper extension. A prominent bedding plane marker just above the end of the clino-rule shows 65mm of normal displacement.

(c) Composite view along the south sidewall of the raise. This is essentially an extended view (from a slightly flatter perspective with the camera exactly in the plane of fracture B) of the exposure of fig (b) on page 44. It shows, with complete continuity, how fracture A approaches B at an angle of about 40 ˚ and merges into it with coalescence occurring across three or four branches. After a confluence of only about one metre, A breaks away abruptly then curves back into the original direction which it followed prior to the intersection.

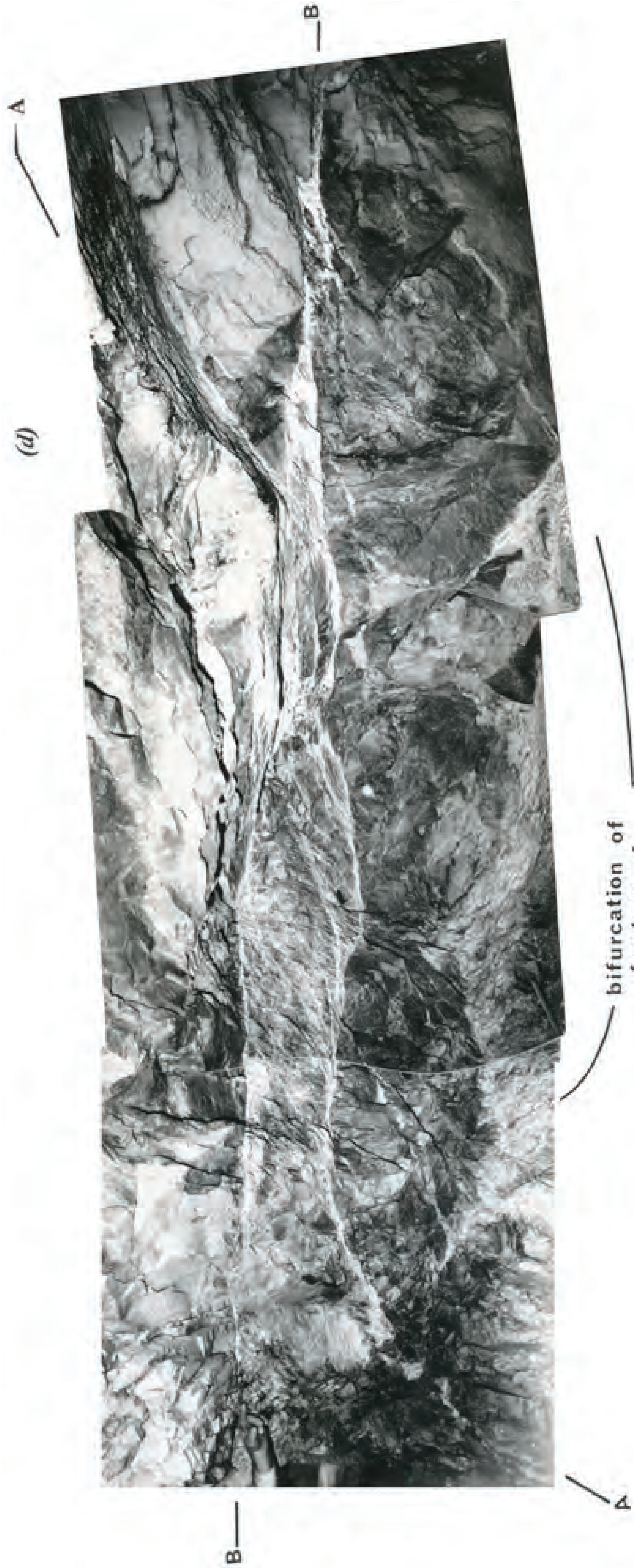
The fact that B is a continuous flat plane for many metres either side of the intersection whereas A makes the strange convolution everywhere that it approaches the intersection, is interpreted as definitive proof that B existed before A was formed. It also strongly suggests that the fracture front forming rupture surface A approached from below following a path somehow determined by the stress pattern imposed by the stoping configuration active at the time. After coalescence, it took the easier path along the already fractured surface of B 'for a short while before the prevailing stress again became the dominant influence and forced the fracture front back into its originally preferred direction.

(d) Close view of the emergence of fracture A from plane B showing the concave curvature of A and its ‘hackly’ texture typical of a burst fracture.

(a)

(b)

(d)



(c)

3.2.4.4 Shear rupture source mechanism - West Claims

Continued exploration of intersecting fracture system

Note

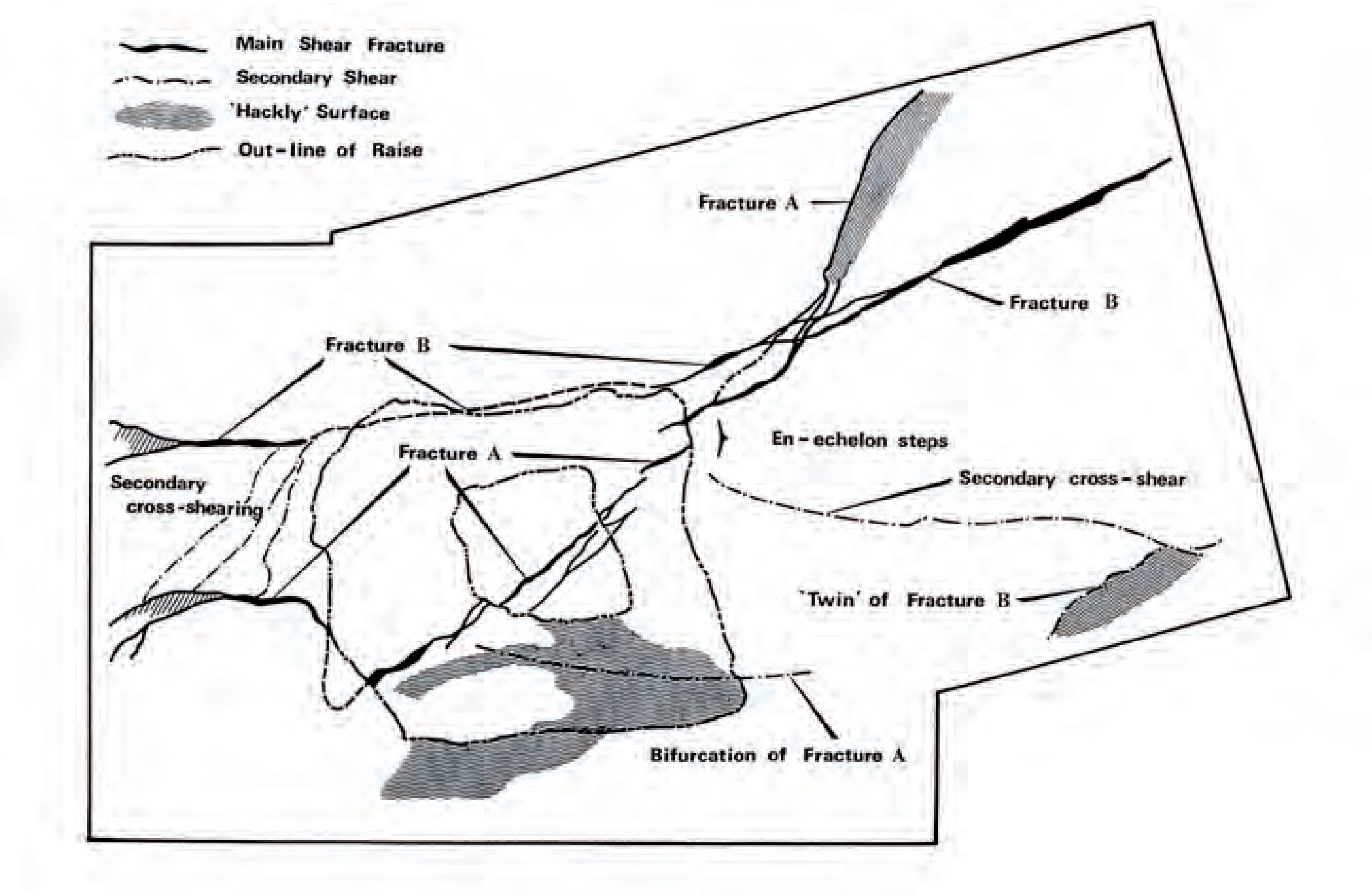
After a delay of one year during which, for operational reasons, it was not possible to continue with development of the raise, exploration recommenced in mid-July 1975. Instead of advancing the original raise which had been stopped 24,6m up from 49 level, it was decided to explore the 'new' fracture B back eastwards in the direction from which it had emerged. Another steeper branch known as the ore-pass raise, was started in order to explore the line of intersection of the two fracture surfaces.

Captions

(a) Interpretative tracing of composite photograph (b).

(b) View on 22 July steeply upwards in a southerly direction into the ore-pass raise which is now 4m up from centre-line of original raise - see fig (c) on page 47.

The line of intersection is hidden just inside the upper right corner of the excavation. The floor of the raise is formed by a conspicuous slightly curved 'hackly' surface which appeared to be a bifurcation of fracture A. This feature persisted for several, metres up the raise. The curved brow formed by the emergent fracture A visible in upper right corner of composite is the feature described in (a), (c) and (d) on page 47.



(a)

(b)

3.2.4.4 Shear rupture source mechanism - West Claims

Lateral termination of fracture B

Introduction

From the intersection of fracture A with the newly-emerged fracture B, the main raise was continued upwards centred on B. For several metres more, the trace of B was more vivid than its ‘shadow’ or twin as evident in (d) on page 45. Thereafter, although it appeared to become progressively more diffuse and the twin possibly more dominant, the direction of the raise was maintained until the face was 25m up from the footwall drive (as measured on the incline).

When it became possible to recommence exploration in mid-1975 only 2m more of advance was made in the original raise. Thereafter it appeared more fruitful to develop branch raises exploring other aspects of the structure.

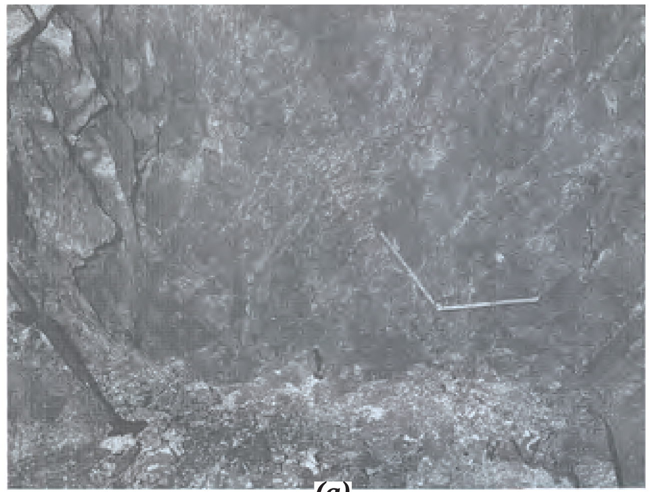
Captions

(a) View of the face at 25m up the raise (17m vertically above 49 level). The main fracture B has become a diffuse band of shear dislocation without marked comminution on any particular plane.

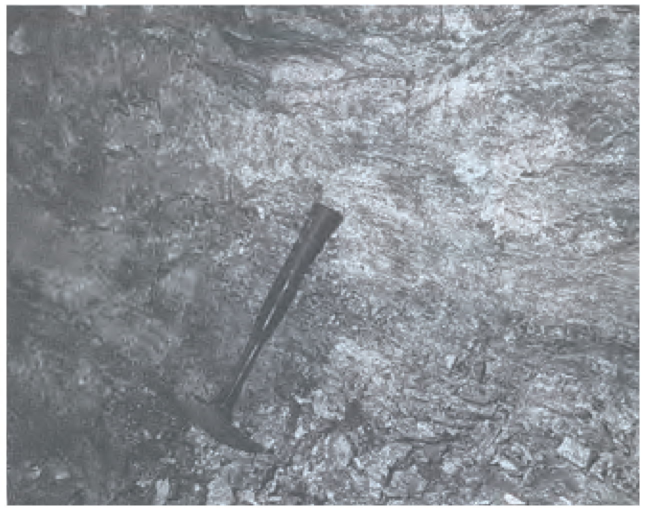
(b) Close view of the ‘hackly’ surface of the fault scarp of B twin which is visible in lower left corner of (a).

(c) Detail of ‘kink-band’ nature of lower portion of shear structure in centre of (a).

(d) View from face down raise showing parallelism of hanging-wall trace of main fracture B (extending beyond inclined arm of clino-rule to the centre of the top edge of photo) and the fault scarp of its twin (the dip direction of which is indicated by the geological pick).



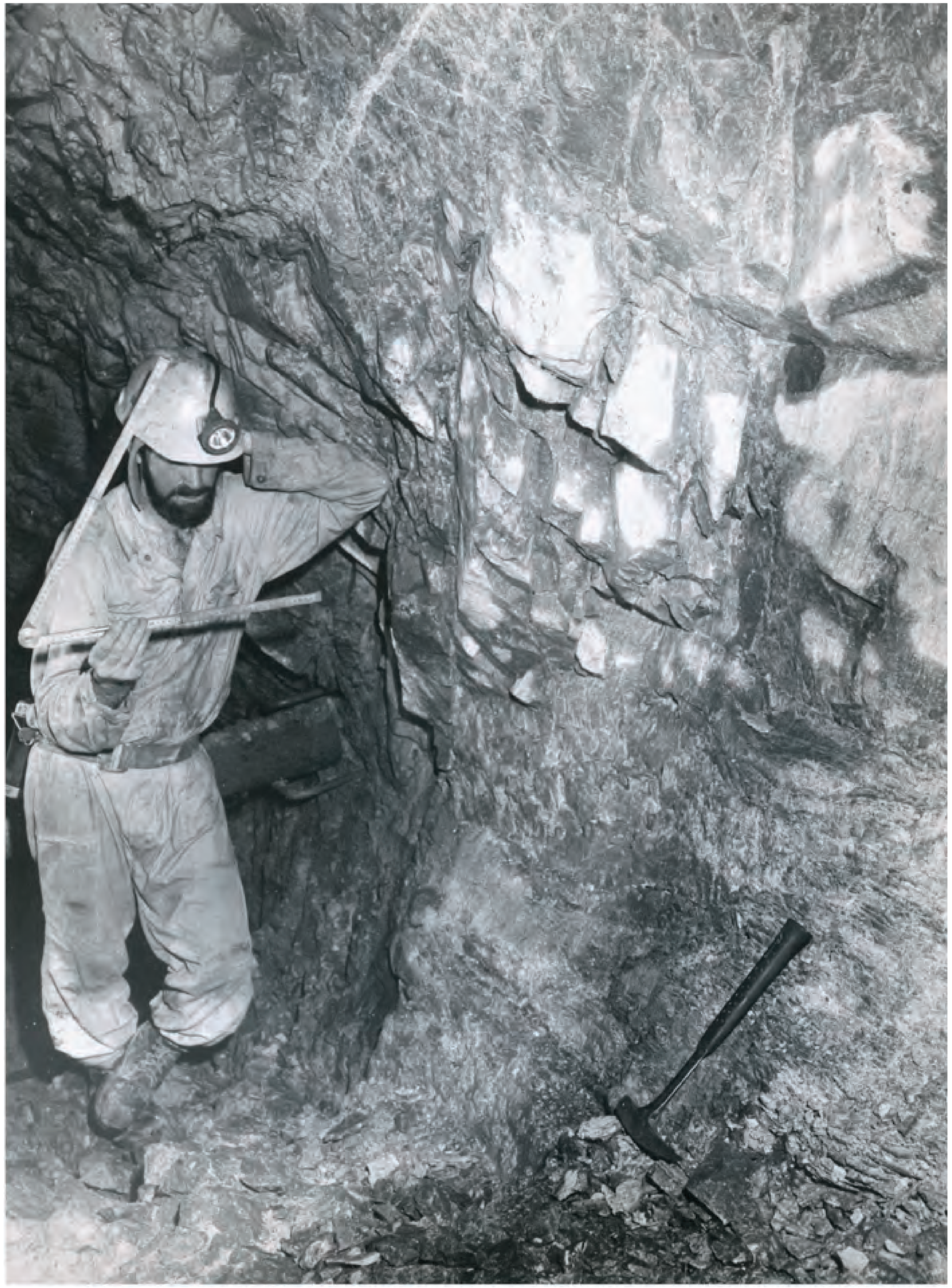
(a)



(b)

(c)

page 49



(d)

3.2.4.4 Shear rupture source mechanism - West Claims

Intersection of fracture A with reef plane

page 50

Captions

(a) View upwards at about 60 ˚ from horizontal into ore-pass raise. On 9 September 1975 the face was about 16m above original raise centre-line or 22m vertically above 49 level footwall drive.

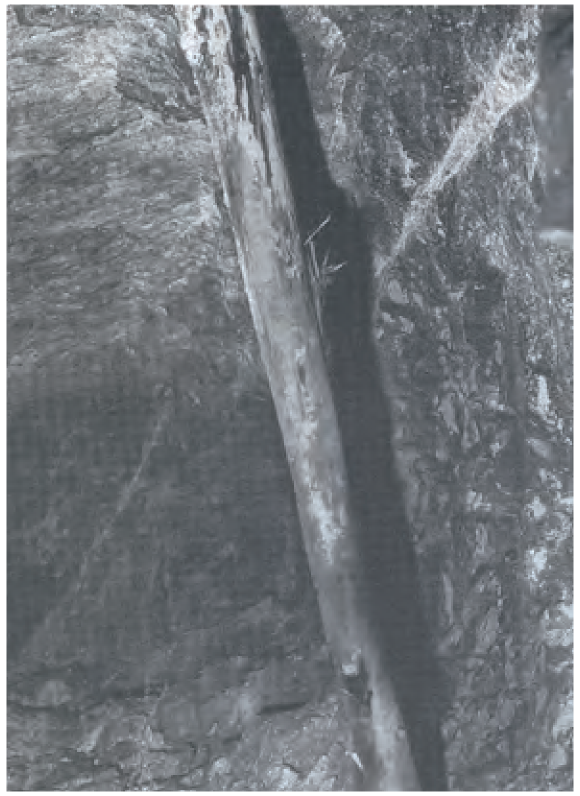
Fracture A is still prominent. Bifurcation of fracture A, which was first evident at the break-away from the original raise (see fig (a) on page 48), is strongly developed forming a continuous floor along the entire length of the ore-pass raise.

(b) Similar view one week later with the raise advanced a further 2,5 m to hole into the back area of the Main Reef stope. The longwall face was mined past this point nearly 5 years previously and the original ± 1,2m now completely converged.

The footwall trace of fracture A is clearly visible in the floor of the raise and extends across the raise face (which is the hangingwall of the old stope) as a rusty trace just above and parallel to the clino-rule. True dip of fracture is 79 ˚.

(c) Three days later on 19 September the face of the raise had advanced about 1m into the hangingwall of the Main Reef. The fracture trace is no longer discernible in its earlier position.

(d) View north-eastward into the South Reef stope which is over-mining the original Main Reef longwall stope, above a waste-middling about 2,5m thick. The ore-pass raise dropping away at 55 ˚ below horizontal, is visible in bottom left corner. The notebook is lying on a surface which might be the dying-out vestige of fracture A. It was not discernible in the hangingwall of the South Reef.



(a)

(b)

(d)

(c)

3.2.4.4 Shear rupture source mechanism - West Claims

Exploration of rupture no. 20

Introduction

Some 10m east of the exploratory raise on rupture trace no. 18, a far less distinct fracture trace was visible. A closer examination showed that it differed in certain respects from the former structure which had became quite familiar by this time. When exploratory work in rupture no. 18 recommenced in mid-1975 it became possible to develop a few rounds on this, the most easterly rupture trace in 49 replacement drive.

Of all 21 burst fractures located along the length of the footwall drive, only fracture no. 20 differed from the characteristic attitude of NW to SE strike with dip varying from about 50 ° to 65 ° north-eastward. The strike of trace no. 20 was N-S and its dip was 73 ° west. This attitude strongly suggests that it was associated with an earlier dip-aligned stope face advancing westwards from some distance away in the east to form the eastern edge of the West Claims no. 1 shaft protective pillar, 27 years earlier in 1948.

Captions

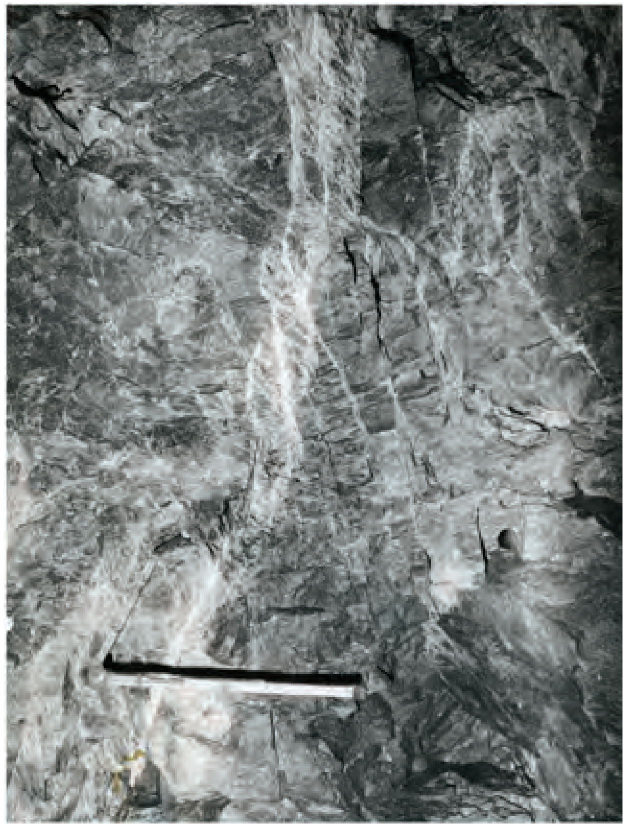
(a) View northward in mid October 1975, into a short exploratory raise driven along trace of rupture no. 20, when face was 5m up from centre-line of 49 footwall drive.

(b) View nortlwards one week earlier when raise on fracture no. 20 was 1,5m above 49 tunnel roof.

(c) Close view of upper portion of rupture exposed in (b). Note that en-echelon overlaps step rightwards and that the displacement is left-lateral. The acute angle formed between the main shear rupture surface and the secondary fractures (pinnate joints) extending away from it, also clearly indicates that the movement of the right side (footwall) block was upwards i.e. towards the old 1948 stope opening some 20m above and to the east. There were no distinct markers to show the magnitude the movement on this dip-slip, normal-sense fault.*

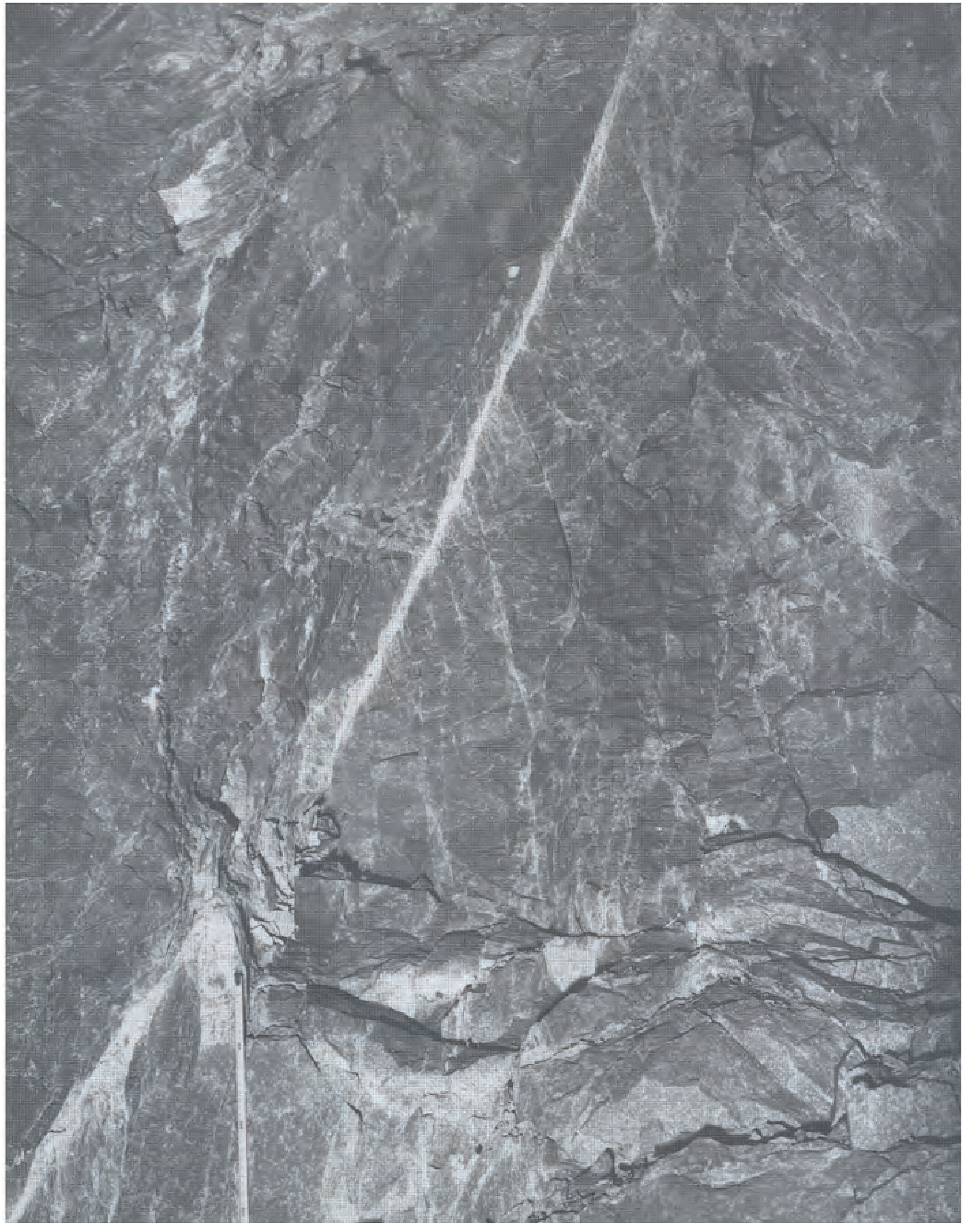
** see page 50 in Fracture Mechanism of Rock - ed. BK Atkinson, Academic Press (Inc). London 1987.*

(b)



(c)

page 51



(a)

3.2.4.6 Shear rupture source mechanism - West Claims

Measurements of shear displacement

Introduction

The most conspicuous feature of the shear ruptures was the visual contrast between the whitened, finely-comminuted 'rock-flour' or fault-filling and the darker, relatively massive quartzite strata which they traversed.

The acute angle formed between the shear surface and the numerous secondary extension fractures, consistently pointed in the direction of the relative movement of the 'fault'. This direction was invariably upwards on the footwall side and downwards on the hangingwall side of the fault, indicating that it was a *normal* fault.

That this sense of movement is characteristic of a mine-induced 'fault' was nicely confirmed by the development on rupture trace no. 20 where the east block moved upwards in marked contrast to all the other 19 traces where the west side invariably moved upwards - see page 51.

Because of the uniformity and massiveness of the country rock, it was usually not easy to find a marker that allowed the amount of shear displacement to be accurately determined. However, a few clearly defined instances were encountered where measurements could be made.

Captions

(a) Bedding plane at tip of clino-rule is displaced about 60mm upward on left side of fault (fracture A).

(b) Blue pebble marker on fracture B near survey peg 5325 about 15m vertically above 49 footwall drive shows 72mm of displacement.

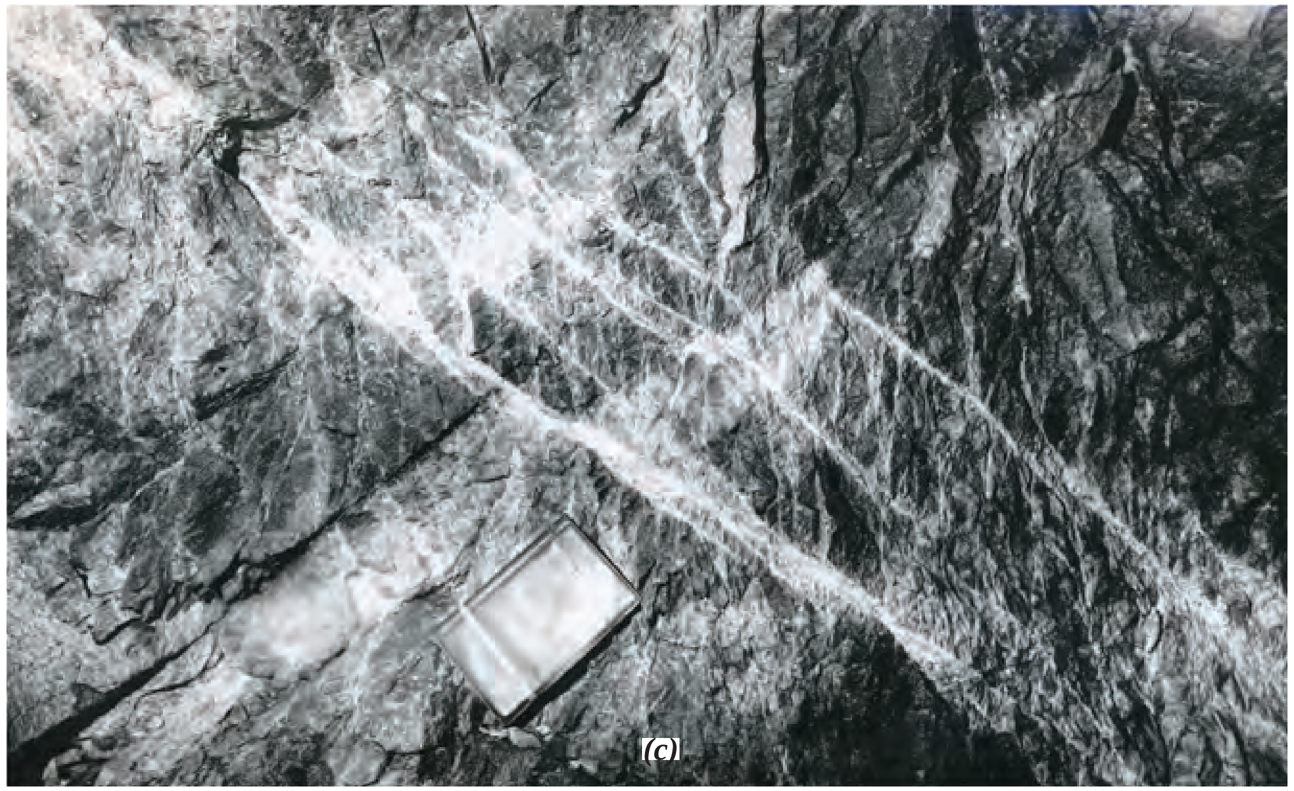
(c) Pale quartzite layer with clear upper bedding surface shows displacement of 100mm across multiple overlapping shears. Nearly 80mm occurs on lowest rupture surface.

(d) Fracture A near peg 5351 about 17m vertically above 49 level. Bedding plane shows 68mm of normal displacement. Comminuted zone is 13 to 17mm wide. Note the distinct rounding of the breccia fragments of about 4mm diameter, surrounded by fine 'rock flour'.

(a)

(b)

page 52



(c)

(d)

3.2.4.7 Shear rupture source mechanism - West Claims

Further exposure of original trace of rupture No. 18

Introduction

Some 20 months after the earliest observation and subsequent intensive exploration of the important exposures of shear ruptures in the eastern part of the shaft pillar, changes in mining priorities brought the investigation to a halt. Nearly four years later, in August 1979, an opportunity became available to do further work in the area. Two light trimming blasts were carried out to obtain fresh exposures of the original traces of rupture no. 18 on the tunnel) sidewalls. Some samples of the apparently undamaged quartzite at various distances from the shear surface, were taken for microscopic examination. The intention was to see whether there was a strong planar concentration of microscopic pre-fracturing along the rupture surface which would indicate that the propagation path had been pre-determined.

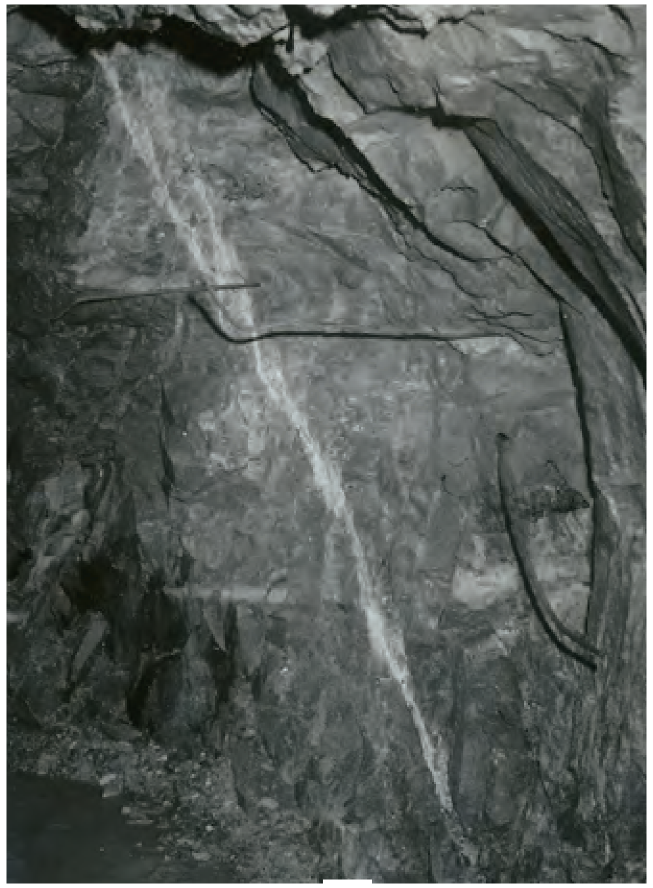
Unfortunately the thin-section micro-photographs were lost before a proper analysis was carried out. A preliminary examination, however, had been undertaken and it had shown a more-or-less uniform and sparse distribution of microcracks throughout the sampled area.

Captions

(a) View north-westward on 16 August 1979 of the trace on north sidewall of 49 drive. This corresponds to fig (b) of page 42. It represents a dip section through the rupture plane about 0,6m farther north-westward.

(b) Closer view of the largest overlap of (a) with a 'jog' or step of about 160mm. The portion below the rockbolt is probably virtually at the same elevation as fig (c) of page 42 and only 0,5m away on strike i.e. deeper into the original sidewall.

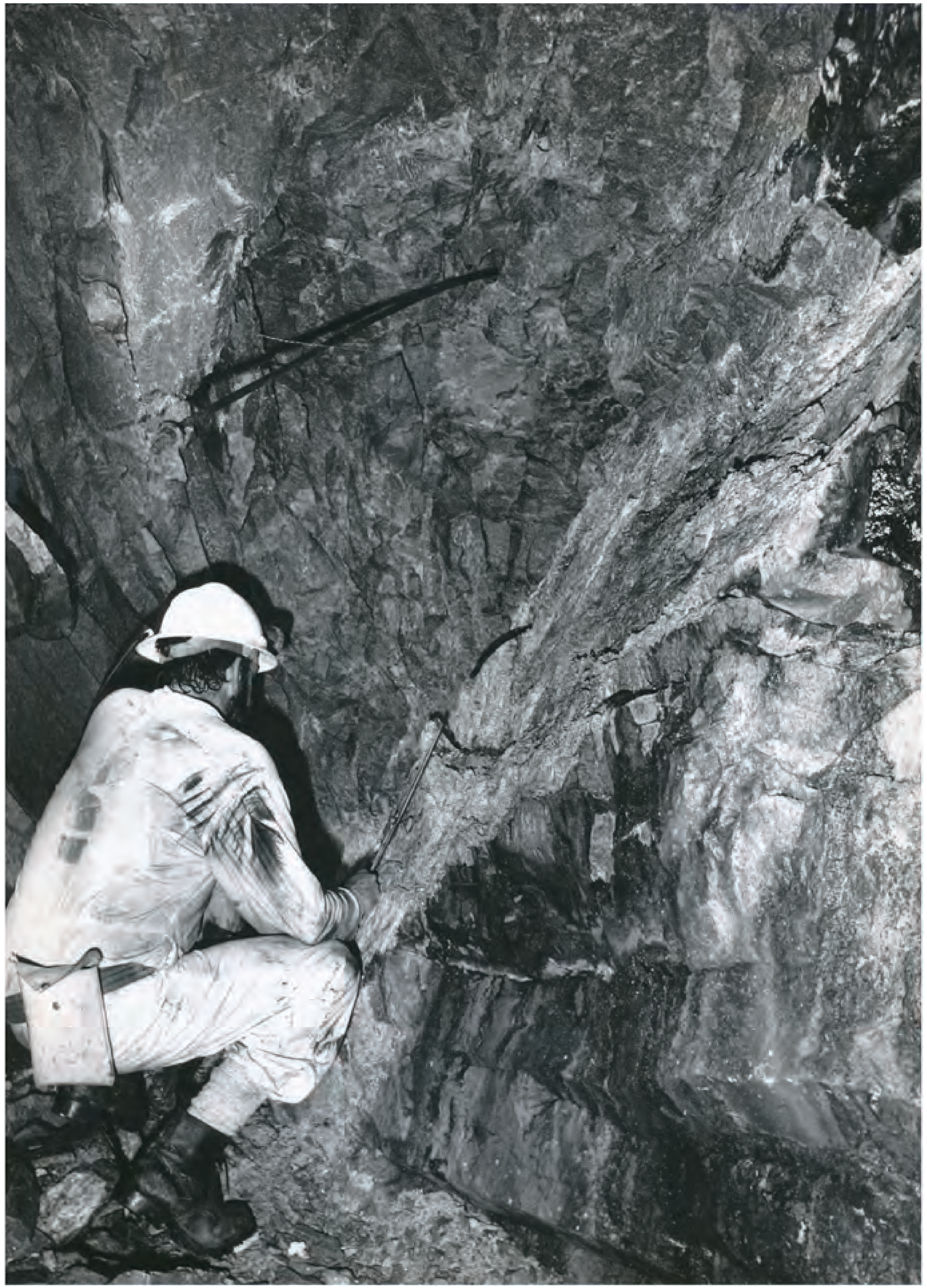
(c) View south-eastward of the south wall of the fan chamber, corresponding to (a) on page 42. The one or two trimming holes removed only the hangingwall side of the fault, leaving the shear surface exposed along a projecting footwall 'bench' about one metre wide.



(a)

(b)

page 53



(c)

3.2.4.7 Shear rupture source mechanism - West Claims

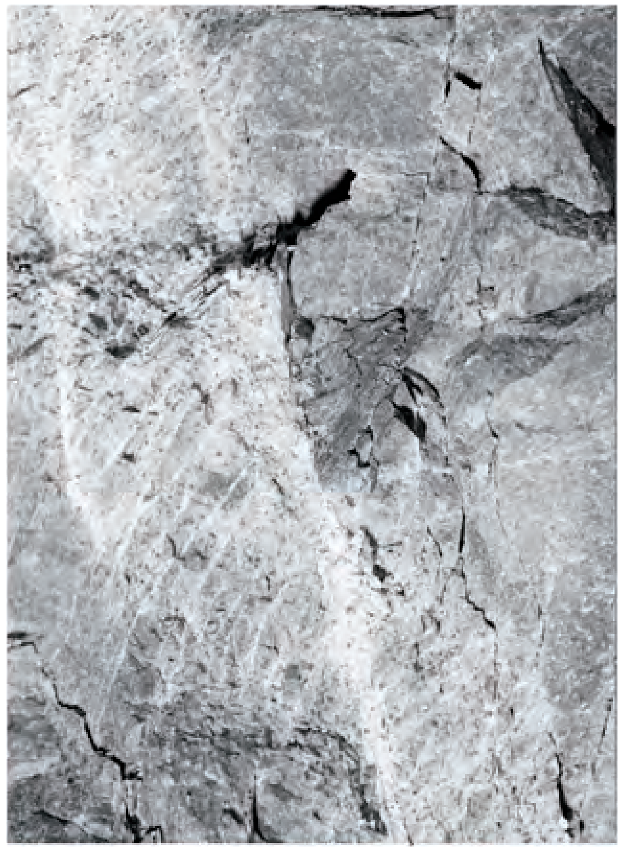
Further exposure of original trace of rupture no. 18

Captions (continued)

(d) Close view of shear surface exposed along the face of the bench of fig (c). The clino-rule is resting on a step in the main shear plane. The amount of offset is 100mm and is in the same sense as invariably found at every jog or step on this rupture system. (It appears to step toward the right because it is being viewed in the opposite direction to that of fig (a), (b) and (f), i.e. it is being seen as a left lateral displacement fault).

(e) Close view, at about life-size scale, of the lineated textured surface of the shear plane. The finely-comminuted rock 'flour' which normally fills the shear rupture will have been washed away as part of the mining procedure. The small black spots are believed to be the oxidation product of extremely finely, shattered pyrite particles. They were not visible when this surface was first seen 4 weeks previously.

(f) Close view of overlap of fig (b) at about a quarter life size. Oxidized pyrite smudges are clearly visible as in (e).



(f)

(e)

page 54

(d)

3.2.4.7 Shear rupture source mechanism - West Claims

Further exposure of original trace of rupture no. 18

page 55

Captions (continued)

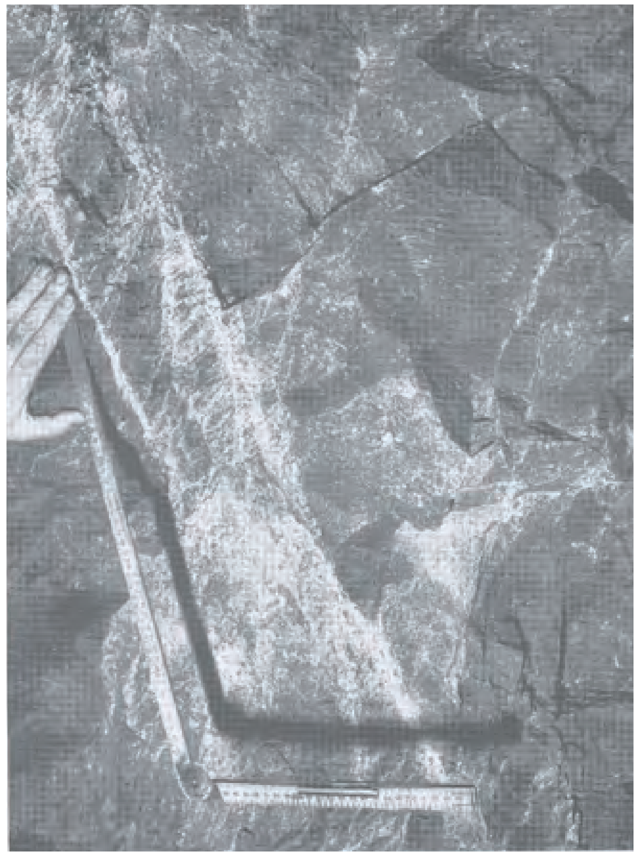
(g) View of south wall of 49 level fan chamber on 3 December 1979 after further blasting has removed the bench of fig (c) on page 53.

(h) Close view of sidewall trace which corresponds closely with viewpoint and scale of fig (d) on page 54. The top end of the clino-rule is at the point where the hinge of the rule rested 10 weeks earlier.

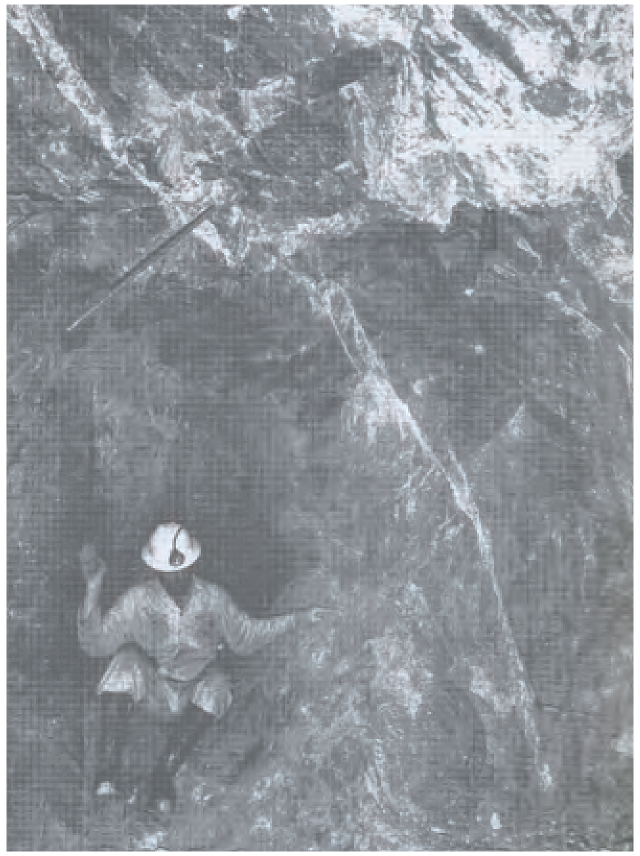
(i) View of north fracture trace from the same viewpoint as fig (a) on page 53. Dr Nic Gay is indicationg a bedding plane surface with his left hand and one of the very rare joints (N-S) with his right hand.

(j) Detail of largest offset of trace 18 at centre of fig (i).

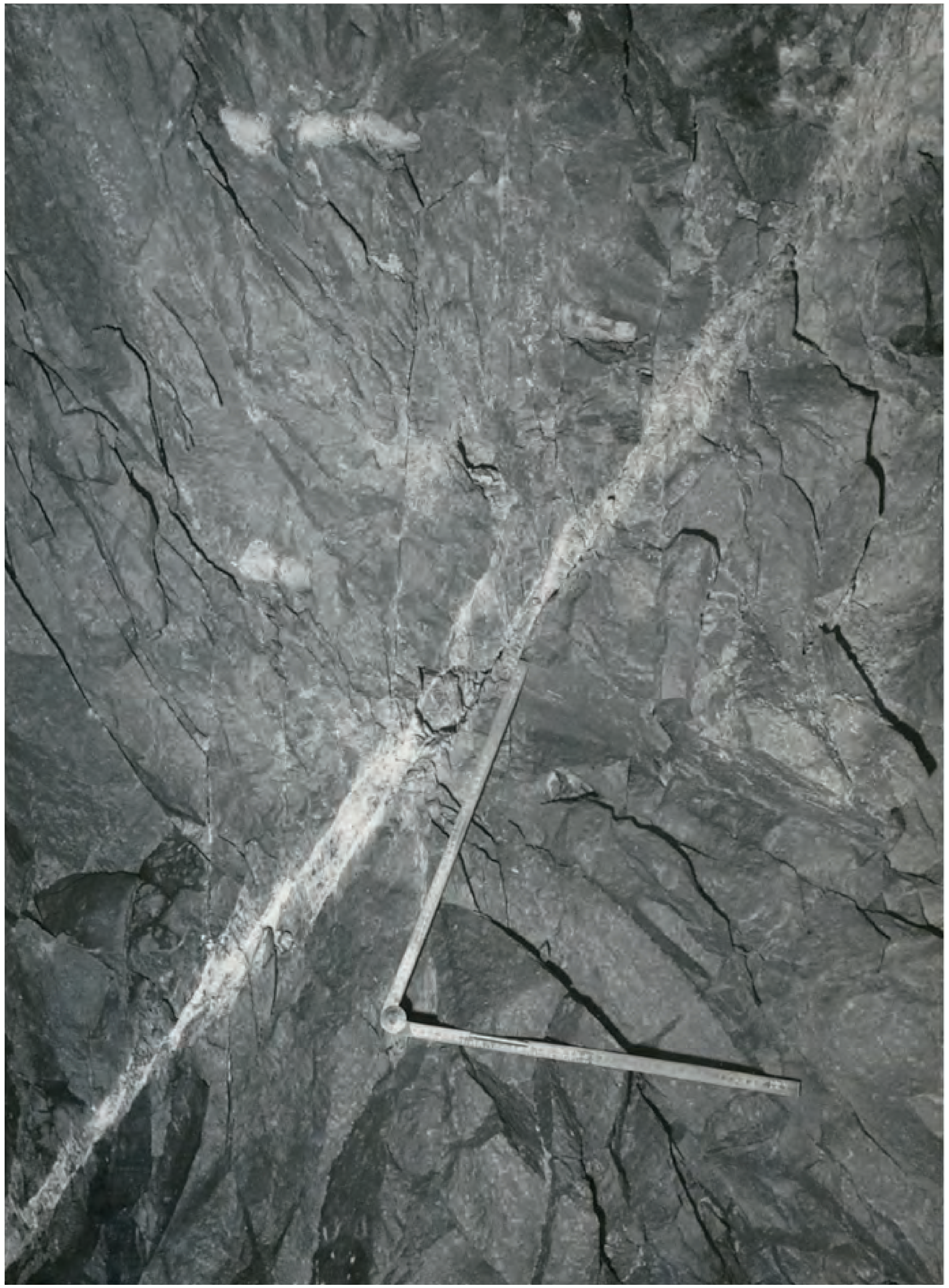
(g)



(j)



(i)



(h)

3.2.4.8 Shear rupture source mechanism - West Claims

Nature of comminuted material

Introduction

In order to gain insight into the energy-dissipation phenomena involved in the rupture processes, optical- and electron-micrographic studies were made of the material on, and close to, the shear surface.

Further minutely-detailed work was done at Massachusetts Institute of Technology by Olgaard and Brace (1983). They discussed, inter-alia, the energy consumed in creating new surface area of the gouge material including particles as small as 0,02 microns.

The techniques employed and the conclusions drawn are fully described in the published papers referenced on page 57.

Captions

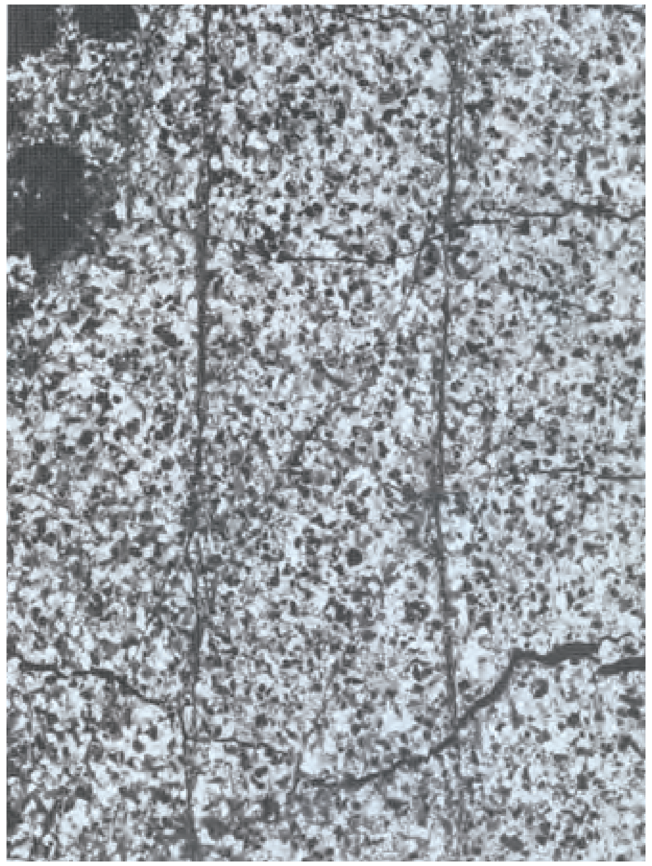
(a) Transmitted light micro-photograph of a carefully prepared thin-section several centimetres in size, showing the micro-structure of the fractured material within an en-echelon over-lap.

(b) Detail of portion of (a) at greater magnification showing that cleavage fractures through individual grains are concentrated near the intersecting micro-fractures and rather sparse elsewhere.

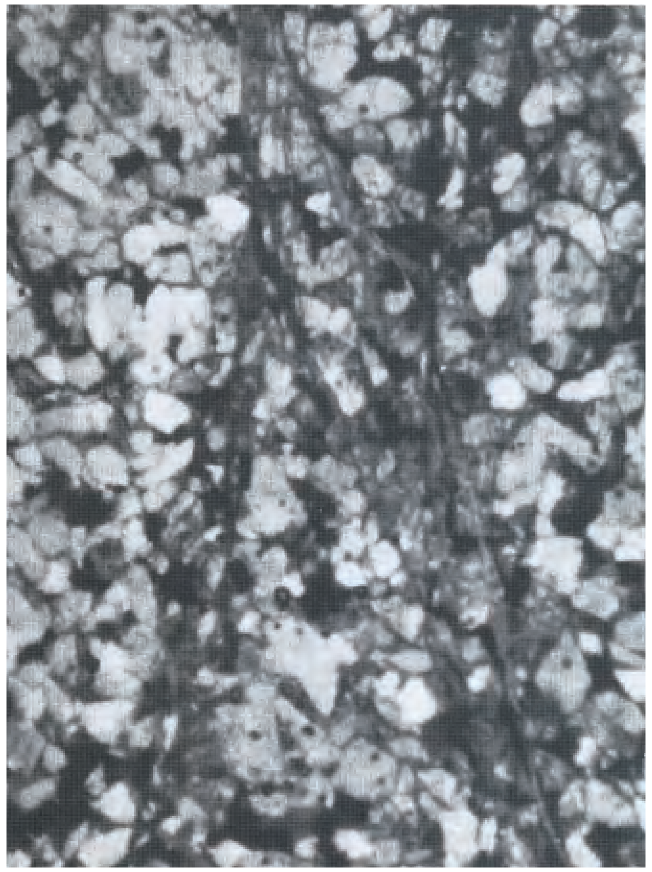
(c) Reflection electron micrograph of near equi-dimensional, euhedral sub-microscopic particles in a self-adherent lump of fine 'rock-flour' which had been carefully prised from the main shear surface of (c) on page 42. Diameter of the larger particles is about 40 microns.

(d) Another area of the sample which showed the crystal-like sub-particles of fig (c) revealed that these particles fully occupied 3-dimensional space within this minute portion of the self-adherent gouge.

A first impression might suggest that the particles are minute crystals of cubic habit. However, a more persuasive explanation is that the photograph is a view of the interior of a quartz grain that has been 'pulled apart' by a transient isotropic tensile stress. This argument is fully developed by Ortlepp (1992).



(a)



(b)

(c)

3.2.4.8 Shear rupture source mechanism - West Claims

Nature of comminuted material

Captions (continued)

(e) Isometric view showing how uniformly-sized rhombic dodecahedra completely fill space. The rhombic dodecahedron has the unique attribute that it has the smallest surface area and the greatest number of facets of all possible geometrical shapes that completely fill space. The rhombic dodecahedron is not a possible crystallographic form for quartz. Thus neither crystal habit nor lattice-determined cleavage is involved in the creation of the minute polyhedra.*

(f) Conceptual stress/strain diagram showing how an isotropic tensile stress could conceivably be imposed on a quartz grain after asperities on a rough, rapidly-shearing surface collide to cause a sudden increase in triaxial compressive loading. As the asperities override one another and 'hollows' coincide, a shock un-loading would occur which would allow the elastically-strained quartz grain to explode into minute elemental particles that would have the property of completely filling space with least surface area.

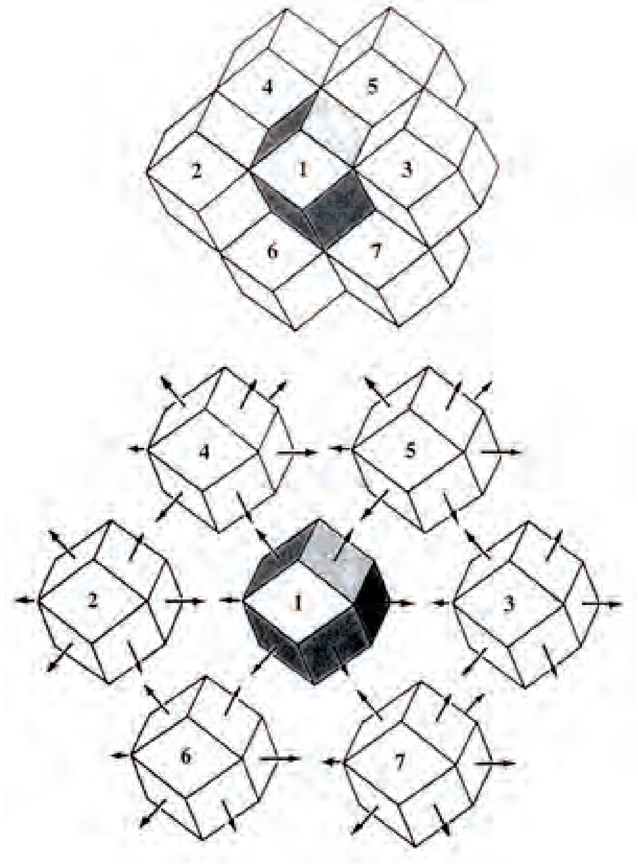
References

N C Gay and W D Ortlepp. Anatomy of a mining-induced fault zone. Geol. Soc. of Am. Bull., Part I, 90, (1979) pages 47 - 58.

D L Olgaard and W F Brace. The microstructure of gouge from a mining-induced seismic shear zone. Int. J. RockMech. and Mm. Sci. 20, (1983) pages 11-19.

W D Ortlepp. Note on fault-slip motion inferred from a study of micro-cataclastic particles from an underground shear rupture. *PAGEOPH, Vol 139, No. 3/4 (1992) pages 677 -694*

It has been suggested (private correspondence - Dr J Ferguson in Canberra, Australia) that the particles might be squat hexagonal pyramids ofcoesite, the high pressure polymorph of quartz. The transformation of quartz to coesite requires a pressure of 2,5 GPa and temperature of over 800 @C. It is usually found in crypto-explosive structures and is taken as evidence of meteorite impact.



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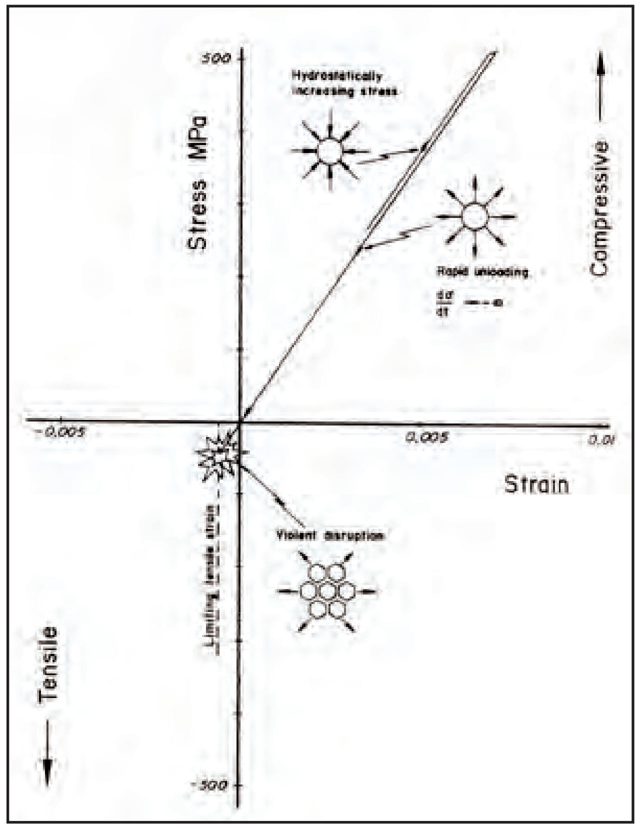

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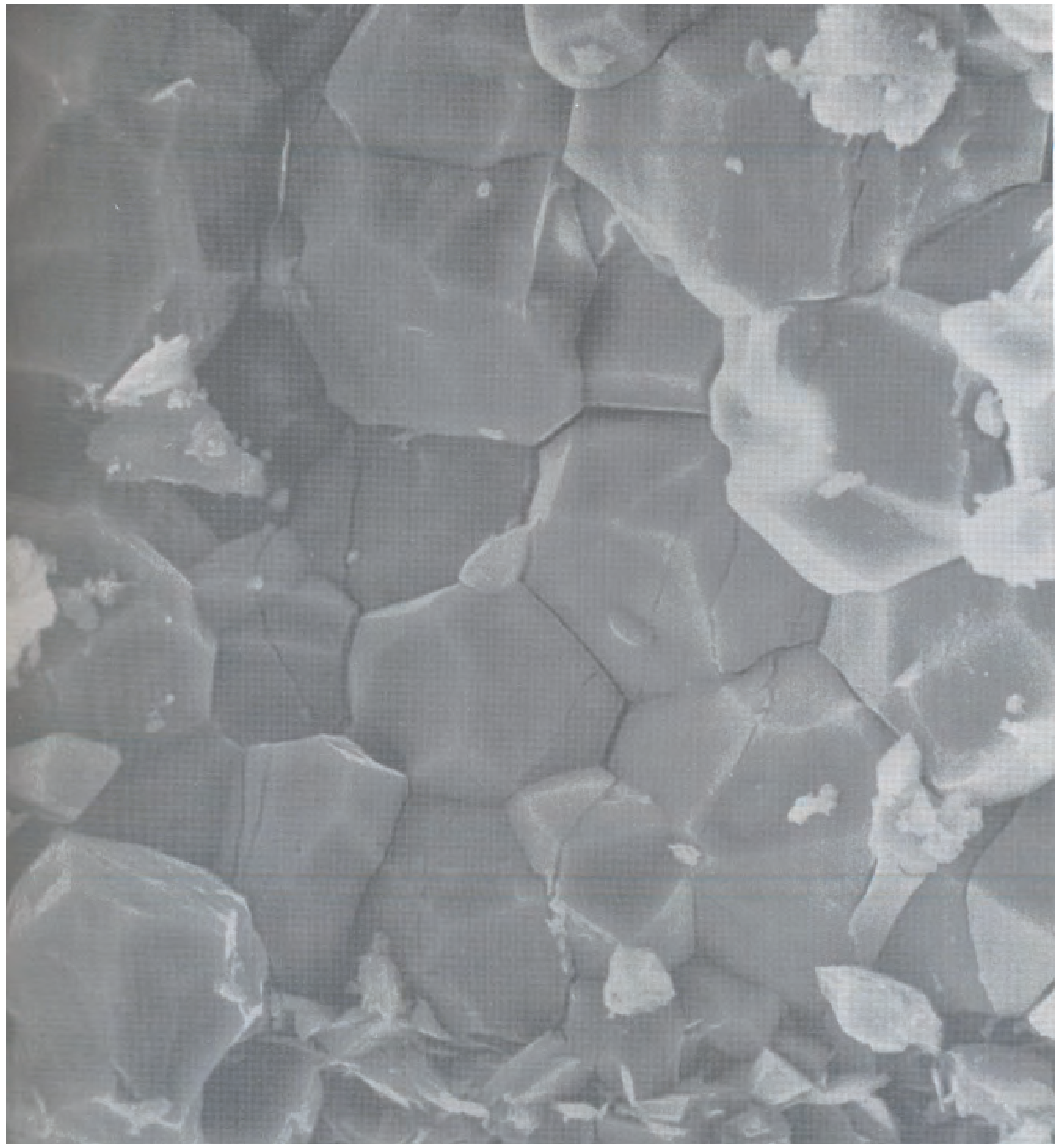


(d)

3.2.4.9 Shear rupture source mechanism - other districts

Burst fracture, Blyvooruitzicht

Introduction

The work done in the West Claims area of ERPM established that the source mechanism for the large seismic events which are characterised by large stress drop and high apparent stress, appeared to be a shear rupture which spontaneously erupts within a highly-stressed longwall abutment in a deep mine. It then rapidly propagates towards the stope plane through several tens of metres of solid rock. Depending on how close the rupture front gets to 'day-lighting' with the stope, these 'man-made' faults have the potential for causing intense damage - see also page 37.

For this concept to be acceptable as a more widely applicable explanation for violent rockbursts, it is necessary to show that burst fractures occur on other mines as well.

'Fossil' traces of these ruptures are only encountered in service tunnels which are driven in the low stress regions behind the advancing longwall faces to access and service the stopes. The reason for this is that any pre-existing tunnel which might have been driven ahead of the longwall would be surrounded by an annular shell of fractured rock which would, in the unlikely event that the pre-developed tunnel survived the rockburst, obscure any subsequently occurring transverse fractures.

Apart from the case described on pages 60 to 62, burst ruptures are seldom never encountered in the Klerksdorp district and have not been reported from the Orange Free State goldfields. This is largely because, in the mines of these two districts, most tunnels pre-date the sloping. The much greater frequency of faulting, which precludes the possibility of longwall stoping and necessitates the pre-development of the tunnels, also provides the discontinuities along which slip movement will preferentially occur. Thus the more common seismic source mechanism in these regions is likely to be that of fault-slip.

In the Far West Witwatersrand area, burst fractures are also rare. A possible explanation for this scarcity is that the strata above the Carbon Leader reef plane are more competent (and more brittle) than the footwall country rock of Jeppestown transitional sediments. Ruptures occurring in the hangingwall and not penetrating the reef plane would therefore not be intersected by 'follow-behind' development beneath the stoping horizon. Following development is very seldom done in the hangingwall strata.

In one instance where a burst fracture on Blyvooruitzicht mine was explored behind B4^{W}
longwall from 24 level, it appeared to have had its origin above and ahead of the advancing carbon leader face. It had overshot the reef plane ahead of the face and penetrated several metres into the underlying strata where it was first encountered in the cross-cut from the follow-behind footwall drive. Because there was no seismic network in operation at the time, the event that left this 'fossil' imprint was not identified. Two years later, 12 metres of exploratory raise was developed on the burst fracture in the hangingwall, commencing some 80m behind the longwall face.

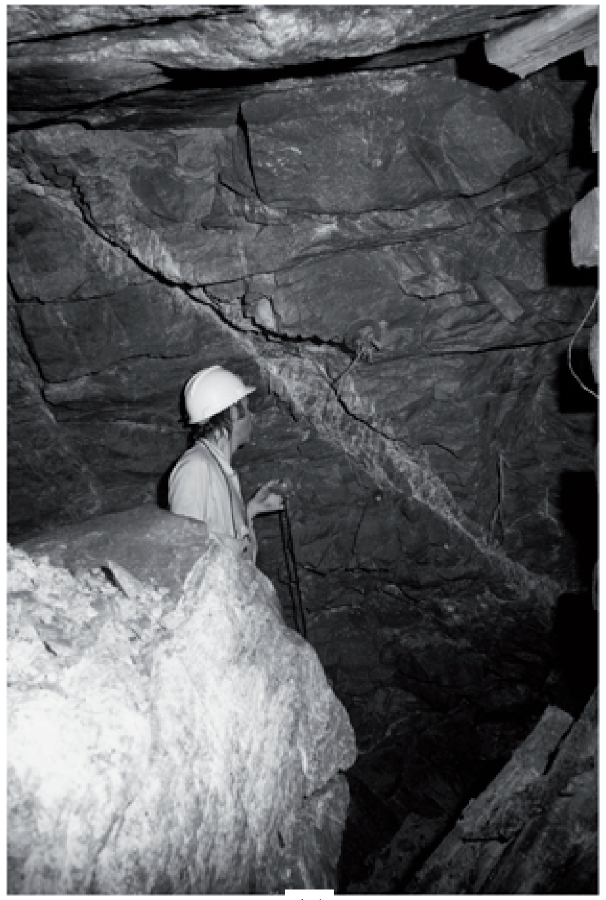
The continuity of the fracture through the worked out area into the hangingwall where the raise was driven could be clearly traced. This fact, together with its altitude below the reef, was interpreted in the following way. The fracture had originated above and ahead of the longwall face and radiated rapidly outwards and downwards towards the reef plane where it by-passed the edge of the fractured zone on a broad front parallel to, and just ahead of the face. Losing energy due to geometrical spreading, it then overshot the plane of the stope to die out several metres into the footwall in the lower stressed zone below and behind the longwall face.

Captions:

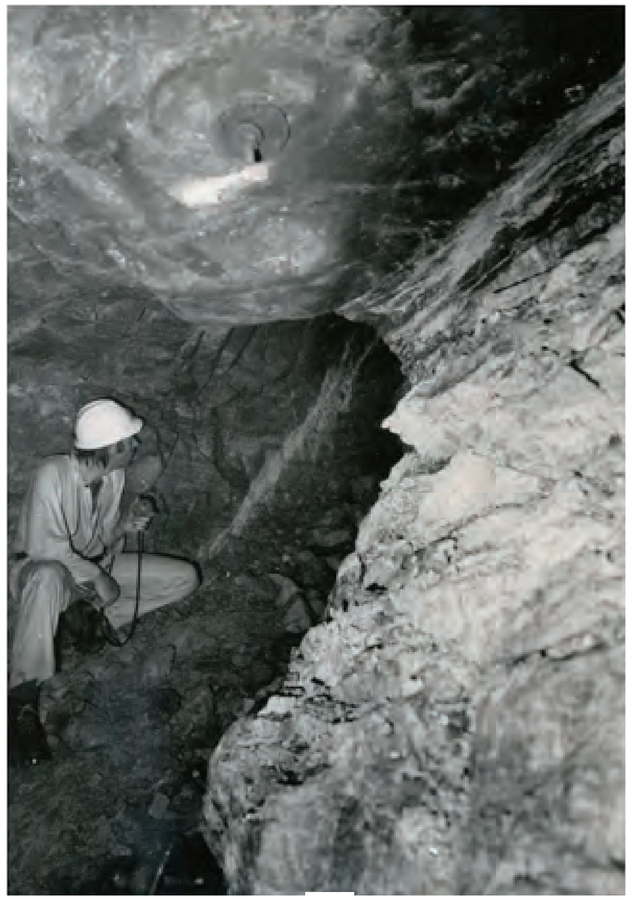
a) View northward of easterly-dipping burst fracture about 7 metres below worked-out area some 30m behind westerly advancing B4^{W} longwall face.

b) View southward into bottom of service-way raise showing ilie same burst fracture extending upwards into tlie old area of the slope.

c) Close view northward of roof of cross-raise into slope hangingwall above (h) showing detail of shear displacement across the burst fracture. Slope face advanced towards the left.



(a)



(b)

(c)

3.2.4.9 Shear rupture source mechanism - other districts page 59

Burst fractures, Hartebeestfontein

Captions

(a) Plan of portion of Hartebeestfontein gold mine showing location of a large seismic event on 4 January 1983. Although not shown in this view, the surrounding area is extensively mined for several kilometres in all directions.

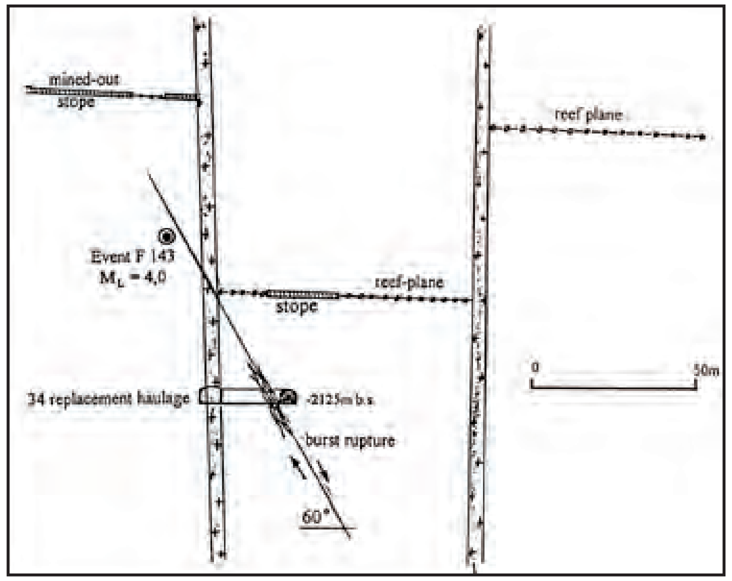
(b) Plan view of area affected by the seismic event of 4 January of 4,0 M_L magnitude. The Klerksdorp regional seismic network indicated the origin at x= 74700, y =22240 and z=2080m. The estimated location error was said to be somewhat less than 100m horizontally and about twice that in the vertical direction.

A first-motion analysis of the seismic data showed the strike of one of the two possible planes of slip to be within 5 ˚ of the strike of the major dyke, and its dip 80 ˚ towards the north.

The 34 S footwall haulage had completely collapsed where it was intersected by the major dyke at B, and 34 E crosscut was inaccessible. Replacement crosscut 34 S was driven after the event, to attempt to re-establish access for the sloping of the down-thrown reef block between the two dykes.

(c) Vertical strike section through AA' of fig (b). The intersection of the replacement tunnel with the main dyke at point C very clearly showed that no movement had occurred along the dyke contacts. This indicated that the discontinuity represented by the dyke contacts was not part of the source mechanism at this point. Closer to the position of the original cross-cut, possible evidence of the actual source was revealed in the sides of the newly-developed replacement cross-cut. New shear dislocations were found trending parallel to the dyke and dipping away from it. These were interpreted as the traces of a 'burst-rupture' zone whose origin was some considerable distance away. The total displacement across this zone was in excess of 150mm and was of a normal, dip-slip nature.

(a)



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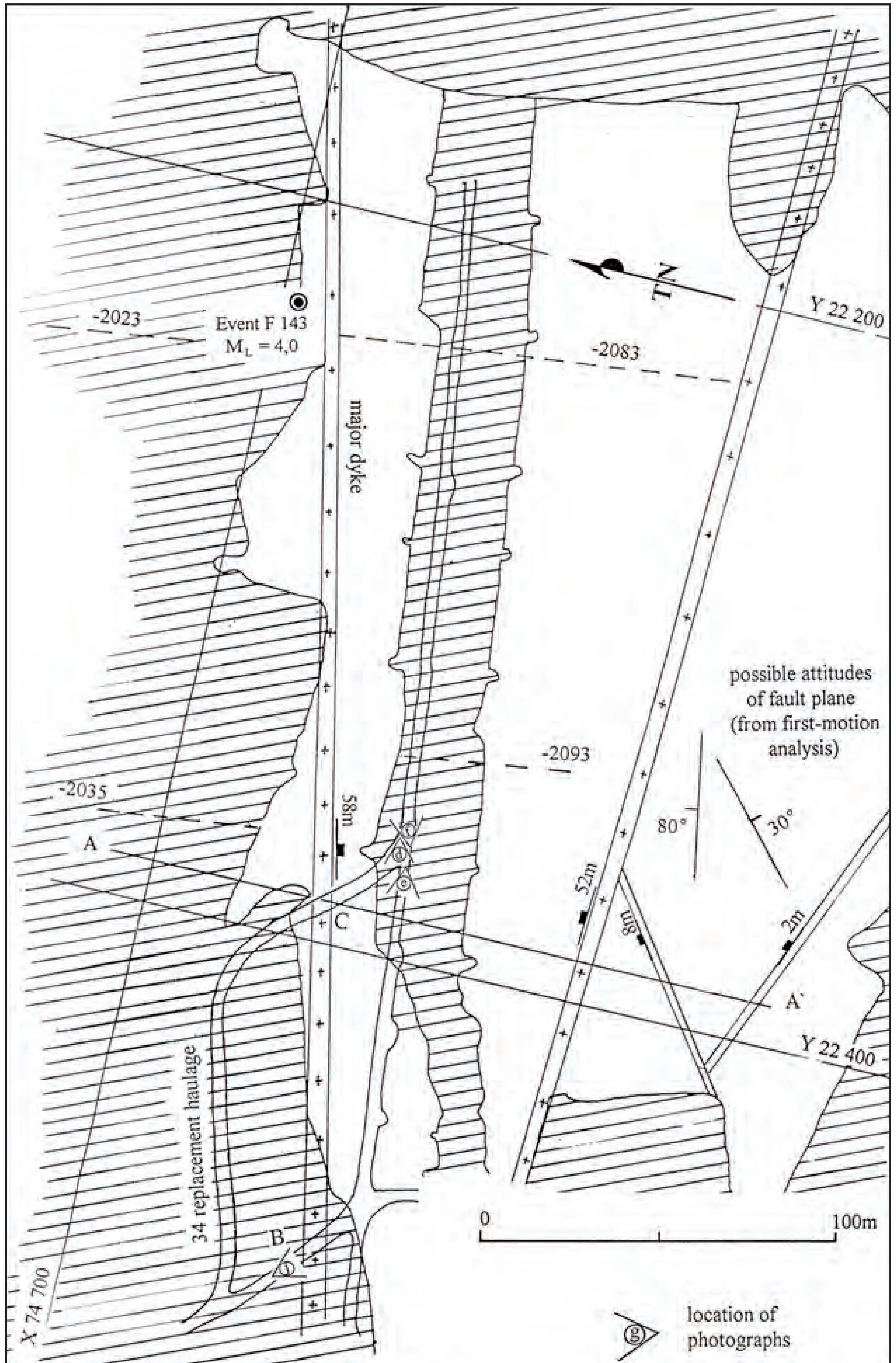


(b)

3.2.4.9 Shear rupture source mechanism - other districts

Burst fractures, Hartebeestfontein (continued)

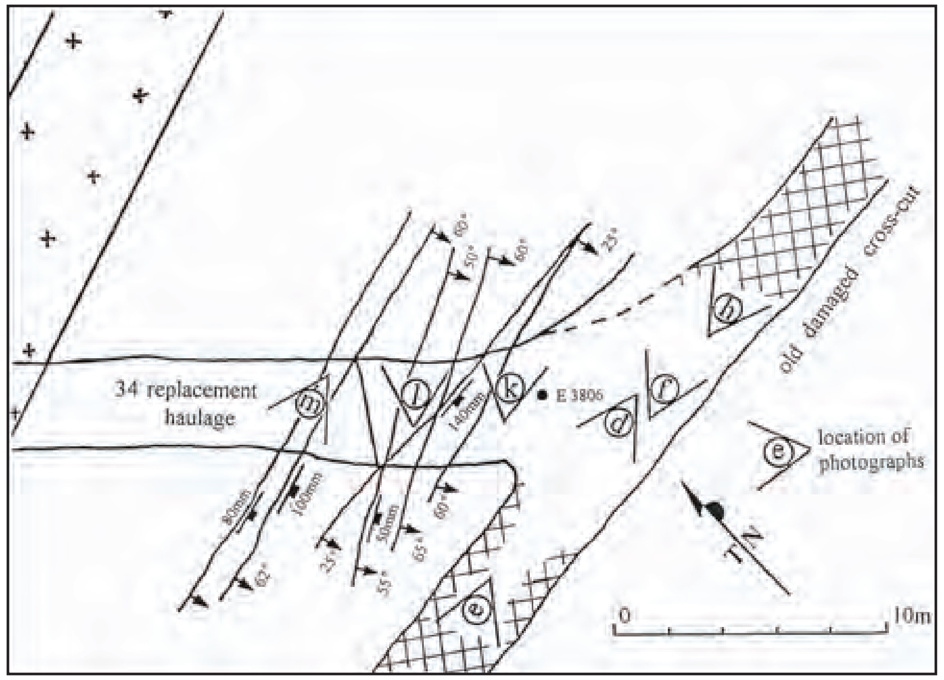
Captions (continued)

(d) View westward into 34 E cross-cut from open chamber formed by clearing out the rockburst debris through the new replacement haulage which holed at this point. The roof above appears quite sound. The timber sets are part of the brow support, newly installed in the intersection. The void above the ejected side-walls is clearly visible. The E-W joints in the roof appear to dip steeply northwards and to have had no effect on the damage. The origin of the event indicated by the regional seismic network was about 150m ENE from this point and 50m above.

(e) View westward into original 34 E some 5 weeks after photograph (d) when several metres of debris had been cleared away. The large broken rock slab which straddles the pipes is somewhat less than 1m thick, and appears to have been ejected from the south sidewall after failure of the expansion shell anchors of three of the rockbolts. About one metre of rock has broken up in the roof and collapsed because of failure of the wire mesh containment.

(f) Sketch plan of intersection of new replacement tunnel with original 34 E cross-cut, showing position of the shear fractures comprising the burst rupture zone which is believed to be the origin of the seismic event of 4 January 1983.

(e)



(f)

page 60

(d)

3.2.4.9 Shear rupture source mechanism - other districts

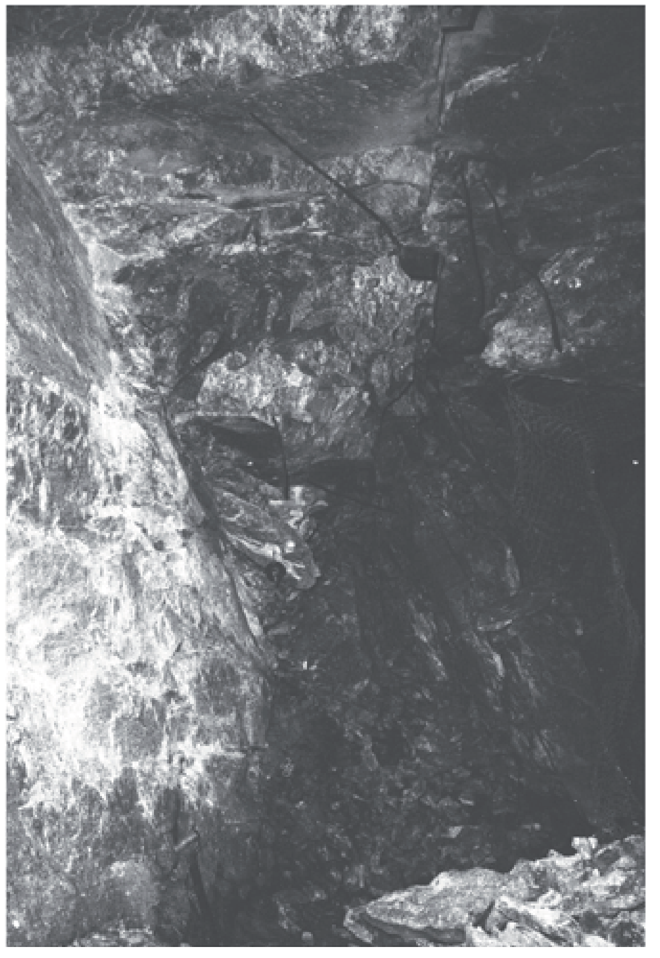
Burst fractures, Hartebeestfontein (continued)

Captions (continued)

(g) View eastwards into 34 ^{E} cross-cut showing the substantially symmetrical nature of the damage. Most of the broken rock, as in (d), has been displaced equally from north and south sidewalls with very little having fallen from the roof. The buckling of the ventilation column and the denting of the compressed air column (h) indicates that the ejection of the side walls occurred at considerable velocity. Most of the rockbolts are not broken because the attachment of the linked mesh to the bolts failed with the 100 x 100 mm square washers easily pulling through the mesh! The length of bolts protruding from the south sidewall indicates that slightly more than one metre thickness of rock was ejected.

(h) Detail of joint which, locally, may have provided a plane of weakness for the separation of the north sidewall, facilitating its ejection into the tunnel. The joint has a similar E-W strike direction to joints visible in the roof of the crosscut (d) but dips steeply in the opposite direction.

(i) Detail of the crushed ventilation column and the dented compressed-air pipe trapped between the ejected side-walls of the portion of crosscut shown in (e).



(h)

(i)

page 61

(g)

3.2.4.9 Shear rupture source mechanism - other districts

Burst fractures, Hartebeestfontein (continued)

page 62

Captions (continued)

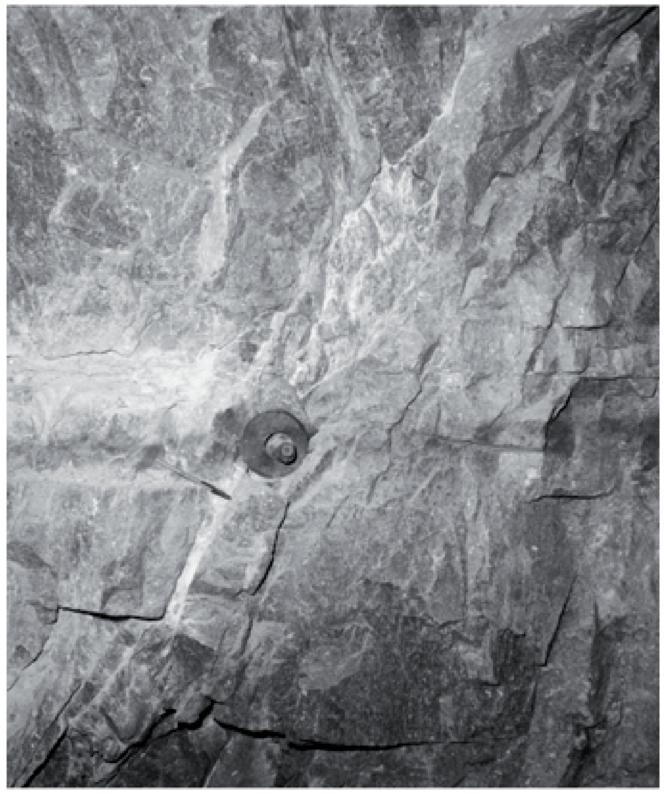
(j) View southward at the point A where the major dyke intersects the original 34 ^{S} footwall haulage. The tunnel is completely choked with rockburst debris comprising large blocks and smaller fragments of quartzite ejected from both sidewalls.

(k) View eastward near point C in fig (b), where replacement tunnel merges with original cross-cut, showing the most southerly fracture of the rupture zone of fig (i).

(1) Closer view of most shattered comminuted portion of the shear fracture shown in (k). The pen in the centre of the photo is pointing at a sedimentary marker which is displaced downward by about 150mm relative to the same trace on the left of the shear zone.

(m) View westward of the trace of the most northerly fracture on the western sidewall of the new tunnel about 5m south of south contact of dyke.

(k)



(m)

(l)

(j)

3.2.5 Fault-slip

3.2.5.1 Fault-slip source: massive convergence damage in stope

Hercules longwall, ERPM

Introduction

It has long been known that the approach of extensive tabular sloping at depth towards a fault or, more particularly, a dyke, considerably increases the risk of a major rockburst. A particularly serious situation exists when the general line of longwall faces is parallel to the discontinuity. It is not known whether residual geological stress is a factor in promoting a particularly large release of seismic energy or whether the large planar weakness afforded by the discontinuity simply allows failure, by slippage, along a very extensive area. This would tap the stored elastic strain energy from a large volume of rock.

Clear evidence of a large linear extent of shear failure along a previously unknown fault of negligibly small throw was provided by one event on ERPM which was studied quite closely.

Captions

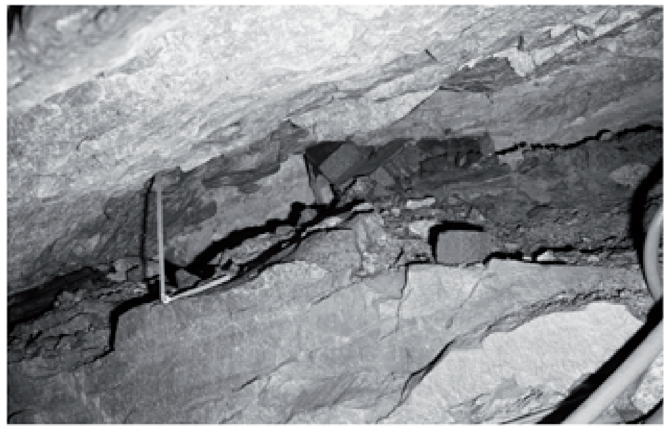
(a) Plan view of ERPM. The conglomerate ore horizon (reef) is seldom more than one metre thick, dips at 20 ° - 40 ° southward and extends from the surface to 3000m and deeper.

(b) Plan view of the deepest stope showing the extent of the area of severe rockburst convergence which resulted from seismic activity on 1 April 1977. The location of photographs (c) to (k) is also indicated. The fault was said to have been exposed at the lower end of the stope a few days previously and the throw was estimated at less than one metre.

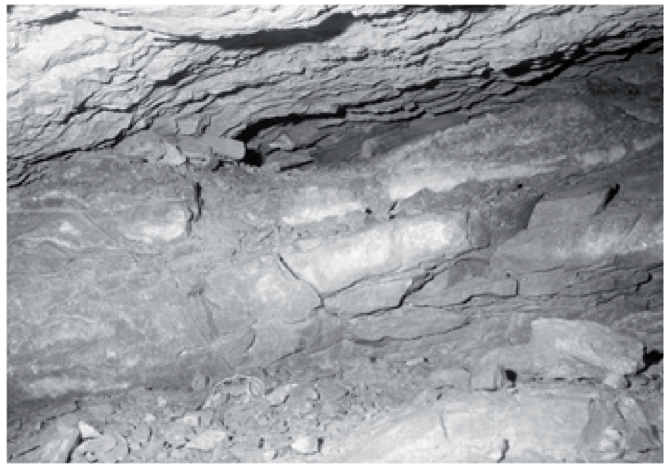
(c) View back from re-opened face near top of stope showing slope width reduced to less than 0,5m.

(d) View up-dip from re-opening trench showing extreme convergence and evidence of strata separation in footwall.

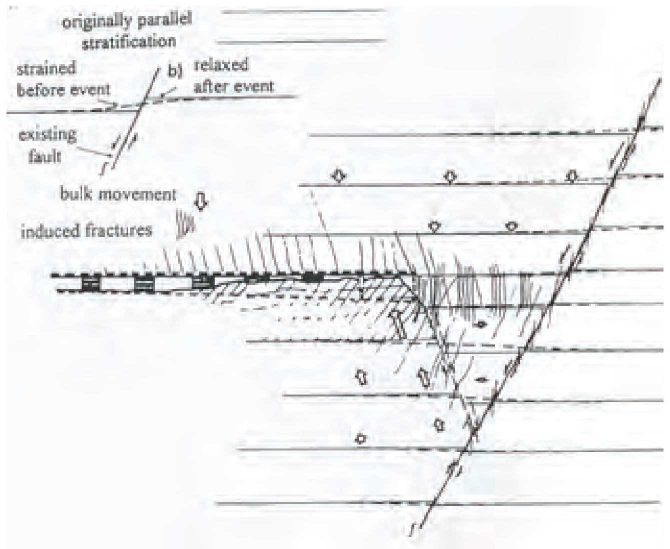
(e) Conjectural section on strike through stope at location of photo (k) showing, by broken lines, the position of the stope before the burst, the mode of dislocation along the fault plane and the upwelling of footwall strata which caused the severe convergence.



(c)



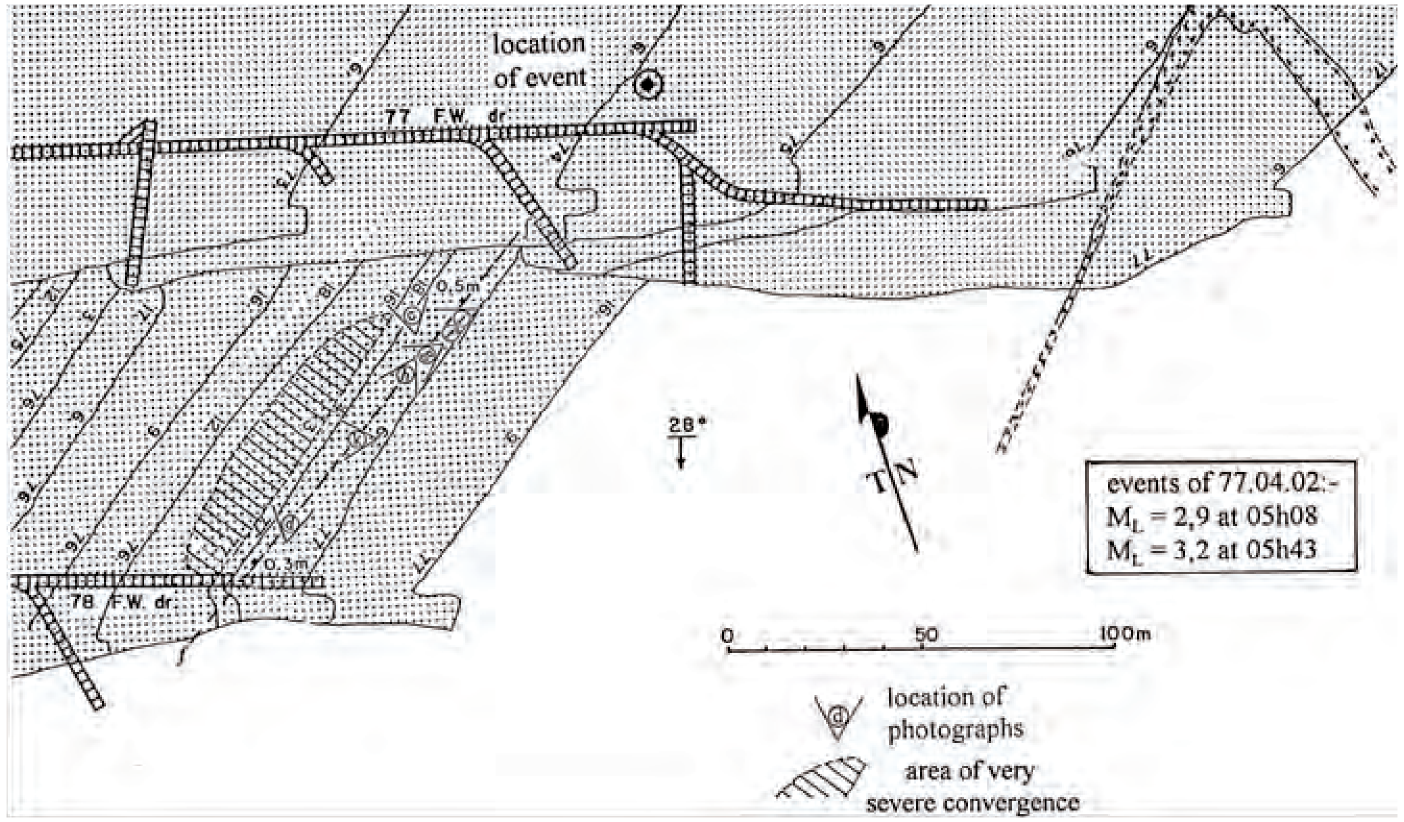
(d)



(e)

page 63

(a)



(b)

3.2.5.1 Fault-slip source: massive convergence damage in stope

Hercules longwall, ERPM

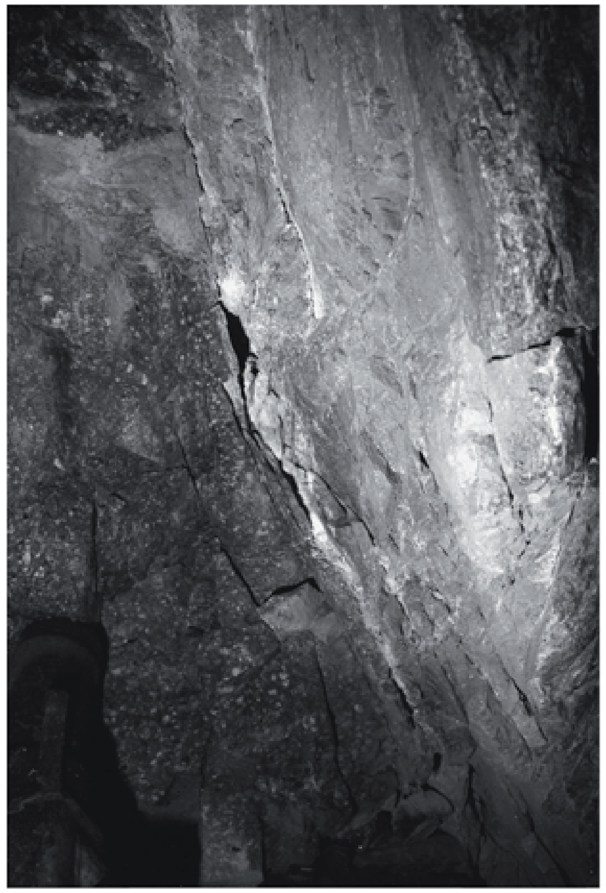
page 64

Captions (continued)

(f) View upward of roof of stope showing opening along the fault trace and the severe comminution which demonstrates the recent movement along the fault.

(g) View down-dip along the fault about 5m behind the steadily-advancing stope face. The width of the burst cavity extending upwards into the roof is not the result of inadequate support and consequent movement of the weak side of the fault but simply the falling out of 'breccia' fragments and gouge.

(h) Close view upwards into the burst cavity. A compacted filling of intensely-comminuted 'rock flour' is visible as a white lens-shaped mass near the top of the cavity in the extreme upper left corner of the photograph.



(f)

(h)

(h)

3.2.5.1 Fault-slip source: massive convergence damage in stope

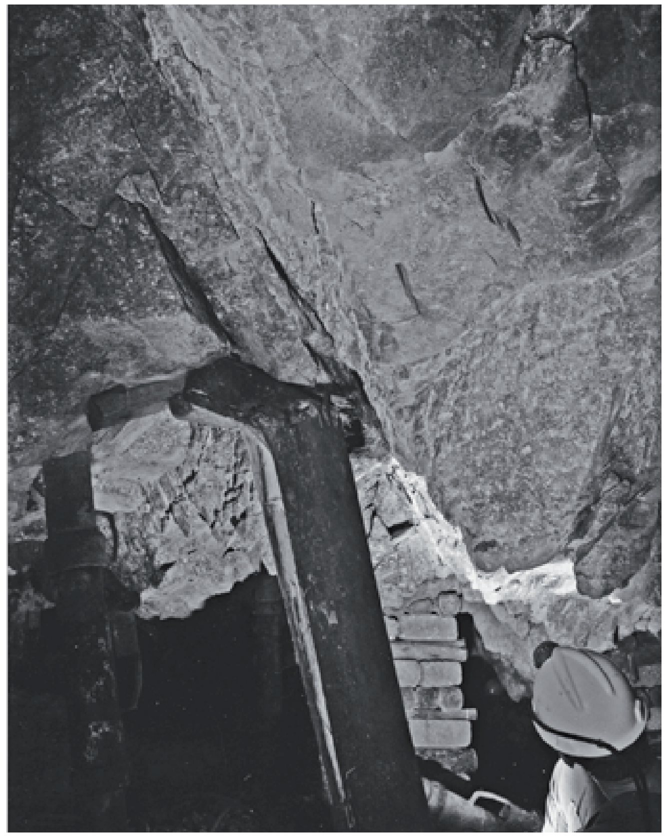
Hercules longwall, ERPM

Captions (continued)

(i) A further view of the burst fracture along the fault showing burst gouge in place along the burst/ fault fracture. Normal, dip-slip sense of original geological movement along the fault is indicated by the lower position of the conglomerate marker on the right hand side of the fault-plane relative to the left side. It is not possible to detect how much more normal displacement was caused by the burst movement.

(j) Section on strike at location of photo (k) showing the remarkable lack of convergence experienced during the sloping from mid-March when the face had been re-opened after the burst and mid-June when the photographs were taken.

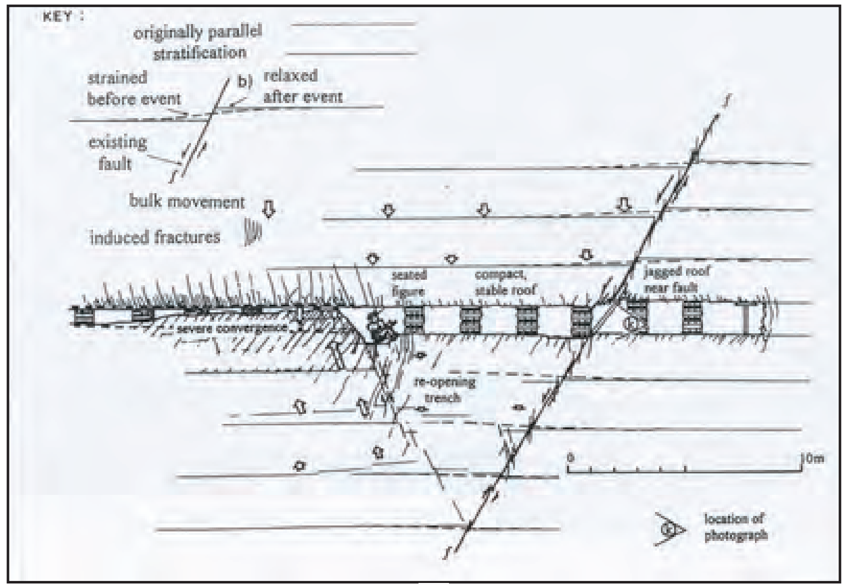
(k) View westward from about l0m back from the stope face with the camera positioned directly below the fault. The complete convergence caused by the burst can be seen just beyond the seared figure in the distance. The complete lack of normal convergence is indicated by the absence of any compression of packs. Normally, packs this far back from the working face (approximately 20m) would have been crushed to less than 50 of their installed height! The unusually good face advance of the following three months (over 12m per month would be considered excellent progress in a well-managed stope in good ground at shallow depth!) supports the view that the absence of convergence can only be attributed to the relaxation of the high stresses that existed before the large seismic events of April 1.



(i)

References

W D Ortlepp. Rockbursts in South African gold mines, a phenomenological view. *Int. Symp. on Rockbursts and Seismicity in Mines, SAIMM Symp. Series No 6. Johannesburg* 1984 pages 165 - 178.



(j)

page 65

(k)

3.2.5.2 Large fault-slip event: Sudbury, Ontario

Introduction

On June 20, 1984 a seismic episode occurred at the Falconbridge mine near Sudbury in Ontario, Canada. In several ways this proved to be the most significant instance of mine-induced seismicity that had occurred in the history of Canadian mining.

It led directly to the establishment of a Provincial Committee of Inquiry which, in due course, made extensive recommendations. These included, inter alia, that a research organisation funded by mining companies and provincial and federal governments should be created and that a special chair in ground control should be established at an Ontario university. The Mining Research Directorate and the Geomechanics Research Centre at Laurentian University in Sudbury were the direct results of these recommendations.

In terms of increased understanding of the whole phenomenon of rockbursting, this event was also particularly significant in that it provided proof, for the first time in North America, that slip on an existing fault was the source mechanism of a large rockburst.

The following passage is quoted directly from the Stevenson Report (the Provincial Committee of Inquiry):

"Then, without further warning, a powerful earth tremor with a magnitude of 3.4 on the Richter scale shook the entire mine, and caused the collapse of the backfill in the nearby stope where the four miners were working. In the next half hour 116 microseismic events were recorded, and shortly after noon a series of large seismic events temporarily interrupted efforts to rescue the trapped men.

A committee of technical experts from Canada, the United States and South Africa was gathered to examine the underground workings to help determine the cause of the rockbursts. The microseismic monitoring system located the epicentres of the events along a series of faults in the immediate area, and the technical committee concluded that the rockburst occurred when a very large mass of rock moved suddenly along what is known locally as the Ore Pass Fault and the #1Flat Fault. The energy generated when the rock moved from one-half to two inches along these faults would be sufficient to cause a tremor of the magnitude recorded at 10:17 on June 20.

The committee's conclusion was confirmed when another large seismic event - 2.5 on the Richter scale - occurred on July 5. The technical Committee immediately inspected the #1 Flat Fault at the 3500 level of the mine, and found fresh evidence that the rock had moved about two inches. When the chief executive officer of the company could not be assured that a similar event would not occur in the future he closed the mine..."

Reference: The report of the Provincial Inquiry into Ground Control and Emergency Preparedness in Ontario Mines. February 1986. T. Stevenson, Chairman.

Captions

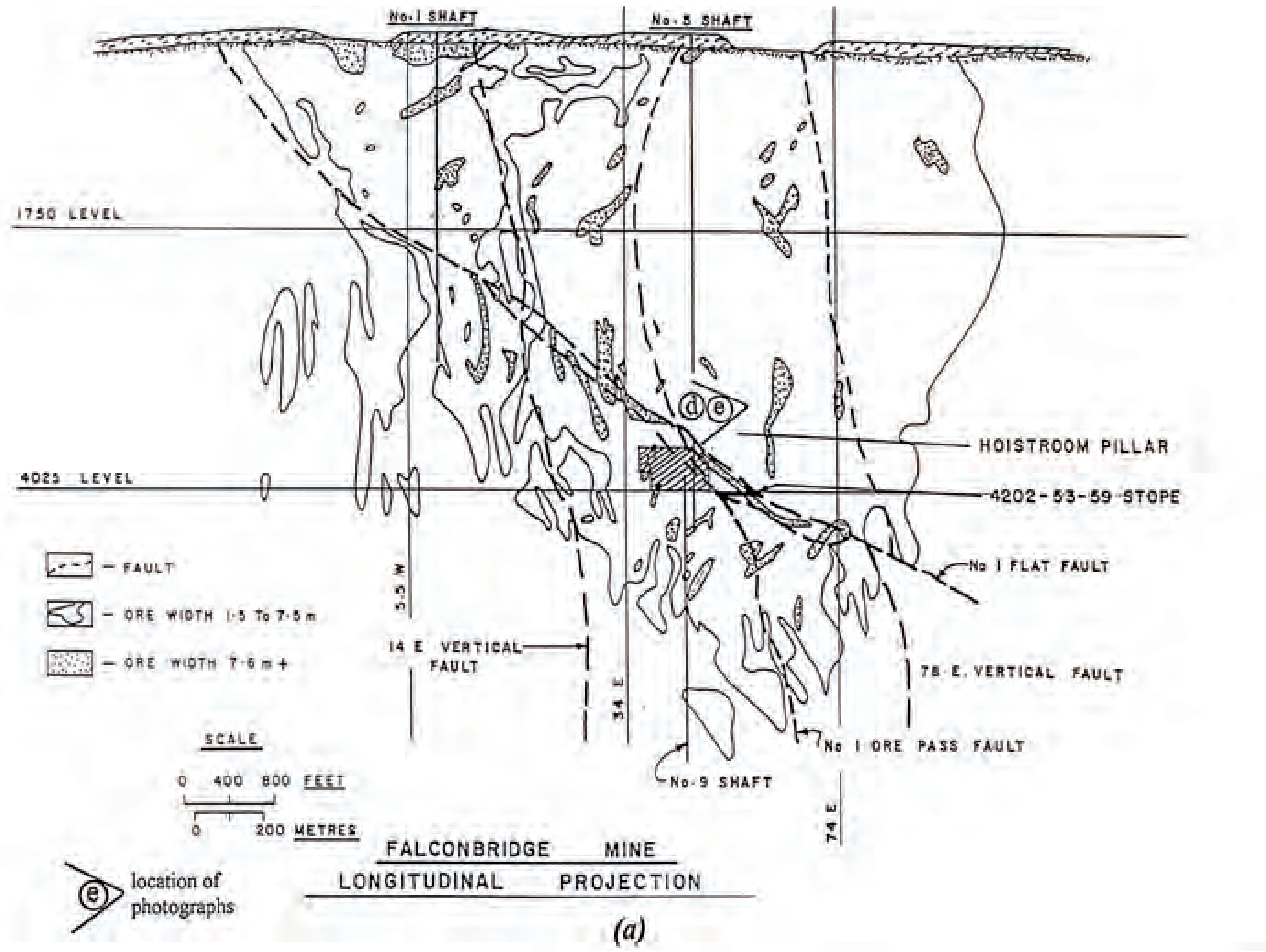
(a) Longitudinal projection showing location of photographs.

(b) Plan of 4025 level showing location of photo (c).

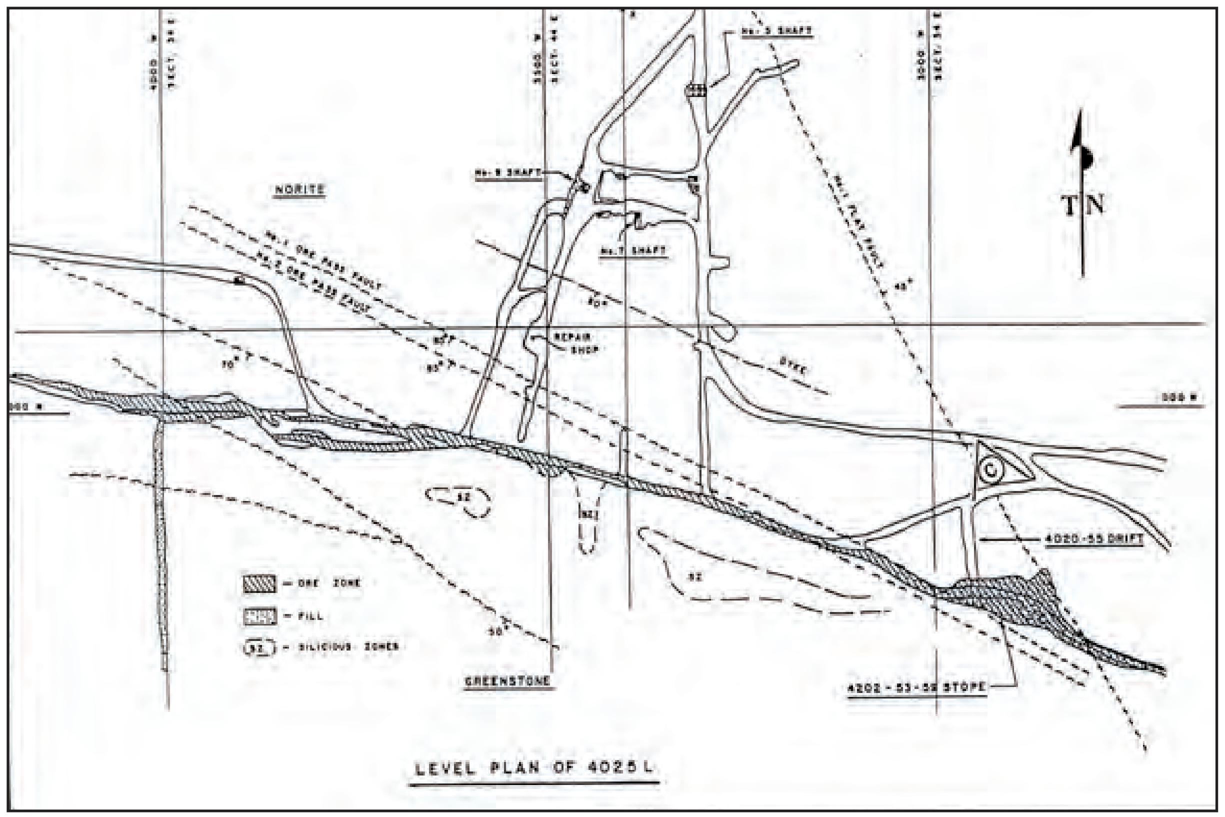
(c) Fresh spa1ling along trace of easterly-dipping #1 Flat Fault on south side of 4020 - 55 drift. There was no detectable slip at this point. The distance to the damaged part of the slope was about 50m. Photographed 3 July 1984.

(d) View north of intersection of #1 Flat Fault drift on 3500 level showing signs of recent movement. There appears to be a small 'fold' in the thin shotcrete layer about 400mm up along the fault trace from the end of the ruler. Photographed 2 July.

(e) Close view of same area as (d) photographed 4 days later on 6 July. The now broken 'fold' in the shotcrete just above the tip of the ruler clearly indicates renewed slip (of about 50mm) following the 2,5 Richter event of the previous evening. The origin of this event was located very close to the fault intersection but the drift was undamaged apart from the minor spoiling of the shotcrete.



(a)



(b)

for captions see page 66

page 67

(d)

(e)

(c)

3.2.5.3 Major fault-slip events: South Africa

The Welkom ‘earthquake’

Introduction

Exceptionally large seismic events happen infrequently in some mining districts. While they are probably induced by mining, they could not easily or positively be attributed to a particular single cause. In some cases the damage resulting on surface was more dramatic and more significant than that caused to the underground workings.

As early as 1908 and 1915 it was recognised by state-appointed committees of enquiry that the ‘earth tremors’, that had already become quite common, were directly associated with underground mining activity. This acknowledgement of causality was widely accepted for most tremors, but an element of uncertainty was preserved until quite recently for the cause of the very large seismic events. Particularly where damage to surface buildings was significant, it was convenient and expedient to be able to invoke the hypothesis that such events were the effects of natural crustal seismicity and not the result of mining.

With the introduction of extensive seismic networks it becomes more difficult to avoid the conclusion that the broad effects of mining over large areas must be the dominant cause of these massive incidents on the major faults in the region.

Without doubt the most dramatic of these was the one which occurred in December 1976 in the Orange Free State goldfields which became known as the Welkom ‘earthquake’. The magnitude was estimated at 5,0 M_L. The epicentre was close to the city centre of the town of Welkom which was extensively undermined at a depth which varied from 1000m to 1500m.

Although not indicated at the time because of the absence of any local seismic monitoring, it was the result of more than 300mm of dip-slip movement along the Dagbreek fault where it was surrounded by extensive mining of the Basal reef at a working height of between 1,2 and 2,0m - see figs (a) and (b) on page 69.
The photographs opposite show the damage caused to a multi-storied apartment building which collapsed some 40 minutes after the quake. Elsewhere in the city damage was relatively much less severe.

The five major fault slip events which have occurred in the Welkom area are tabulated below (G van Aswegen, 1990).

Major seismic events in the Welkom Goldfields

Relaxation of the ‘clamping’ effect of confining stresses, which have existed over millions of years

Date	Fault	M_L	Fault ‘throw’	Co-seismic slip
1972	Erfdeel	4,5	300 m	?
1976	Dagbreek	5,1	900 m	300 mm
1982	Wesselia/ Erfdeel	4,8	360/300 m	410 mm
1986	Dagbreek	4,9	900 m	> 200 mm
1989	Brand	4,6	350 m	370 mm

in a relatively very stable cratonic environment, is the probable reason for the ‘momentary’ rejuvenation of ‘tectonic’ movement.

Large events of a similar nature have also occurred in the Klerksdorp area. These have usually been accompanied by serious underground damage although surface effects have been of a minor nature.

References

G Van Aswegen. Fault stability in SA gold mines. *Proceedings of the Int. conference on Mechanics of Jointed and Faulted Rock*.
P Rossmanith (ed.) Vienna, Austria, April 1990.

L M Fernandez and P K van der Heever. Ground movement and damage accompanying a large seismic event in the Klerksdorp district. *Int. Symp. on Rockbursts and Seismicity in Mines. SAIMM Symp. Series No. 6*. Johannesburg 1984.

page 68

3.2.5.3 Major fault-slip events: South Africa

The second Welkom 'earthquake'

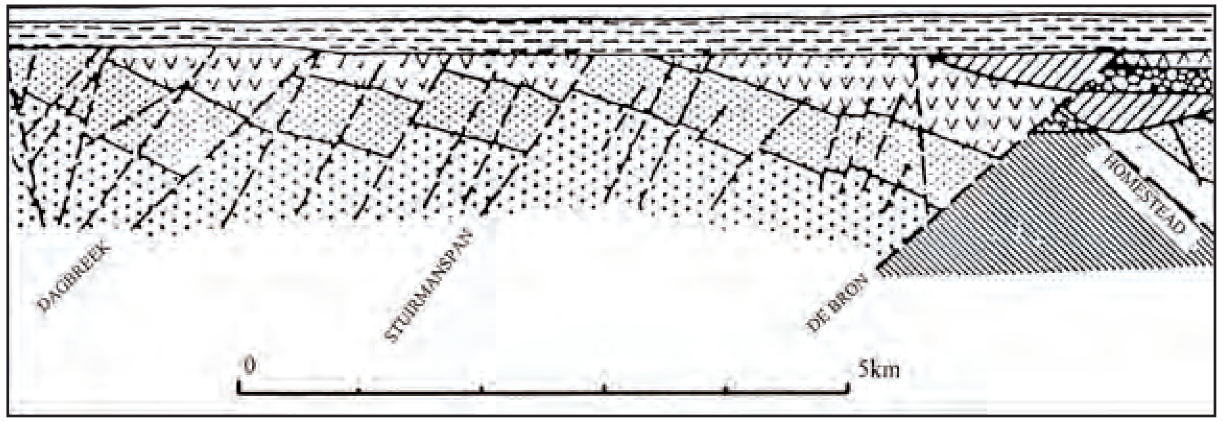
Introduction

Twelve years after the 1976 Welkom earthquake, a severe tremor again shook the city causing noticeable cracks in a few buildings, overturned shelves, collapsed ceilings and broke windows in shops and offices. Although two possibly larger events had occurred in the district during the intervening years (see table on page 68), these had been further afield and, although considerably more serious underground damage had resulted, there was no damage to commercial areas. Where significant surface damage does result from fault slip induced by extensive mining in the region, it might be appropriate to refer to such events as 'mine-quakes'.

The 4,6M_L event of 25 January 1989 was labelled as the 'second Welkom earthquake' by the media but its real significance lay in the fact that it was the first of the major fault-slip events to be properly documented by a sophisticated seismic system (1SS). Three-component, full wave forms were recorded at 13 underground seismic stations including one situated only 700m from the origin. Here ground motions of 200mm/s were recorded - Van Aswegen (1990) (reference cited on page 68). Fresh dip-slip displacements of up to 37cm - fig (c) - were found along the Brand fault (350m throw) over a strike length of 2400m between the Dagbreek and the Arrarat fault - figs (a) and (b).

Analyses of the seismograms showed that the stress drop was low and the shear displacement occurred in a relatively 'gentle' fashion. The change in elevation of the tracks and the gradeline painted on the sidewall and the formation of a small waterfall in the drain, were dramatic indicators of the displacement across the fault-trace. However, the absence of any significant fall of rock and the lack of damage to the light mesh and lacing that comprised the tunnel support was clear evidence of the non-violent nature of the damage.

(a)



A simplified geological section across the southern part of the Welkom gold field. Approximately 500 m Phanerozoic strata overlies tectonically disturbed ancient lava and quartzite of the Ventersdorp and Witwatersrand Supergroups respectively

(b)

page 69

3.2.5.3 Major fault-slip events: South Africa

Erfdeel, Wesselia and Vlooi Faults

Introduction

Of the major seismic events tabulated on page 68, two others caused severe disruption to the mine infrastructure and therefore warrant brief description.

On 6 September 1973 at 18:15 a major tremor was felt strongly to the north-west of Welkom. Significant damage was done to the shaft steelwork and to the concrete brattice wall in No. 1 shaft of the Free State Geduld mine where it was intersected by the 70m throw Erfdeel fault at 1380 m depth - Williams (1976) (reference page 34). Buckling and disalignment of the steel guides made movement of the conveyances in the shaft impossible until 17 days of intensive repair work had been completed. Although no mention is made in the cited reference of dislocation observed across the fault, examination of the published photographs suggests that a few centimetres of relative movement may have been detectable. There was no seismic network in the Orange Free State goldfields at the time of the event.

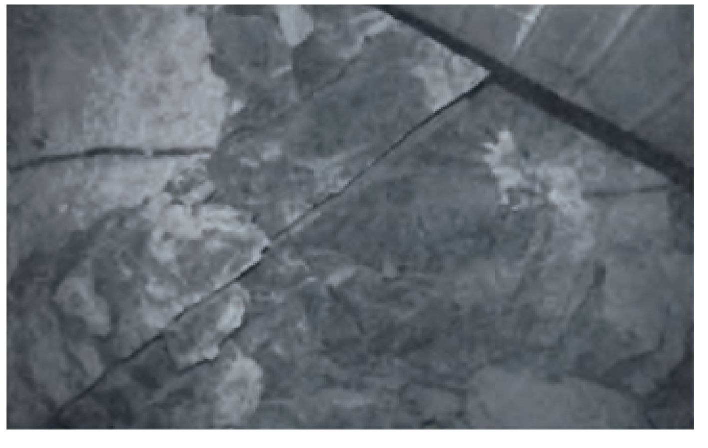
By the time the region to the north-west had suffered its second major tremor on 13 April 1982, a regional seismic network had been established around Welkom. Underground infrastructure, especially No. 1 shaft where it had previously been affected in 1973, and No. 4 shaft 2km further south, was severely damaged. Production and man-hoisting activities were halted for several weeks and workers had to be evacuated through alternative outlets in adjoining mines.

Although the seismic location network recorded only the arrival times of seismic waves, the system could, to some extent, distinguish between P-wave, S-wave and false arrivals at the different stations. This enabled Mendecki et al (1988), to make use of a simplified 3D seismic velocity model and specially-developed software to locate the main shock and several after-shocks - fig (c). Careful study by Van Aswegen (1990), (reference page 68) of slip displacements of up to 44cm, at intersections of tunnels with the Erfdeel, Eureka and Wesselia faults, led to a credible hypothesis and analyses which showed conclusively that the source mechanism of the major tremors was re-juvenated slip on the major regional faults. This slip was invariably of a normal dip-slip nature.

In one instance in the Klerksdorp gold mining district apparent reverse movement was observed on Buffelsfontein gold mine - fig (b). The event occurred on the Viooi fault on 11 November 1985, and had a magnitude of M, = 3,6. This event is significant because it is the best documented case to date where reverse fault slip was observed - Brummer and Rorke (1990).

The movement was seen in one particular tunnel which intersected the fault below the upthrown segment of the faulted reef. Fig (d) is a section in a strike direction which shows where the displacements occurred on the fault plane. Reverse slip which amounted to 300mm was observed at A. At B, normal slip of roughly 100 mm was seen.

This event demonstrated that both normal and reverse slip can occur simultaneously on different parts of a fault plane during a mining-induced seismic event. The sense of the slip is such that the tendency is to close the stope excavations, as would be expected intuitively.



(b)

(a)

3.2.5.3 Major fault-slip events: South Africa

Erfdeel, Wesselia and Vlooi Faults (continued)

Captions

a) About 250mm of normal dip-slip displacement on the Erfdeel fault just west of No. 1 shaft.

b) Reverse movement on the Vlooi fault evident on sidewall of cross-cut.

c) Simplified geological plan of part of the Free State Geduld mine showing the extensive mining on Basal reef and the fault losses of the major faults. Also indicated is the data pertaining to the April 1982 'earthquake'.

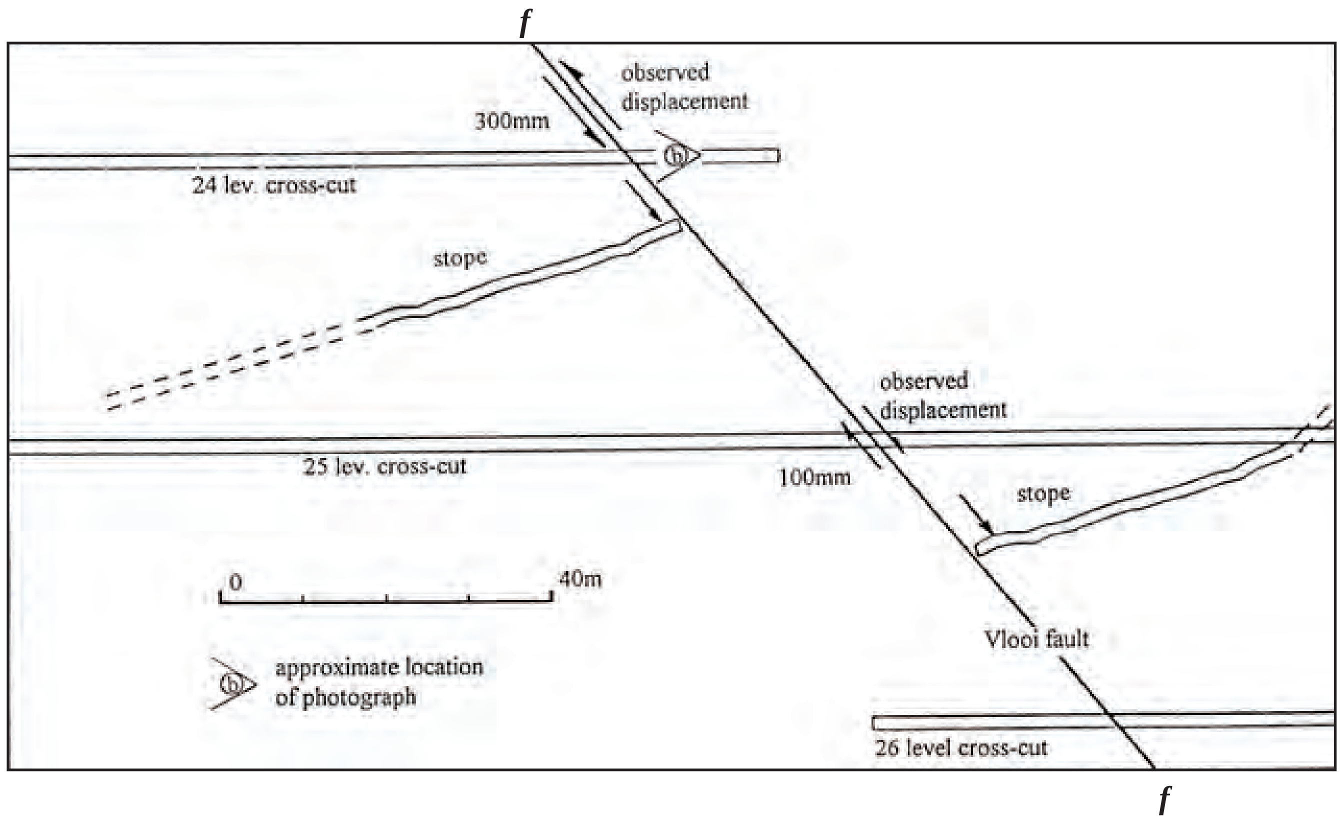
d) Section through the Vlooi fault showing the observed off-sets (after R Brummer).

References

A W Williams. Technical notes on the recovery operations in a vertical shaft damaged by ground movement. *Papers and Discussions of the Assoc. of Mine Managers of S Africa*, pp 11 - 21, 1976-77.

A J Mendecki, G van Aswegen, and W D Ortlepp. The Wesselia mine-tremor of 13 April 1982: some speculations. *AAC Gold Division: TDS Internal Report 1988.*

R K Brummer and A J Rorke. Case studies on large rockbursts in South African gold mines. *2nd Inst. Symp on Rockbursts and Seismicity in Mines*. Edited by C Fairhurst, Minneapolis. AA Balkema 1990.



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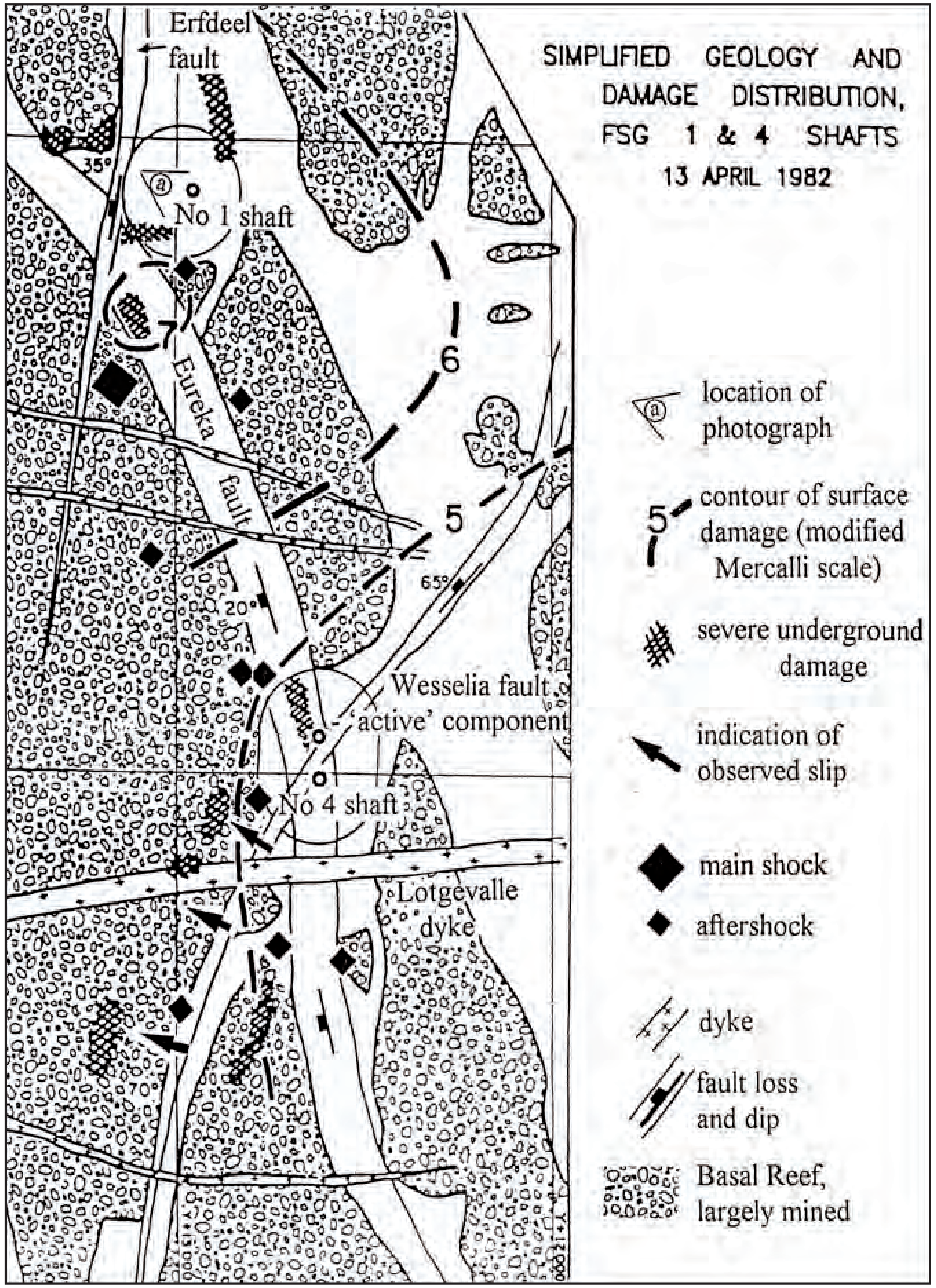


(c)

3.3 MECHANISM OF DAMAGE

3.3.1 Rockburst in Tunnels

3.3.1.1 Tunnel in abutment ahead of stoping

Harmony gold mine - 25 level stoping and haulage

Introduction

When severe rockburst damage occurs as a result of a major seismic event it is usually associated with failure along some geological discontinuity. The effects are frequently wide-spread and damage can result in sloping areas and in the tunnel infrastructure. Sometimes the damage is due to separate seismic events which are part of a complex major episode - see pages 96 - 98.

Sometimes a single very large seismic event causes damage at different locations because of the large amount of energy available and the presence of related or communicating geological structures.

At 11:30 local time on 2 June 1975 a large seismic event occurred some 15 km to the east of the town of Welkom in the Orange Free State. The Richter local magnitude was given by the national seismological network as $M_L = 4,0$.

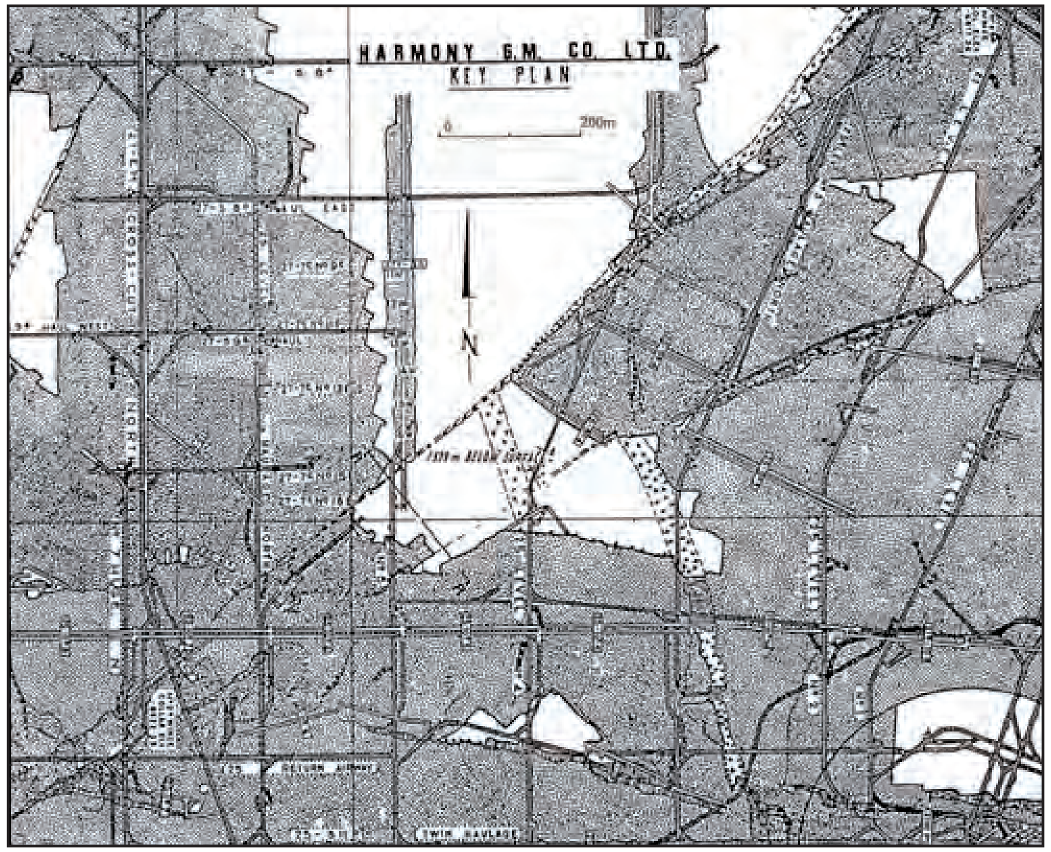
In the mid-1970's, the concept that mining-induced re-juvenation of faults could be the ultimate cause of major rockbursts was not widely accepted. Because this event was believed to be a particularly convincing example of such a cause/effect association, it was studied with particular care. Some details were published previously - see references on page 78.

A more complete photographic decription follows.

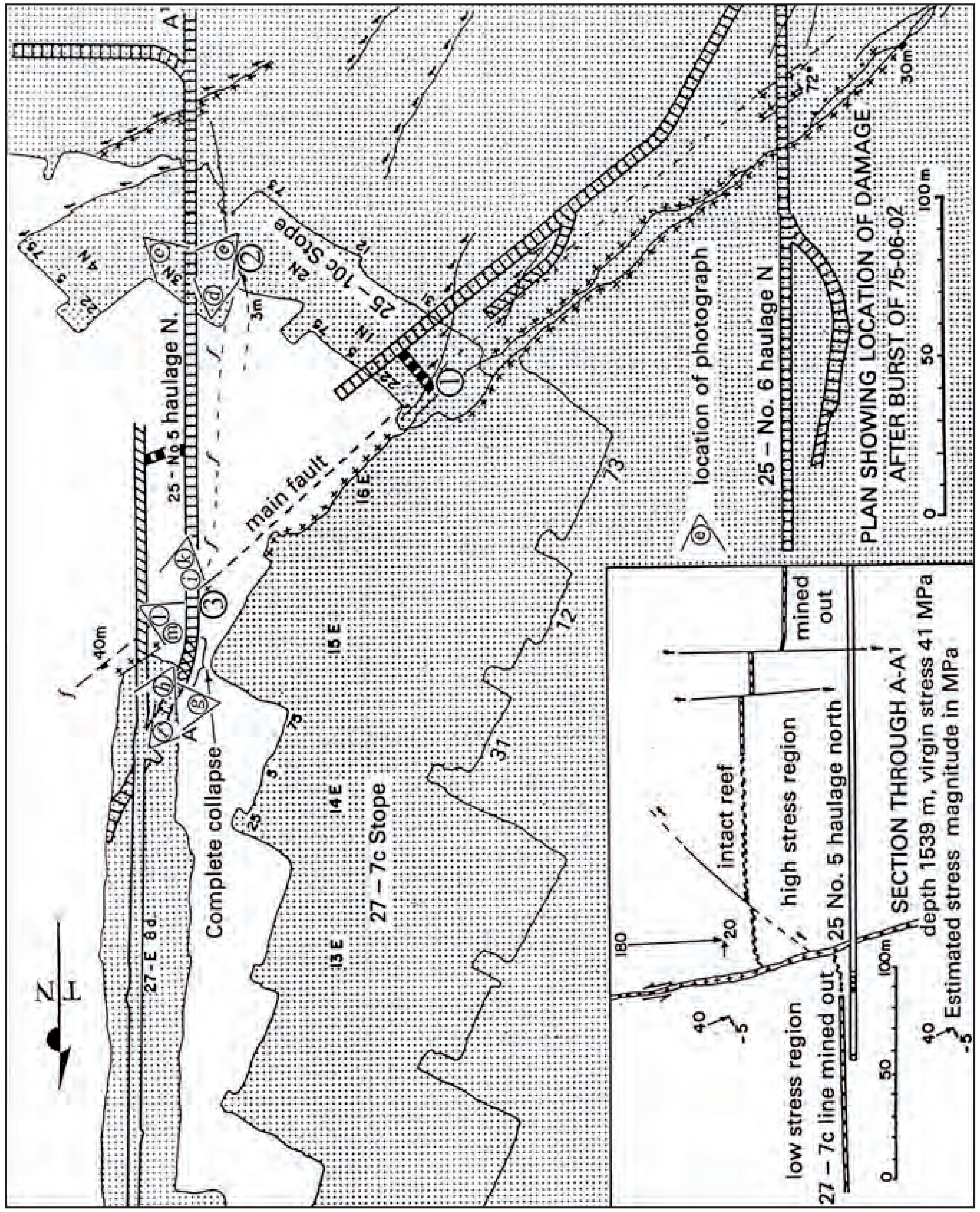
Captions

(a) Plan showing the major geological structures and the stoping configuration over an area of 1 by 1,5 km to the north-west of No 2 shaft, Harmony gold mine.

(b) Detailed plan of the 27-7c and 25-l0c longwall slopes, and the main geological features. The location of the photographs compiled on the following three pages is also indicated.



(a)



3.3.1.1 Tunnel in abutment ahead of stoping

Harmony -- 25 - 10^{C} stope

Introduction (continued)

Relatively minor damage to the hangingwall between props and face was reported for panels 13^{E}, 14^{E} and 15^{E} in 27-7^{C} east longwall. Panel 16^{E} was worked out and therefore not examined after the burst.

About 1,5m of the roof and side collapsed in the ore-pass raise which was close to holing in the strike gulley serving 1 North panel in 25-10^{C} stope - location 1 in (b).

Damage was relatively light with about 0,5m of roof collapsed at the face in panels 1, 2 and 3 of 25-10^{C} north stope except close to the fault between 2^{N} and 3^{N} where 2m of roof was lost - location 2 in (b).

The most intense damage occurred in 25 No 5 haulage north, close to its intersection with the main fault - location 3. Other tunnels on 25 level which were as well supported as No 5 north, suffered no damage.

Captions (continued)

(c) View north-wesnvard down 3N panel from tipping point (up-dip scrape). Induced fractures in roof marked -1- are not parallel to panel face but parallel to general abutment shape. Maximum hangingwall lost was 0,5m.

(d) View southward away from the toe of 3N panel showing the height of the collapsed cavity. Fracture surfaces marked -1- on the left, are the abutment-induced stress fracture while -2- (seen end-on over the distant pack on left) appear to be a joint set. The illuminated surface -3- has a freshly-comminuted appearance and is believed to be part of the 3m throw N-S fault which probably communicates with the main fault some 70m further north.

(e) View northward towards toe of face showing negligible damage to permanent support. Induced fractures -7- cut straight across the corner and are steeply dipping. Ragged bedding-planes are ‘dragged’ open on joint set 2. Open ‘skeleton’ pack on left is a temporary support installed during re-opening after the burst.

(c)

(d)

page 73

(e)

3.3.1.1 Tunnel in abutment ahead of stoping

Harmony -- 25 No 5 haulage

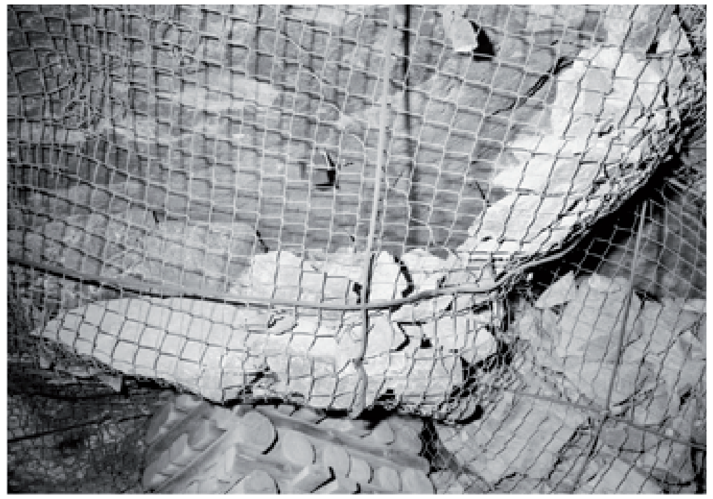
Captions (continued)

(f) View south showing completely collapsed section of No 5 haulage North. The illuminated portion in the centre of the sagging roof shows the cavity above the fall which made it possible to access the shallowly over-stoped haulage to north from the open tunnel to the south of the collapse. Photo (h) was taken in this tortuous and confined passage.

The failure of the connecting ferrule of one of the fully-grouted rope tendons allowed the lacing cross-over point to sag more than one metre.

(g) Closer view of the lacing cross-over. The failed ferrule of the grouted tendon is visible just to the right of the rockbolt washer in top centre of photo. It appears as if the steel eye which is crimped on to the rope end by means of the aluminium ferrule is fractured and straightened out. The rock (of mass less than 1 ton) which tore the lacing free at this point was probably a prominent bulge in the original roof. Bottom right of photo shows another grouted rope which failed above the ferrule probably just where it was fully bonded into the hole. Since it would require a transient force greater than about 60 kN to fracture the steel eye and break the rope, a considerable acceleration (of the order of 6g) must have been imposed on the roof at the instant of the burst to have caused this damage.

(h) View north over top of collapse from near its southern extremity. Pack in right background (centre right of photo) marks northern limit of collapse. It is the same pack as that in left foreground of (f). Height of collapse is almost 2m where full length of old rockbolt is exposed in centre of photo, and grouted rope on left-hand side.



(g)

(h)

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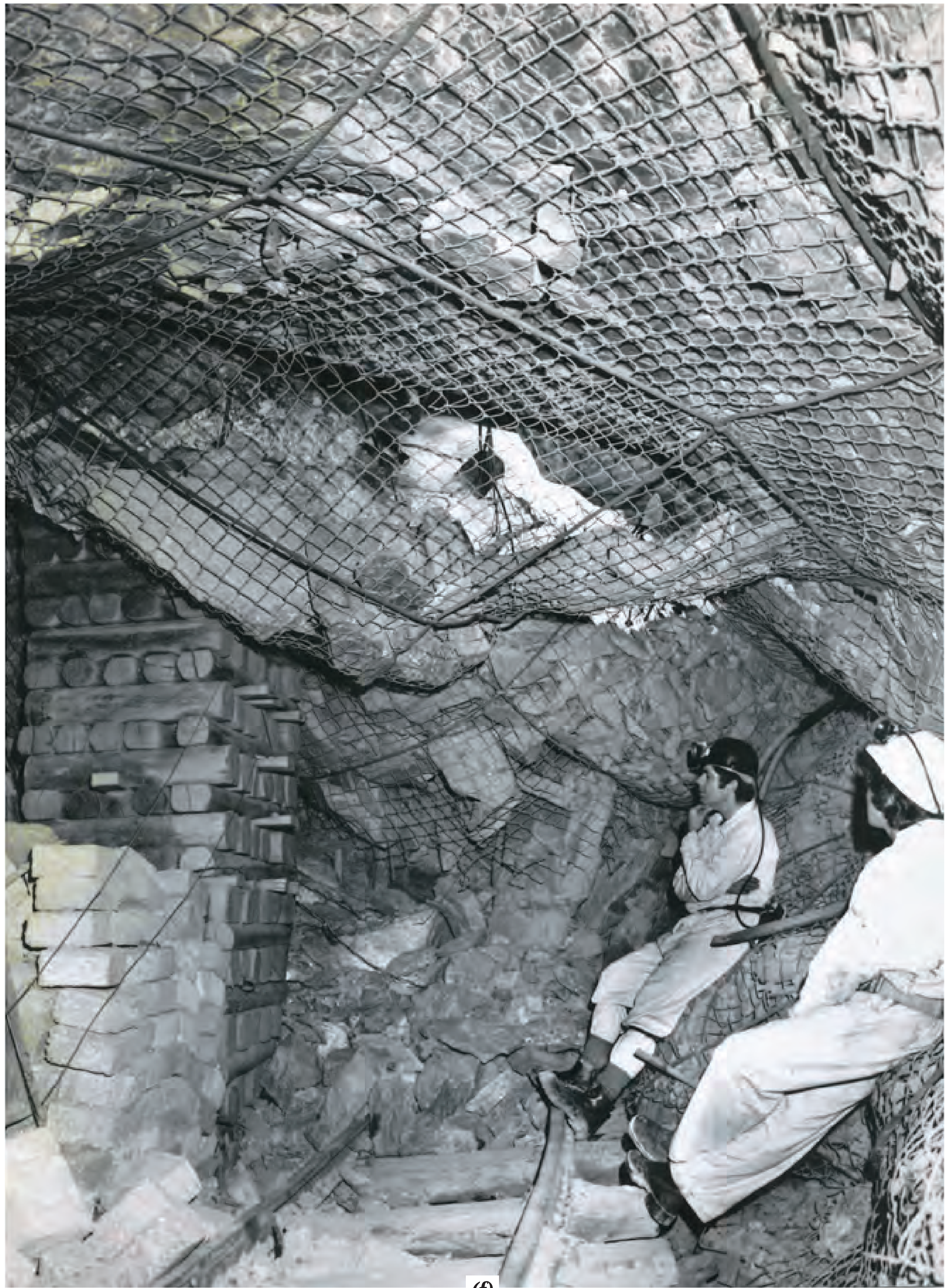


(f)

3.3.1.1 Tunnel in abutment ahead of stoping

Harmony -- 25 No 5 haulage

For captions see p 76

page 75

(i)

(j)

(k)

3.3.1.1 Tunnel in abutment ahead of stoping

Harmony -- 25 No 5 haulage

Captions (continued)

(i) View northward from a low camera angle, about 12m from start of collapse which is just beyond pack in background. From here northwards for twenty metres at least ten rope anchors failed - mostly on West side.

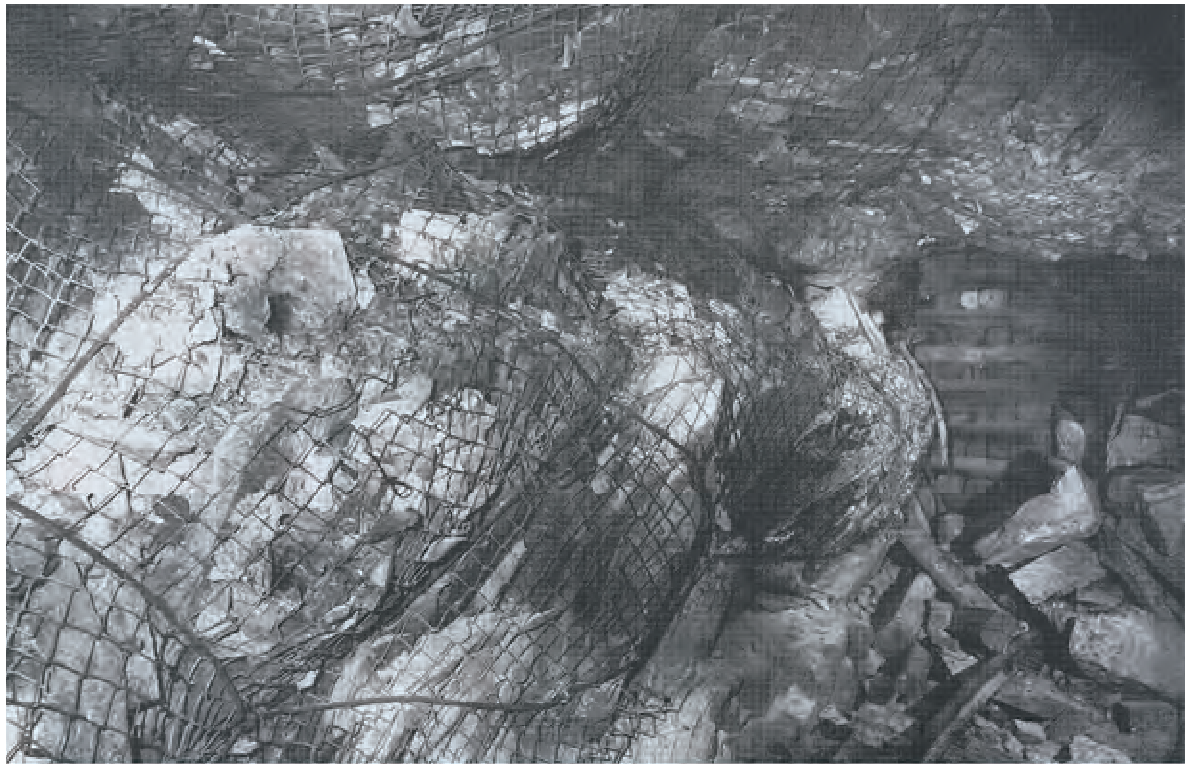
(j) View northward from about 16m from collapse with camera at higher position than in (i). Hangingwall damage is now quite marked. Support in foreground is mainly unbroken. Rope anchors and some grouted ropes failed further on. The southern edge of the fault zone is very close to the camera position but the fragmented tunnel walls make it impossible to locate the fault contact exactly. The original dimensions of the tunnel were 3,5 x 3,5m.

(k) Detail of damaged west wall about 8m from southern edge of collapsed portion. The pointer is indicating the destroyed concrete base of one of the many failed 10m long pro-stressed cable anchors of 900 kN capacity.

(l) Although the tunnel walls are intensely fragmented and have suffered severe dilatation, the bulging is well contained by the mesh and lacing. The fully-grouted ferruled rope-strand tendons appear not to have failed, probably because their entire 3m length is contained within the fractured surround which is moving more-or-less 'en masse'.

Because the 10m long multi-cable tensioned tendons are anchored to an unmoving portion of the rock mass, they are subjected to the full elongation effect of the dilatation and stretched beyond their capacity. Sometimes the failure is in the form of slipping of the tapered collets at the collar end and sometime presumably by tensile failure of the strands. The steel base-plates have fallen away from the badly-damaged concrete pedestal on the centre-left of this view.

(m) View north of worst damaged sidewall about 10m beyond intersection with main fault. Completely collapsed 7m portion of tunnel is just beyond this portion. Note the 'spalled-off' nature of the rock fragments caught up in the overhead mesh.



(l)

(m)

3.3.1.2 Tunnel near steeply-dipping stopes

52 haulage, DRD mine

page 77

Introduction

It is often difficult to locate tunnels, which serve deep, steeply-dipping tabular ore-bodies, in zones where stresses are moderate or adequately relaxed by 'over-stoping'.

In 1977, a footwall haulage at a depth of 2700m was found to be badly damaged over a distance of 90m after 3 tremors occurred in the space of 5 minutes during the off-shift period. The local magnitudes of the two largest were recorded at Pretoria (some 60km away) as M_L = 2,1 and M_L = 2,0.

Stress measurements had been made some 15 years previously at a location 200m above and 500m further west. The maximum principal component of virgin stress was indicated to be 88 MPa inclined at 18 ° below horizontal in a NNW direction. The k ratio was 1,44. The quartzite is virtually free from joints with a UCS of 200 MPa.

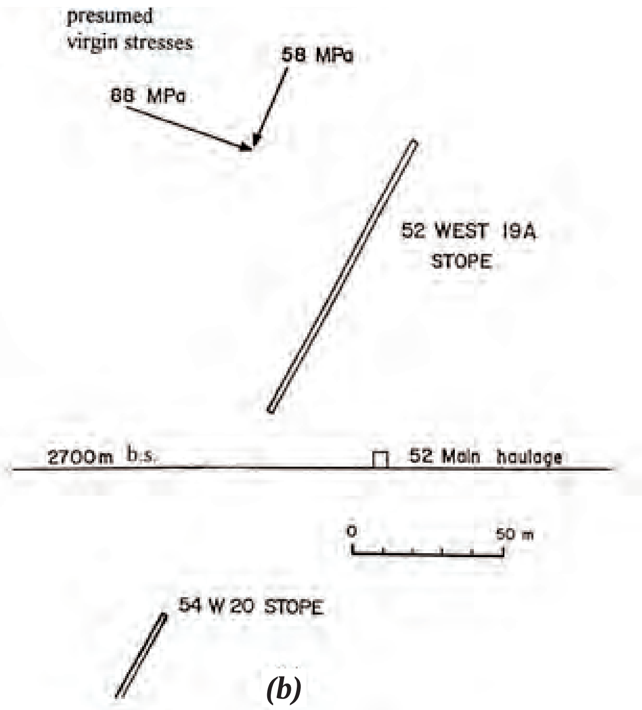
During over-stoping, large slabs had formed mostly in die south sidewall and a pattern of 20mm diameter end-anchored rock bolts had been installed. Steel arches formed from old rails had also been erected.

Captions

(a) Plan of affected area.

(b) Dip section viewed towards the west.

(c) View westward showing start of severe damage. Plumose traces and 'mirror zones' are visible in top right.



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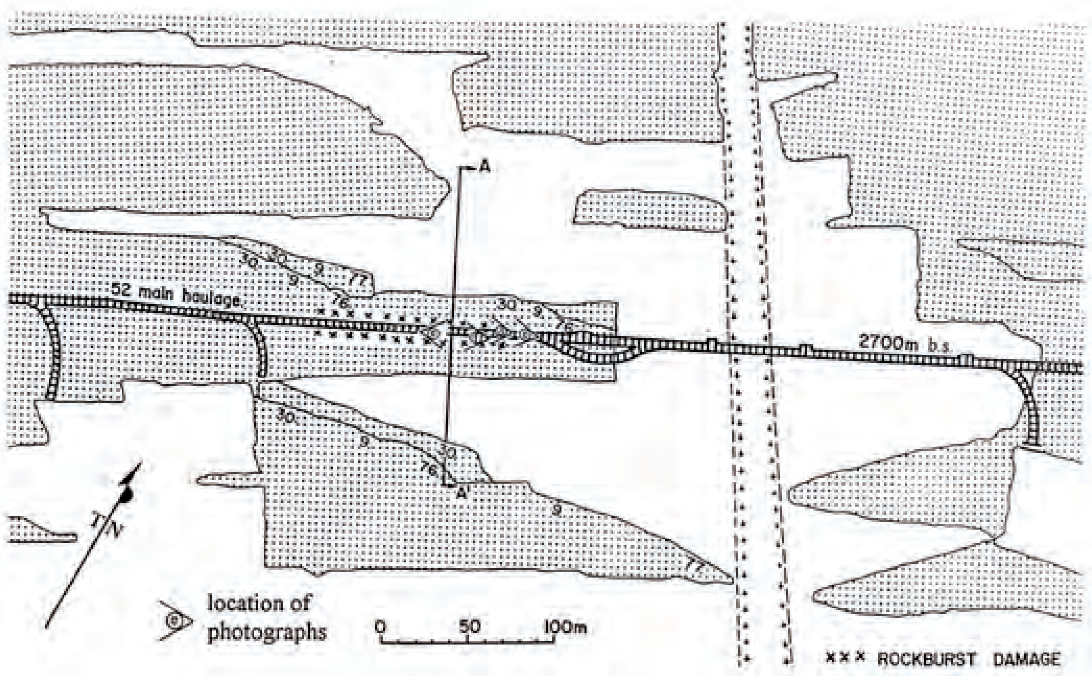


(a)

(c)

3.3.1.2 Tunnel near steeply-dipping stopes

52 haulage, DRD mine

Captions (continued)

(d) View westward showing typical mode of damage with large slabs ejected from roof and south side. Plumose traces on slightly conchoidal surfaces suggest that the extension fractures which separated these slabs from the rock mass above, had formed very rapidly. A vestige of a short length of circular arc immediately above the end of the wedge in the top centre of the photograph, may be a 'mirror zone' such as those described on page 19.

(e) View eastward from a point about 15m west of (d), showing abrasion in the dip direction down the steeply-dipping bedding plane on right. Note necking and tensile fracture of rockbolt protruding from collapsed rock pile in centre fore-ground.

(f) View westward from 6m east of (e). The 'bell-crank' dislocation of rockbolt in left reflects the bedding-plane shear movement described in (e). Apparently no shear movement occurred on the bedding surface which forms the now-stable surface on left.

Reference

W D Ortlepp. Rockbursts in South African gold mines - a phenomenological view. *Proceedings of the 1st International Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, SAIMM, Johannesburg 1984.*

(e)

(f)

page 78

(d)

3.3.1.2 Tunnel near steeply-dipping stopes

Second rockburst in 52 haulage, DRD mine

Introduction

Nearly 5 1/2 years after the rockburst described on page 77, with relatively little change in the local stoping configuration in the interim period, a rockburst caused further severe damage to 52 level haulage over a 90m length extending westward from a point about 50m west of the section damaged in August 1977.

Compared with other deep Witwatersrand gold mines, rockbursts occur very infrequently on DRD. The two rockbursts within one decade in the same area thus represent an unusual co-incidence. Although this suggests a common cause, the source mechanism remains totally obscure.

As before, the largest amount of rock came from the south sidewall where damage had occurred in a stable manner during the previous several years.

The local magnitude at Pretoria was M_L = 1,8. Although ejection of small fragments at very high velocity had occurred from the lower sidewall and floor, there was easy access along the north side. Thus the damage could be examined and photographed before any clearing-up was started.

To be able to obtain an undisturbed view of the entire spread of damage, was very unusual. Thus a comprehensive set of photographs was taken. An interpretation of the observed phenomena was published in the reference cited below.

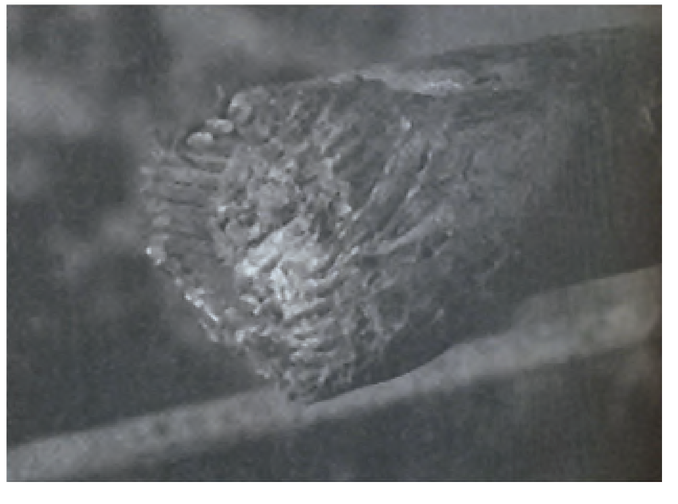
Captions

(a) View eastward from the western end of the damaged section.

(b) View eastward from about midway along severely damaged portion of tunnel. Large slabs have been thrust from the lower portion of the northern sidewall. The large pipe along the right edge of the photo carries chilled water for cooling the ventilating air. The insulation of 25mm thick foamed polystyrene covered by 1mm skin of tough PVC, was pierced by sharp-edged rock fragments and spattered with mud.

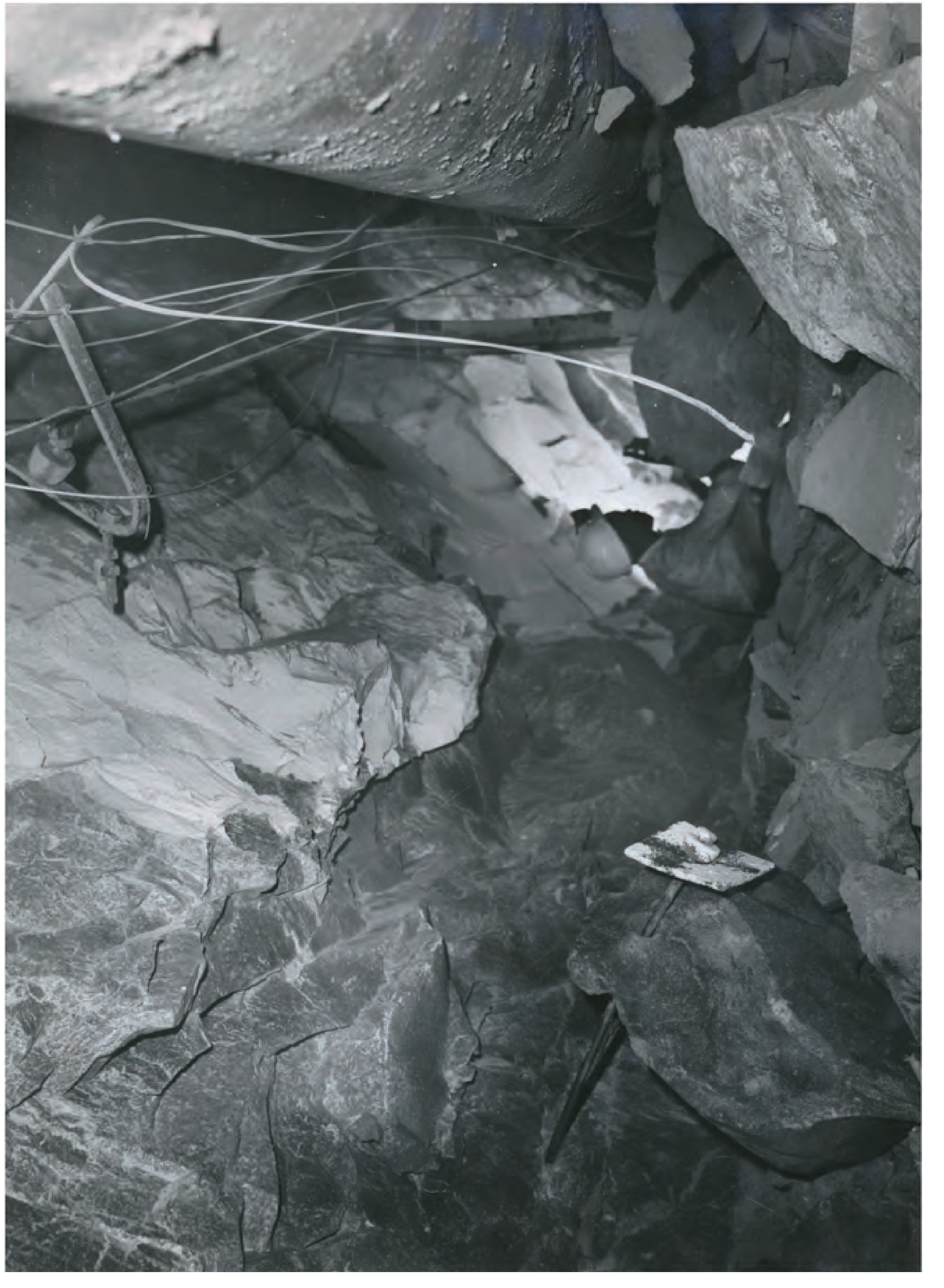
(a)

(c)



(d)

page 79



(b)

3.3.1.2 Tunnel near steeply-dipping stopes

Second rockburst in 52 haulage, DRD mine

page 80

Captions (continued)

(c) Close view of a piece of rock 'shrapnel' stuck into the lining.

(d) Detail of an armoured electrical cable severed by a larger rock fragment.

(e) View westward showing where cable was severed on lower portion of the northern side of the insulated column.

(f) View westward showing typical nature of the - a few large slabs were ejected from the lower northern sidewall while a much larger mass of smaller fragments have buckled away from the already statically damaged south side. These are mostly retained by the fallen chilled-water columns. In upper left of photo a lump of concrete is balanced on a strand of wire cable which was nailed to the upper end of a line of timber poles which formed a barricade against the south sidewall before the rockburst.

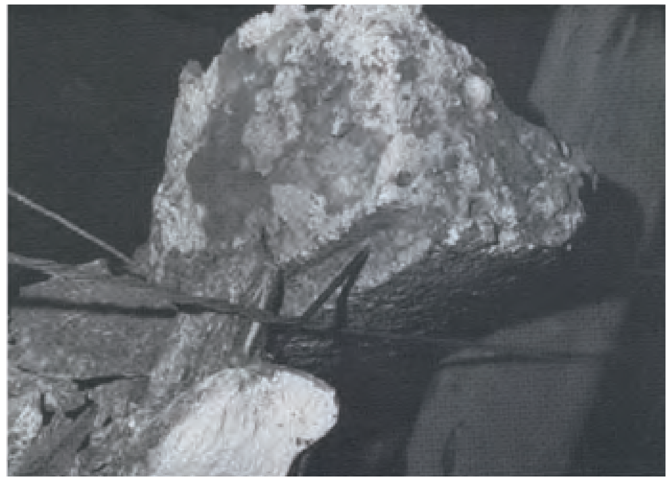
(g) Close view of the concrete fragment. The pencil pointer shows a rebate impression which located short planks of timber which formed the cover of the drain on the south side of the haulage track.

(h) Interpretative sketch showing the inferred trajectory of the concrete fragment. Consideration of the energy changes incurred by the fragment yields a minimum value of 8m/s, for the ejection velocity with which it must have been projected upwards at the instant of the rockburst if it had already broken away from the rest of the drain. If the drain was unbroken prior to the event, the impulse imparted to the drain by the seismic wave, which first had to break the drain into several pieces, could conceivably have generated a higher ejection velocity.

Reference

W D Ortlepp. High ground displacement velocities associated with rockburst damage. *Proc. 3rd Int. Symp. on Rockbursts and Seismicity in Mines.* Kingston, Ontario 1993.

(e)



(g)

(h)

(f)

3.3.1.3 Deep haulage parallel to fault

Introduction

In deep tabular mines where the gold distribution permits extensive longwall sloping, the main access for men, materials and ventilation and the removal of rock is provided by main haulage tunnels driven some distance below the stoped-out area.

Provided that they are not advanced ahead of the longwall faces into the highly-stressed abutment areas, such tunnels are generally considered to be immune to the threat of serious rockburst damage. The low stress environment below extensive worked-out areas affords protection until elastic convergence causes effective contact between hangingwall and footwall. However, there are features which can seriously compromise the stability of these tunnels. These are principally remnants and fault losses. A particular threat which may not easily be perceived, is the one presented by structures which extend along strike some distance away from, and parallel to, the haulage. An especially severe example occurred in a strike haulage at a depth of 2700m where a strike-aligned dyke/fault persisted for a distance of 6,5 km. The tunnel was at the same elevation but was never closer than 80m to the loss of ground caused by the fault.

The seismic event that caused severe damage to about 100m of the tunnel, had a magnitude of M_L = 4,0 and was located by the local mine network on the fault plane some 40m below the elevation of the tunnel and 80m north of the most intense damage.

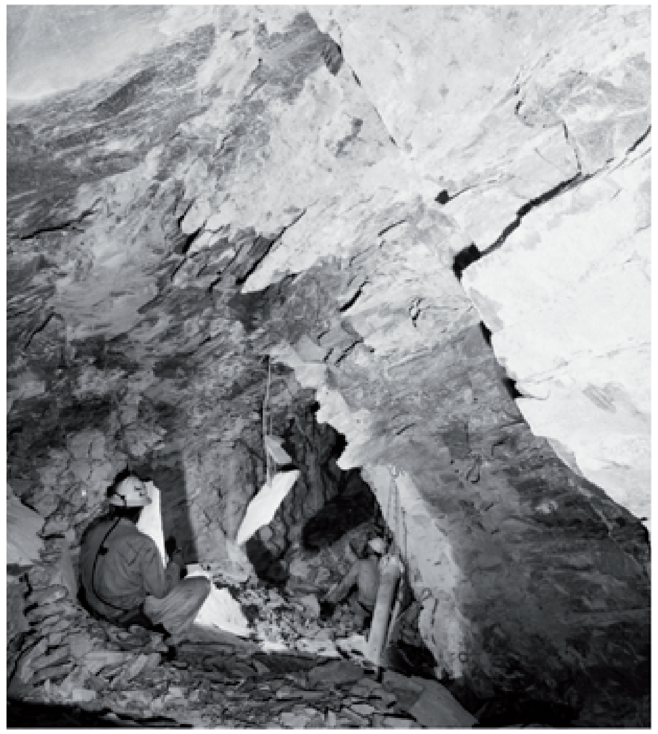
Captions

a) View westward showing recently installed mesh/lacing secondary support and the abrupt onset of the severe damage.

b) View westward some 20m beyond (a) where almost 2m of roof had been shattered. Much of the debris was in the form of almost uniformly sized, sharp-edged, slightly curved shards of rock.

c) Position of severest damage where the greatest loss of roof was perhaps conditioned by the conspicuous steep joints visible on the right. There was some indication that the rock debris was piled up more along the south side of the tunnel and that the horizontal transverse stresses were higher than the vertical. This seemed plausible in view of the fact that the tunnel was over-sloped directly above it and the fault-loss existed some distance away to the north, and at the same elevation.

(a)



(c)

page 81

(b)

3.3.1.4 Tunnels remote from stopes - Canada

Introduction

A further example of widespread and severe damage to tunnels caused by a large remote seismic event, occurred on a deep mine in the Sudbury Basin in October 1989. The magnitude of the event was reported as 3,6 Nuttli.

The origin, calculated from many geophones (which recorded only first arrivals), was hundreds of metres from the nearest extensive massive slopes. Such a large event occurring so far from a stope or major pillar is believed to be the result of slip on a fault. Slip may be driven by tectonic stress residuals, but it is triggered by relaxation of 'clamping' stresses following sloping in the area. Usually the location of the fault is not known and the extent of the area of slippage cannot be inferred from the distribution of the damage.

The event was believed to originate somewhere along a N-S shear parallel to a crosscut which was severely damaged by the rockburst. Rehabilitation of this tunnel by means of welded square mesh and rockbolts, is shown in fig (a). What appears to be a solid end to the tunnel is actually intense damage which resulted from a 1,6 M_N rockburst which occurred 18 months after the large event of Oct 1989. This ended the re-opening effort and the crosscut was abandoned.

An example of more typical rockburst damage was observed in the Timmins district in Ontario. Although only minor damage of a few tens of tons of ejected rock had occurred, good examples of a phenomenon which has far-reaching implications for tunnel support design were revealed. Several support tendons, including split-sets, had broken and, importantly, three grouted re-bars were broken in a brittle 'chalk-stick' manner. The strength of the re-bars is 5 to 20 times greater than the gravity load of the volume of rock attributable to each bar. The fact that the tendons did break is typical of rockbursts in all parts of the world and indicates that stiff grouted support is inappropriate where rockbursts or large static displacements may occur.

Captions

(a) View along a tunnel which was being rehabilitated after a large rockburst which occurred 18 months previously.

(b) General view of damage caused by a seismic event which had occurred only three days before the photograph was taken. Most of the debris was in the form of rather large fragments and blocks of rock.

(c) Close view of broken re-bar in ejected block of rock with an estimated mass of 200 - 300 kg. There is no 'necking' or decrease in diameter at the broken end of the tendon.

(d) Close view of 'chalk-stick' appearance of end of broken re-bar.

(c)

(d)

page 82

(a)

(b)

3.3.2 Rockbursts in Stopes

3.3.2.1 Collapse of roof at face

64^{W} K longwall, ERPM

Introduction

Frequently, a feature of the damage which results from a rockburst of moderate severity in a deep tabular hard-rock stope is extensive loss of hangingwall along the length of the working face with relatively little convergence in the excavation. Although the mechanism of the damage is often not obvious, there is usually clear evidence that distinguishes the collapse from a simple gravity-driven fall of ground.

In July 1967 a seismic event was located about 50m ahead and 50m above the plane of the 25 ˚ dipping longwall of a deep central-Witwatersrand gold mine (ERPM). The depth of the damaged stope was 2590 m below surface. The seismic energy released was estimated from the seismograms to be 15 MJ.

Captions

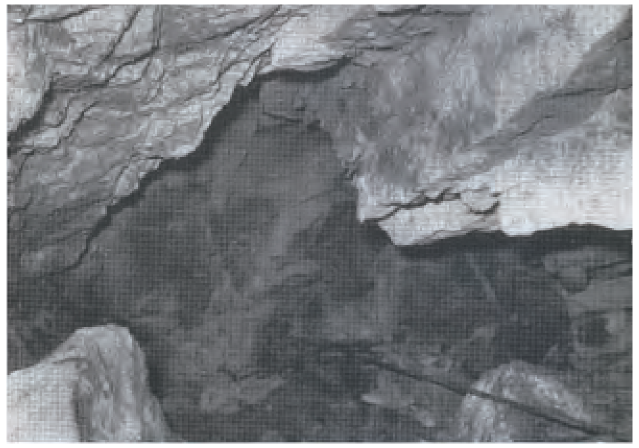
a) View up-dip parallel to stope face showing loss of triangular-shaped, extensive block of roof between the face and the front row of support. The fall is bounded by a near-vertical, pre-existing sheared surface on the right and afresh, jagged inclined surface extending backwards and upwards from the face. There is a small bed-separation at the apex. The support pack on the right has been compressed by about 250mm.

It appears as if the transient acceleration imposed on the unsupported part of the roof was sufficient to overcome the tensile strength of the rock material and tear away the triangular block along the jagged inclined surface.

b) View up-dip along the face, some 35m down-dip from (a) showing a similar loss of hanging wall above the scraper path.

c) Closer view of the 'choked' face area above fig (b). The wedge-shaped collapse appears to be bounded by pre-existing sheared surfaces on both sides and truncated by a bedding-plane about 1,2m above the original hangingwall plane.

(c)



(b)

page 83

(a)

3.3.2.1 Collapse of roof at face

64[W] K longwall, ERPM

Introduction

About three months after the event described on page 83, a rockburst caused relatively minor damage to portion of 66 stope on the east side of L longwall about 1500m to the east of the earlier event. The stope depth was about 150m deeper, at 2750m below surface.

A thickness of roof rock of 0,5 to 1,0m collapsed between the face and the first line of support over a face length of about 15m.

The seismic event which caused the damage was determined by the location network to have originated directly below the affected area at a depth tentatively estimated to be 150m. The seismic energy released was reported to be about 0.2MJ.

Captions

a) View down-dip at southern end of fallen area. Loss of roof was 0,5m bounded above by a smooth, low-cohesion bedding surface. The intensity of face-parallel, near-vertical extension fractures is quite typical for large-span tabular stopes at these depths. Permanent support comprises 150mm rise, 600mm long slabbed timber chocks built into 4-pointer skeleton packs.

b) View up-dip near northern end of affected area where about 0,4m of roof height collapsed. The limited compression damage to the timber prop installed as temporary face support indicates that co-seismic convergence was probably less than 50mm.

c) View up-dip near centre of damage showing greatest loss of the fractured rock bridge between face and front line of support. The separation from the weak 'false' roof is clearly evident. The presence of this surface and the magnitude of the horizontal stress in the 'bridge', are probably the most critical factors in determining its stability.

The timber pieces on left of photo were temporary cribbing installed during rescue operations.

(a)

(b)

(c)

page 85

3.3.2.2 Destruction of limited thickness of roof of stope

Blyvooruitzicht 6-10^W shaft pillar extraction

Introduction

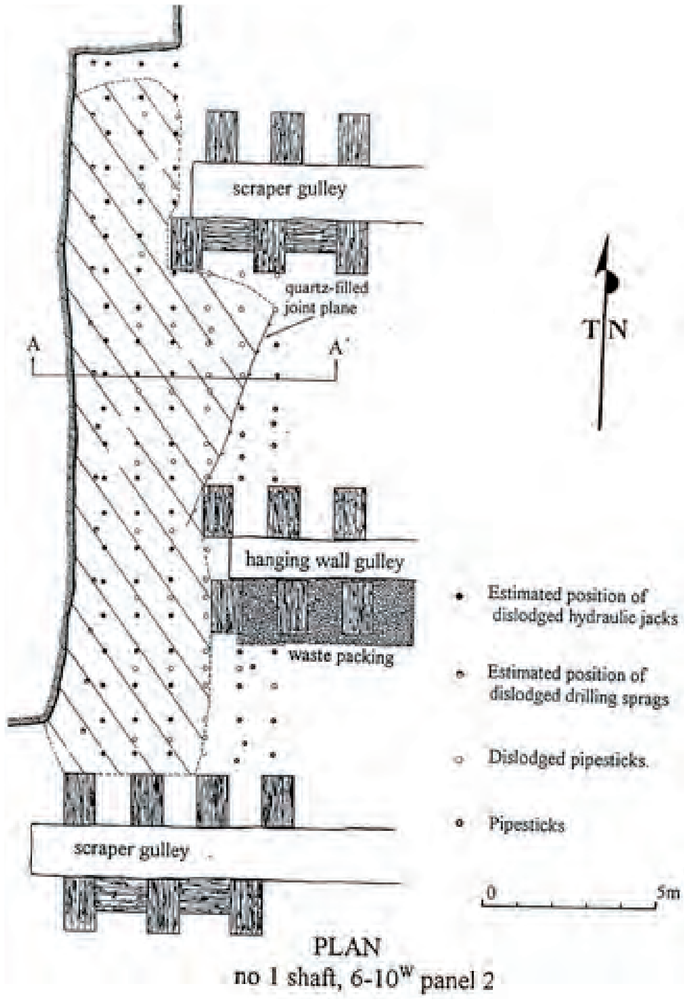
Perhaps the greatest enigma that is encountered in a serious study of rockbursts, is the apparent complete lack of correspondence between intensity of damage and amount of energy released seismically. Indeed the essential nature of the damage can vary widely even within the same geological environment.

Some 5½ years later, in the same stratigraphical layer and only about 2400m up-dip from the location of the devastating occurrence described on pages 90 to 93, a rockburst resulted from a seismic event of magnitude M_L = 1,9. This represents a release of seismic energy that was three orders of magnitude less than that of September 1977. The damage which resulted from the release of less than one-tenth of one percent of the seismic energy, was nevertheless significantly destructive.

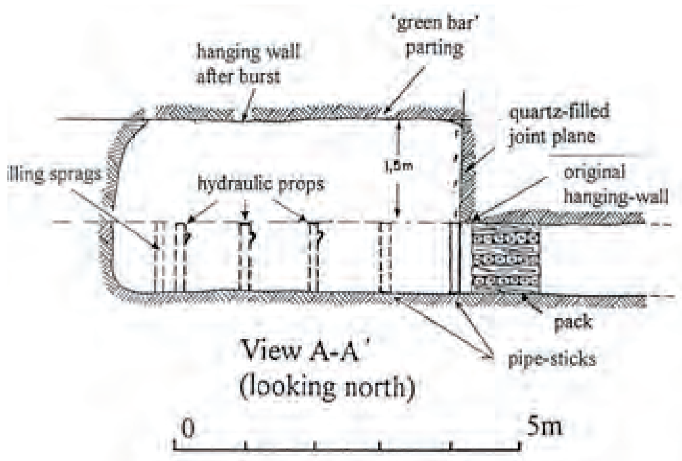
The earlier event was characterised by massive convergence with dramatic penetration of props into the footwall rock but with no breaking or loss of the hangingwall. By contrast, the incident described below caused very little convergence but the first 1,5m of roof strata was totally lost over most of the face working area of one panel.

This panel was the centre panel of a 65m mini-longwall dipping 22 ° southward and breasting towards a steep west-dipping fault with a 17m down throw on the west. The strike of the fault was sub-parallel to the stope face so that the lowest panel was 20m away and the top panel 45m away from the reef-fault trace.

In an effort to elucidate the source mechanism of this event, three further visits were made to the up-dip sloping which was started up to remove the remnant between the fault and the mini-longwall face that had been stopped after the burst. Observations made during the visits over the following months provided an interesting basis for speculation as to what might have been the possible reasons for the marked difference in roof behaviour between this event and the M_L = 4,0 rockburst in 1977. These observations are illustrated on pages 87 and 88.



(a)



(b)

(c)

3.3.2.2 Destruction of limited thickness of roof of stope

Blyvooruitzicht 6-10^{W} shaft pillar extraction

Captions

a) Plan of 2^{W} panel showing extent of collapse and original distribution of support.

b) Section at mid-length of 2^{W} panel.

c) View N-E of strike brow formed along edge of solid timber pack on south side of strike gulley of 1^{W} panel above. Two hydraulic props trapped in broken rubble can be seen, one virtually dead-centre of photograph and the other a short distance down-dip from it. Since they are in a near-upright position and not lying flat beneath an unbroken rock slab, the impression is gained that they may have punctured the immediate roof and been partly instrumental in its breaking up into smaller fragments.

(d) View N-E of dip-aligned brow formed by quartz-filled joint which limited the collapse along its eastern margin. The pinch-bar inserted into the bed-separation gap (centre top of photo) illustrates the weak and persistent parting between the immediate hangingwall and the 'green bar' above.

(e) View down-dip near toe of 2^{W} panel showing how the collapsed area is terminated by the solid timber packs in the north-siding of the strike scraper gulley. Two more props are visible trapped in near-upright positions.

(f) View down-dip into top of 3^{W} panel which is leading the toe of 2^{W} panel by 3m. The immediate roof is closely fractured by the normal face-parallel extension fracture planes but adequately supported by the rapid-yield hydraulic props.

(e)

(f)

page 86

(d)

3.3.2.2 Destruction of limited thickness of roof of stope

Follow-up observations in 6-10^W stope

Introduction

Following well-established practice, the remnant remaining between the 6 - 10 ^{W} 'mini-longwall' and the main fault to the west was mined out by means of a shorter, strike-aligned face mining in the up-dip direction - fig (a).

The first of three visits, attempting to elucidate the mechanism of the rockburst of 20 January 1983, was made when the north-advancing panel was abreast of the area of greatest damage viz. the centre of 2^W panel. A subsequent visit was made after a further face advance of about 7m and repeated after a further advance of 17m. On all three visits inconspicuous, steep-dipping faults parallel to the main fault were observed close to the western end of the panel. These were all clean-cut discontinuities with negligible displacement.

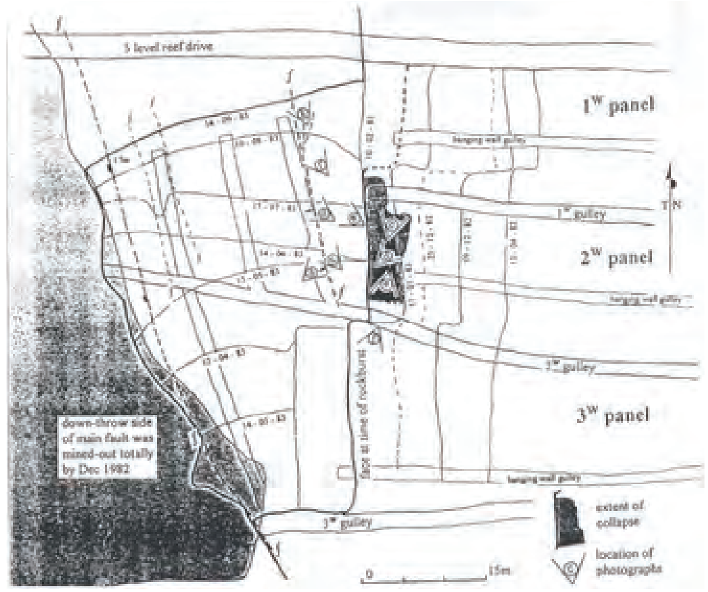
Contrasting strongly with these insignificant features, there was a flat westerly-dipping fault also with small normal-sense displacement, near the east end of the panel. This fault was characterised by the presence of a very finely comminuted, fresh-looking gouge of varying thickness of up to 10mm which strongly suggested recent movement along the discontinuity. Samples were taken for SEM analyses but unfortunately there was no report back of any results.

Captions

a) Plan of remnant showing monthly progression of 'north-facing' and position of discontinuities and of photographs.

b) View of flat fault near east end of panel. Dip-aligned extension fractures parallel to now-abandoned 2^W panel seem to be more intense below fault plane than above it.

c) Closer view of fault at point of maximum development of fresh gouge. Sense of displacement is normal with lighter coloured footwall rock exposed on right of fault.



(a)

(b)

(c)

page 87

(d)

3.3.2.2 Destruction of limited thickness of roof of stope

Follow-up observations in 6-10^{W} stope

page 88

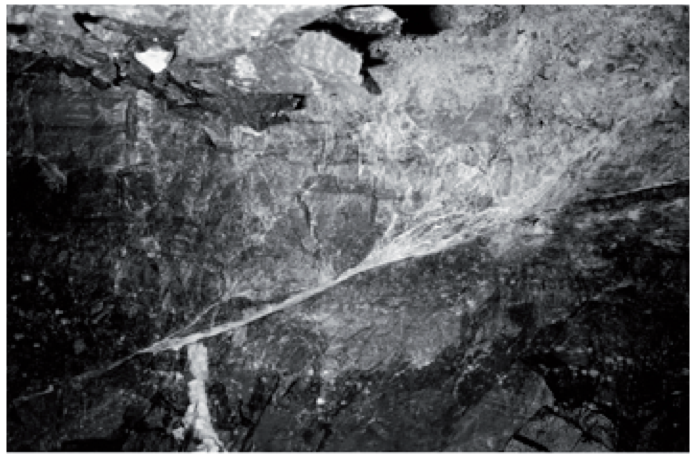
Captions (continued)

d) Close view further east along fault trace.a Note that the minor 50 °-dipping structure behind the clino-rule also appears to show normal displacement.

e) View west from eastward end of north-face. Upward extension of flat-fault is exposed in roof as crushed, whitened zone which appears to merge with lower contact of green bar which is exposed above the crush pillar separating the north face from the abandoned breast face of 2^{W} panel.

f) View northward of flat fault two weeks later after about 7m advance. Fresh gouge is well developed near stope floor where a steeper-dipping secondary shear zone merges with the flat fault. A similar steeper secondary shear is also seen in (d).

g) View northward about one quarter of face length away from east end of north face about 10 weeks later showing that the flat fault persisted for another 15m at least.



(f)

Speculation

If, for some intrinsic reason associated with the original faulting process, a significantly high residual stress existed ahead of the 6-10 longwall with the major principal stress aligned horizontally E-W, then the shear component along the minor flat fault could have promoted shear slip along this surface as the approach of the 6-10W longwall provided relief for the 'clamping' normal component. The possible planar conjunction of this slip-failure surface with the green-bar contact might have caused the major seismic response to take the form of surface waves (Rayleigh or Love waves) rather than body waves. Trapped in the quartzite middling between the immediate stope roof and the green bar contact 1,5m above, and amplified by the local site effect, these waves were the transient stresses that simply shattered the roof of 2W panel.

(g)

(e)

3.3.2.2 Destruction of limited thickness of roof of stope

Non-stratified rock

Introduction

An even more graphic illustration of rockburst damage that was confined to the immediate roof layer of a stope, but which demands a more appropriate description than is implied in the term 'rock fall', was observed in 1991 on a nearby mine.

The roof rock was the strong brittle lava hangingwall of the Ventersdorp contact reef which is notoriously difficult to support adequately under rockbursting conditions.

Unlike the case described on pages 85 and 86 where the evidence of sudden destruction of the stope hangingwall was inferred from the attitude of only a few hydraulic prop supports, in this case the behaviour of many tens of support tendons argued strongly, even incontrovertibly, for the same explanation -- a very high, in-plane, stress transient.

The roof of the strike-aligned tunnels above and below the 30m long stope face had been supported with a close pattern of friction-anchored rock stabilisers and fully grouted 'shepherds-crook' re-bars. Almost without exception these support tendons remained fixed in the roof, albeit by only a small traction of their original embedded length. Only a few had single blocks or smaller fragments of rock attached to them. The greater majority were 'stripped' clean of any trace of the rock that had, up to the instant before the rockburst, surrounded each tendon and filled the entire space between them. The undamaged bearing plates of the split-sets and the undistorted crooks of the re-bar denied any possibility of rock fragments sliding off because of inadequate grouting or insufficient friction. Yet more than one metre thickness of rock which, although somewhat fractured could not be described as intensely-jointed before the event, had disrupted into small fragments and virtually 'evaporated' away.

Captions

a) View eastward along lower tunnel. Three support tendons are dislodged while 18 remain fixed in the roof.

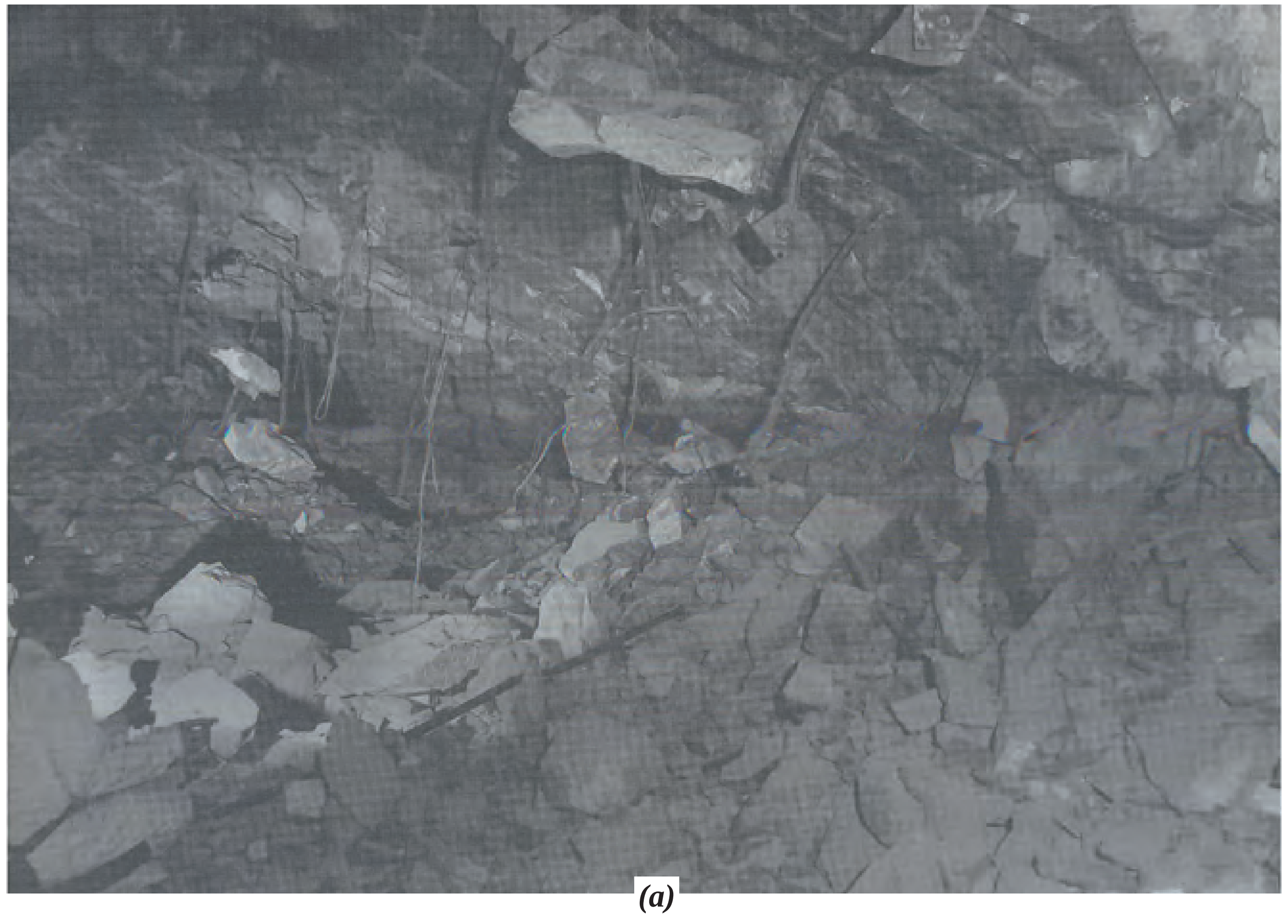
b) View eastward along upper tunnel just east of top access into the stope. The majority of tendons are stripped bare.

c) View down-dip along slope face showing absence of damage to slope face while there has been a considerable loss of fragmented roof 5m hack.

Face fracturing is clearly visible, with no buckling of slabs. Very little convergence has occurred over the temporary face support. Strongly-developed and closely-spaced E-W and NE-SW jointing is clearly visible in the lava hanging wall, as well as bedding-parallel 'jointing' between packs on right.

(c)

page 89



(a)

(b)

3.3.2.3 Massive convergence near geological structures

Blyvooruitzicht B2^E longwall

Introduction

The circumstantial association of severe rockbursts with large geological structures would probably be found to have strong statistical significance if all the data were available and could be subjected to proper analysis.

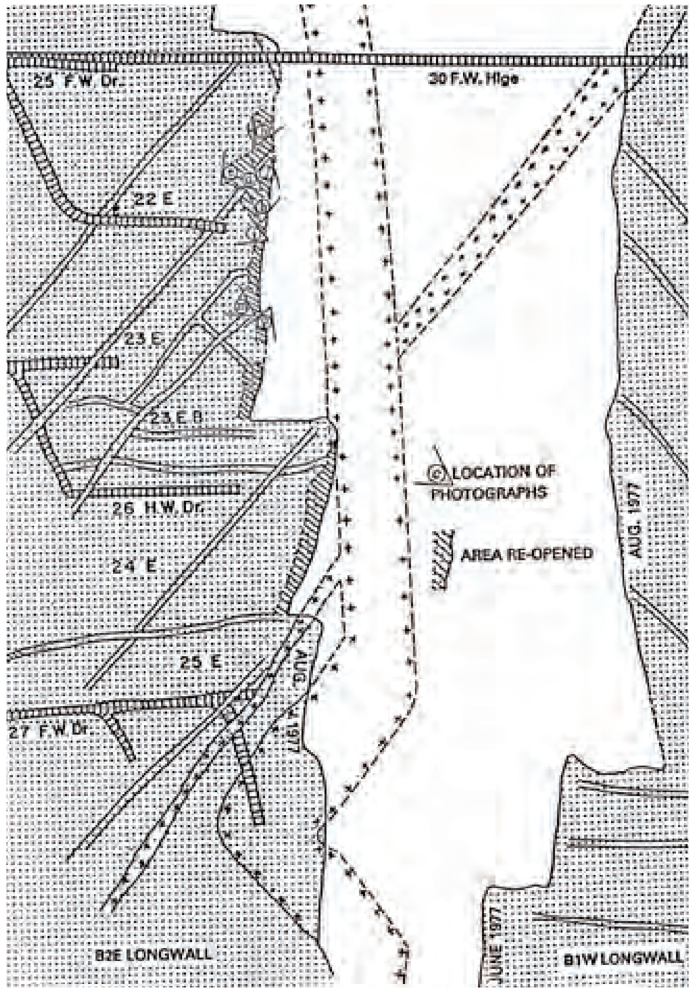
One of the most vivid instances of this kind occurred in the far-West Witwatersrand goldfields in 1977. Although it has been briefly described before by Ortlepp (1984), a more complete disclosure might enable greater insight into cause and mechanism, if reviewed in the light of current knowledge.

At 10:35 on 2nd September, 1977, a very severe tremor was felt on Blyvooruitzicht gold mine in the Carletonville district. Based on information from the WWSSN station at Pretoria, the magnitude of this event was estimated to be ML = 4,0. The accompanying rockburst caused catastrophic damage to sloping in the lower east side of B2 longwall at a depth of 2200m below surface. During the third quarter of 1977 the long narrow abutment between the lower portions of B1^W and B2^E longwalls was about 100m wide. It contained a 20m wide dyke aligned in the dip direction, as shown in fig (a).

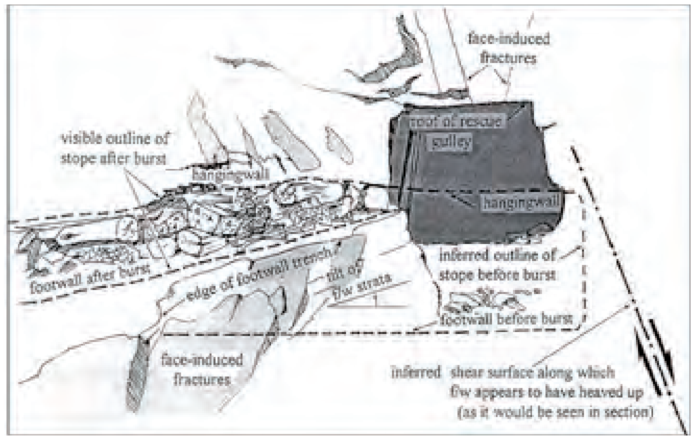
The estimated stress, from a numerical analysis (MINSIM) averaged over a 15 x 15m unit area ahead of the lower four panels, was typically 400 MPa and the energy release rate (ERR) was 65 MJ/m^2.

All sloping on the west side of Bl longwall had been stopped to prepare for extraction of the final remnant by north-facing once the B2^E- stopes had stripped out against the dyke.

The most severe damage occurred over 180m of B2 causing complete closure of the bottom four panels.



(a)



(c)

page 90

(b)

page 91

3.3.2.3 Massive convergence near geological structures

Blyvooruitzicht B2^E longwall (continued)

Captions

(a) Plan of peninsular remnant between B1 and B2 longwalls. Stippled area is sloped out at original working height of about 1m on Carbon Leader reef dipping at 22° southward.

(b) View up-dip along rescue gulley cut along face.

(c) Interpretative tracing of (b).

(d) View up-dip from just above diagonal scraper gulley of crushed pack estimated to be about 6m from inferred position of stope face. Prop is the same as seen in foreground of (e).

(e) View NE showing that the up-dip edge of the pack is crushed down to about 100mm. Timber slab on left edge of photo is seen in fig (d) to be the lower member of the down-dip side of the pack which was compressed to about 220mm. Very little roof has been lost and footwall appears to have converged upward in a shallow undulation.

(f) Detail of nearer prop which has penetrated the footwall by a minimum of 270mm. The footwall strata are distinctively lighter in colour than the hangingwall rocks. The UCS of intact footwall rock is 200 MPa.

(g) Detail of the more distant prop of (e) where the penetration was at least 240mm. This shows clearly that there was no 'indentation rim' and that the rock material, surrounding the buried prop was not pulverized. Further speculation on this remarkable and inexplicable phenomenon is given in Ortlepp (1993).

(g)

(f)

(d)

(e)

Blyvooruitzicht B2^E longwall (continued)

Captions (continued)

(h) View North-westward from about midway down 23^E panel showing crushed packs in first line back from face.

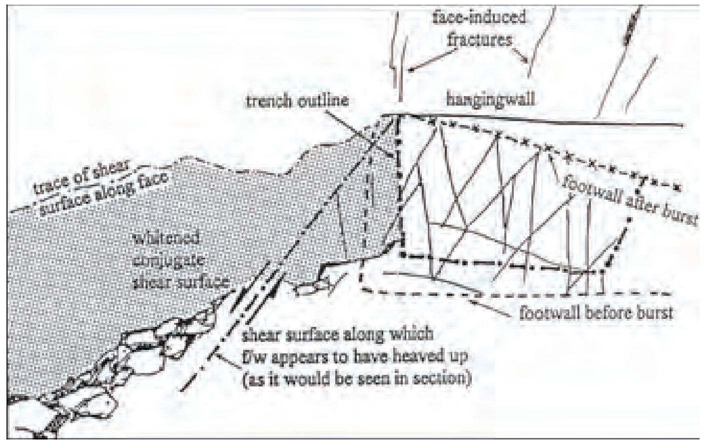
(i) View up-dip of eastern wall of rescue gulley alongside face showing footwall thrust up against roof on centre left. The 'hackly' surface on upper right of the main photo probably indicates the plane of the shear surface along which the upward thrust of the footwall occurred.

(j) View down face showing a very comminuted, 'slickensided', undulating surface dipping steeply down to the right. This is believed to be conjugate to the main displacement surface along which the footwall heave occurred. The spot just right of centre where the footwall can be seen to be buckling outward from its 'point of impact' with the roof, is the same spot which is highlighted in centre left of (i).

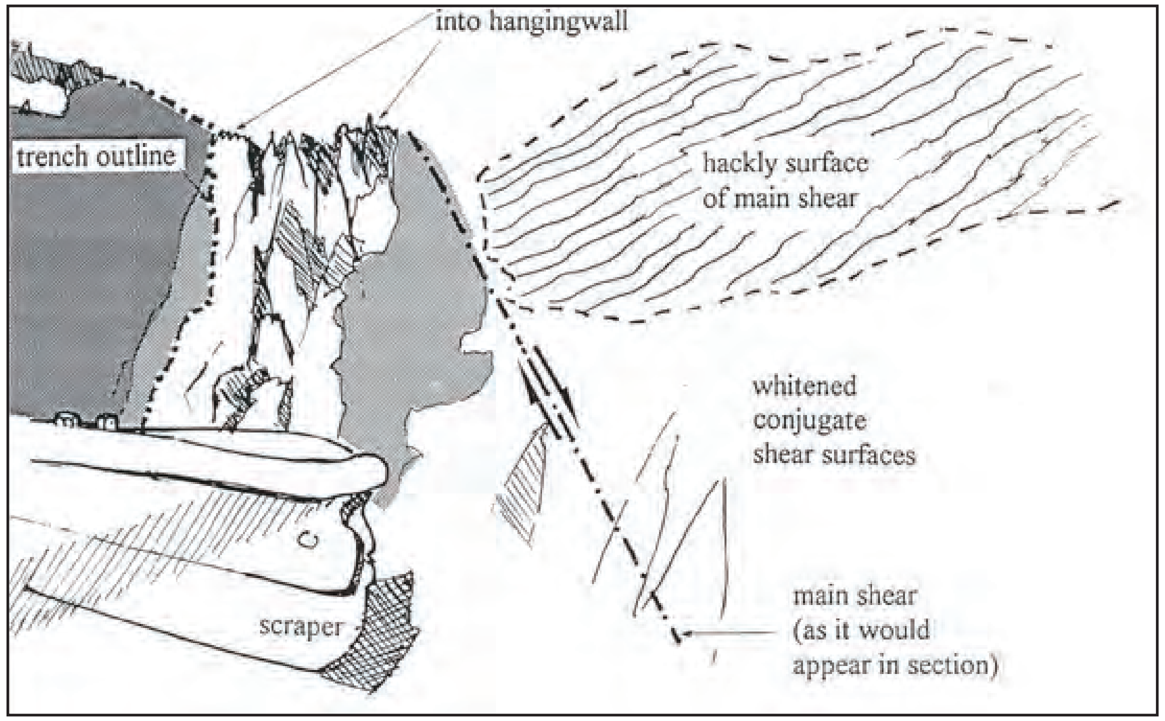
(k) Explanatory sketch of photo (j).

(l) Interpretative tracing of photo (i). Compare the texture of the hackly surface with photos (b) and (d) on page 49.

(j)



(k)



(l)

(h)

(i)

3.3.2.3 Massive convergence near geological structures

page 93

Blyvooruitzicht B2^E longwall (continued)

Captions (continued)

(m) View north-westward into trench cut into fully-converged area at lowest portion of 23^E panel. Portion of a rapid-yield hydraulic prop which has completely penetrated the footwall rock is visible at end of trench. This appears to be the extended ram of the prop and not the outer cylinder. The distinctive colour difference between hangingwall rock and footwall strata is clearly visible.

(n) Detail of penetrated ram in (m).

(o) Interpretative tracing of (m) outlining a small 'scree-slope' of fine pulverized rock which presumably represents the material displaced by the penetration of the steel ram of the prop. It was the absence of such pulverized material that is puzzling in the case of photo (g).

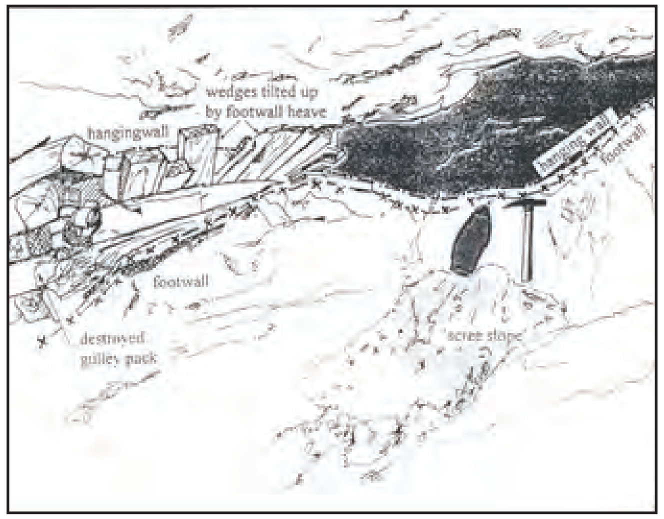
(p) View down-dip slightly away from face-direction at upper end of 24^W panel showing complete closure with scraper ropes caught up against the roof. One of them seems to have been severed. It appears likely that this panel had been blasted at the end of the previous shift and not yet been cleaned at the time of the burst.

Reference

W D Ortlepp. Rockbursts in South African Gold Mines. A Phenomenological view. *Proc. 1st Int. Symposium on Rockbursts and Seismicity in Mines*. SAIMM Symp. Series No. 6, Johannesburg 1984, pages 165 - 178.

W D Ortlepp. High ground displacement velocities associated with rockburst damage. *Rockbursts and Seismicity in Mines 93, Proc. of 3rd Int. Symposium.* Kingston, Ont. August 1993. pages 101 - 106.

(n)



(o)

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3.3.3 Rockburst of Remote Origin

3.3.3.1 Rockburst of remore origin

ERPM 78 Hercules footwall winze (i)

Introduction

At times rockburst damage is observed in unexpected places or is located far from the origin of the seismic event which is believed to have caused the damage. The cause-effect association is usually made when both are known to have occurred at the same time.

Over a period of 10 months three instances were observed on the Hercules section of ERPM mine which illustrate this aspect of rockburst phenomenology. The circumstances have been previously detailed (Ortlepp 1984) hut are worthy of further illustration.

All three incidents caused significant damage to a 115m long winze pre-developed on true-dip about 9m below the plane of the reef. The east and west advancing faces of 78 stope were opening up the first level below a 600m long strike abutment 3380m below surface. The stope was over-stoping the winze but not quite symmetrically. A numerical analysis (MINSIM) estimated that the maximum principal stress ahead of the stope panels would range from 125 MPa at the lower end of the winze to 195 MPa at the upper end 10m below 77 abutment. These theoretical stresses were the average values over 10m grid blocks.

In each case the stope, only a few metres above, was completely unaffected and the intense damage in the winze mainly affected its sidewalls. Damage in the roof was absent or appeared to be a secondary effect. The upper 10m of the winze which was traversed by strike-parallel extension fractures induced in the highly stressed abutment, suffered no damage at all.

Captions

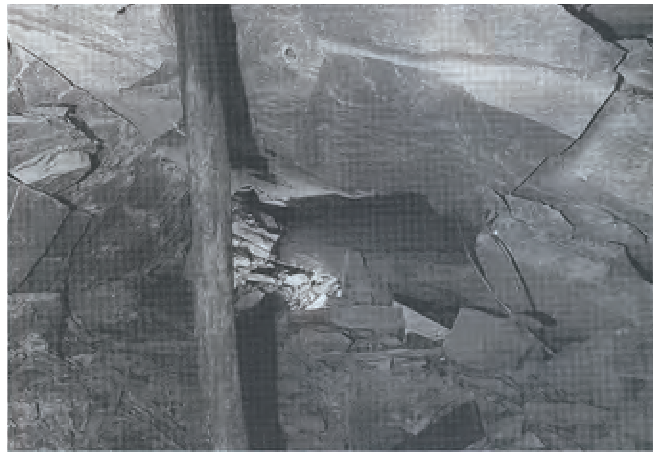
(a) View southward of complete collapse in the winze extending for 13m beyond a point 8m down-dip from the lowest transverse extension fracture. This damage was discovered by the night shift on 12 October 1971 some hours after a M_L 1,7 seismic event was recorded at about blasting time by the Pretoria WSSN seismic station, with a seismic signature characteristic of an event of ERPM origin.

(b) View up-dip of lower extent choked portion of 78 waste-winze. Several failed rockbolts are visible.

(c) Close view of 'rippled' texture on the concave surface of hangingwall from which the large slab visible in centre background of photo (a) appears to have been violently torn away.

Reference

W D Ortlepp. Rockhursts in South African gold mines: a phenomenological view. *Proc. 1st Int. Symp. on Rockhursts and Seismicity in Mines. SAIMM Symp. Series No. 6.* Johannesburg. 1984.



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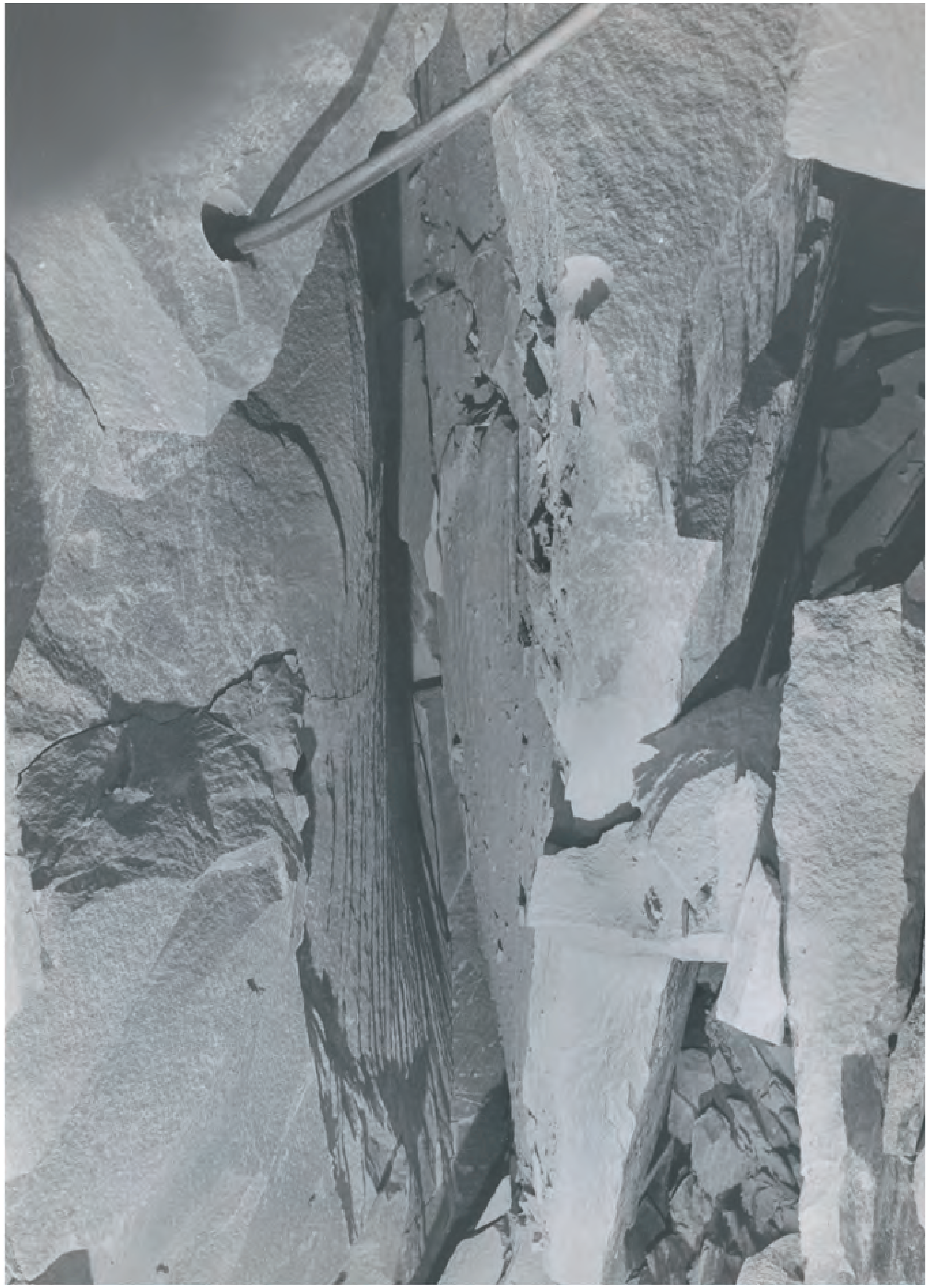


(c)

3.3.3.1 Rockburst of remore origin

ERPM 78 Hercules footwall winze (i)

Introduction

At 22:45 on 4 February 1972 a large seismic event caused widespread and, in places, intensive damage in the lower portion of Hercules longwall on ERPM.

The magnitude of the event was estimated from the Pretoria station records to be M_L = 2,9. The origin was located by means of geophones of the local underground seismic network at a point 500 m N-E of the winze near the top of 75^E stope and some 5 m above the reef plane in elevation.

Although 75^E stope was badly damaged, the intensity of the damage diminished with distance from source. The vulnerable top corners of 761^E and 77^E slopes further down the longwall had suffered minor falls and the footwall drives and cross-cuts on these levels were undamaged. Still further from the source, 78 stope itself was completely unaffected but the waste winze immediately below was severely damaged.

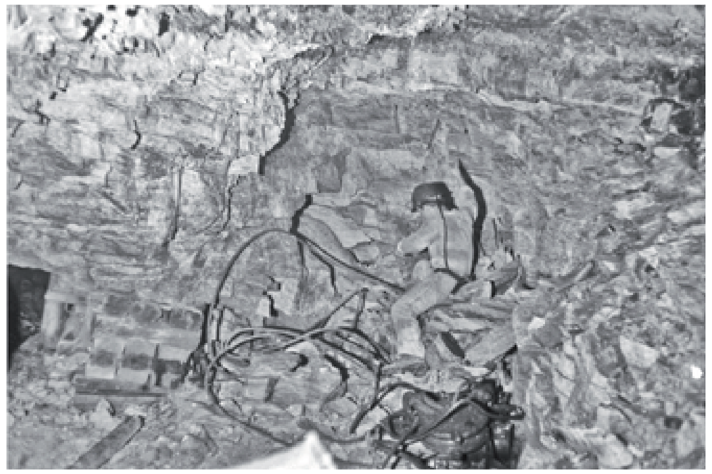
Captions

(a) View northward from about 30m down-dip from upper end of 75^E stope showing complete choking between face and first row of pack support about 2m back. Approximately 1,3m of quartzite roof has collapsed up to the base of the 'chert-dyke', a sill-like felsitic intrusive above the reef.

b) View down 78 waste winze showing severe buckling damage to the roof and fracture of some of the rockbolts.

c) Plan and section of 78 Hercules stope and waste-winze, showing location of rockburst damage.

d) General view of the top portion of the winze showing extent of loss of roof as a result of the cumulative effect of 3 rockbursts.



(a)

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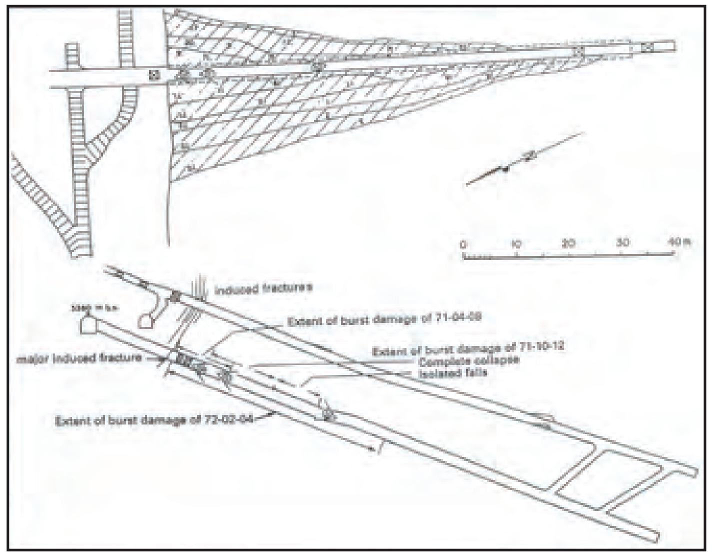

(c)

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(d)

3.3.3.2 Rockburst of remore origin

Multiple-source episode

Introduction

A rockburst is not always the consequence of a single, large and violent release of energy. The following description records some of the essential features of an episode which possibly provides the best example of a multiple-source set of related damaging events that has ever been documented on any mine.

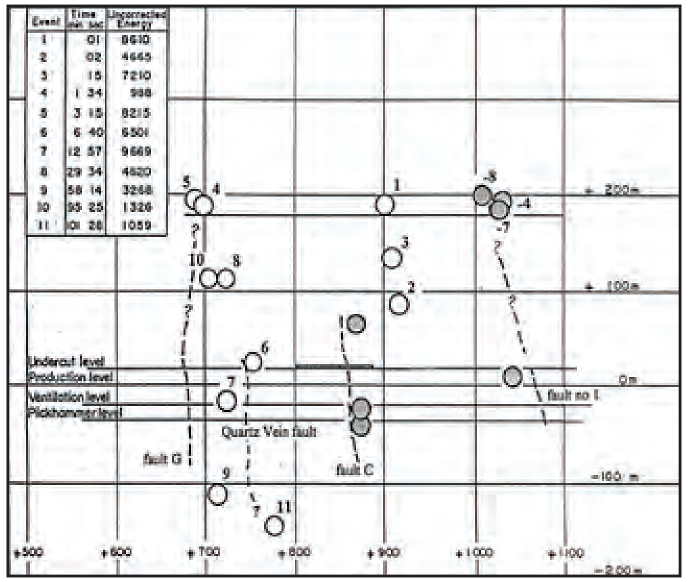
The occurrence, times and locations of the several hundred sub-events that followed the Richter 4,0 main event were recorded by means of a seismological network that provided accurate locations by virtue of a large number of seismometers spread over a good three-dimensional configuration.

A rough distance-dependant relative energy number was the only other information that could be derived from the records. The 10 events with the highest energy numbers were located on the mine plan and their relationship to damage distribution and to the known geological structure was studied. The largest sub-event (no 7) occurred 13 minutes after the main event, and the tenth sub-event 88 minutes later.

Captions

(a) Plan view of cross-cuts on the pick hammer level showing the four most prominent of several major E-W striking, steeply dipping geological structures. N-S and NW-SE structures were also well developed but somewhat less so than the E-W trend. The extent of the blasting of the undercut level to initiate the panel caving process is shown by the cross-hatching. The main and sub-events are identified in the sequence in which they occurred, by the consecutive numbers in the plotted circles. The adjacent 2 to 3 digits indicate their elevations relative to the production level which is at 2100m above sea level.

(b) Vertical NS section on + 900 E showing projected locations of sub-sources no. 1 to no. 11

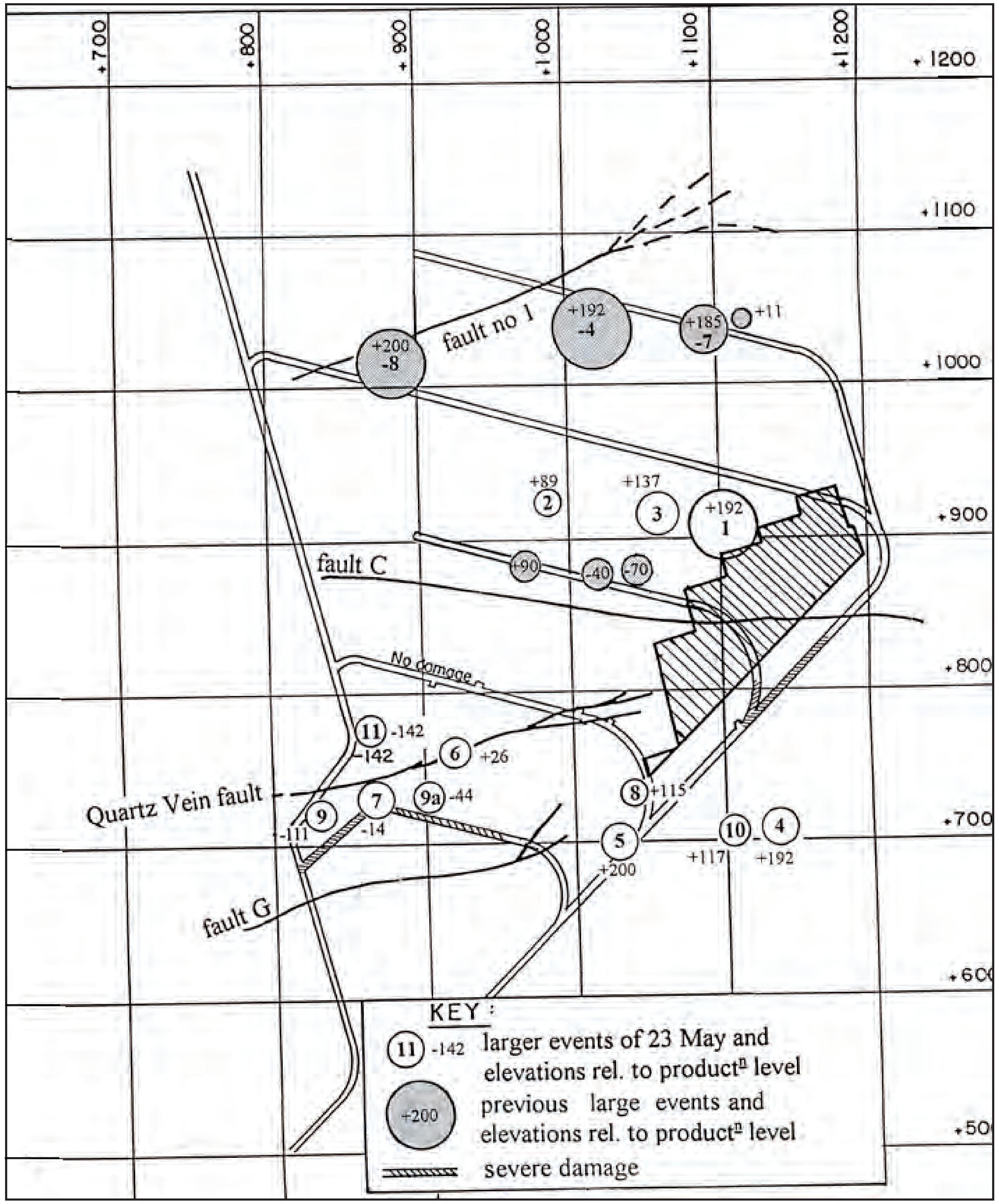


(b)

and some previous significant events, including three large events, also plotted in (a) and identified as numbers -8, -7 and -4, which occurred at the same elevation as the main event no. 1 and just 8, 7 and 4 days respectively earlier than it.

No damage was reported for these earlier seismic events probably because of their considerable elevation above the working levels. Similarly, only minor damage was recorded on the production level beneath the locations of the main event (no. 1) and the large sub-event (no. 3) which followed 15 seconds later.

It is believed that because of its close proximity to the 'quartz vein' fault and to the working levels, the strong 'aftershock' (no. 7) was the cause of the intense damage in photographs (c) to (i). It is likely that the source mechanism was one of shear slip on the quartz-vein fault. This was possibly triggered by a 'stress transfer' following the relaxation of stress that accompanied the release of the stored strain energy resulting from the initial movement (main event no. 1) on some structure (possibly parallel to fault C) some 200m away.



(a)

3.3.3.2 Rockburst of remore origin

Multiple-source episode

Captions (continued)

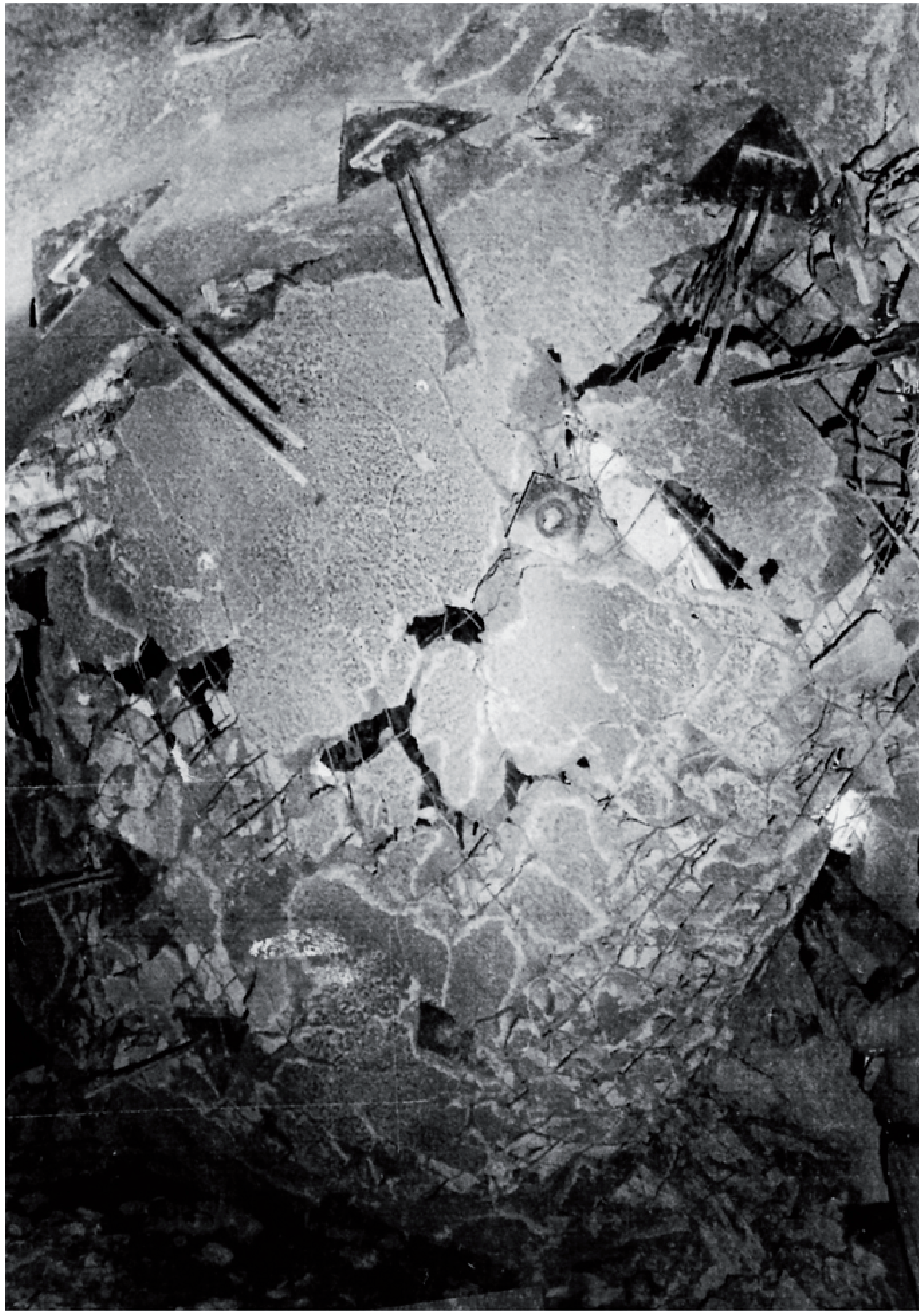
(c) View westward in pick hammer cross-cut at coordinate 700N, 950E showing the first of three repeated localized 'eruptions' of intense damage of the south sidewall. In each case a few metres of undamaged support separated these zones of damage. West of the third zone, continuous damage of the south wall prevented further examination. As far as it was possible to gain access to examine the tunnel, it appeared that the north side of the cross-cut was not damage at all.

(d) View eastward of the western edge of the first eruption or 'spall' of intense damage in the mesh-reinforced shotcrete lining of the pick hammer tunnel. One broken 500kN stressed cable anchor is visible in upper right foreground of photograph.

(e) View eastward of the western end of the second 'eruption' of intense damage. The containment effect of the mesh-reinforced shotcrete cladding was sufficiently strong to break at least two grouted 22mm diameter reinforcing bars and two 500 kN stressed cable anchors.

(d)

(c)



(e)

3.3.3.2 Rockburst of remore origin

Multiple-source episode

Captions (continued)

(f) On production level, viewed south-westward along access roadway towards intersection with rock-haulage roadway at coordinate + 740N, +850 E - fig (a). The "quartz-vein" fault, as plotted on the geological plan, was shown to pass through this point although its actual intersection was not visible because of shotcrete and the concrete lining between steel arch support. The most conspicuous damage, right foreground, was upheaval of the floor in the future drawpoint, which was paved with 1 metre thick concrete. Interestingly, the floor of the production drift which consisted of compacted ballast, did not suffer noticeable damage.

(g) Detail of damage to steel arches and concrete lining in future drawpointjust beyond the illuminated spill of disrupted shotcrete from obtuse corner of intersection in centre background of photo (f). The overthrust of concrete slab on the left suggests that the 'quartz vein' fault passes through the sidewall at exactly this point with sense of movement being normal dip-slip.

(h) View eastward of footwall heave of massively thick concrete floor of ventilation cross-cut at approximate coordinates + 750N, + 1000E.

(i) View northwards along future drawpoint at coordinates +710N, 815E on production level showing complete collapse of unlined portion of tunnel where support consisted of grouted reinforcing bar, steel mesh and shotcrete.

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(g)

(h)

(i)

(f)

David Ortlepp graduated in mining engineering at the University of Witwatersrand in Johannesburg, South Africa in 1952. After a brief period as a graduate learner on a deep level gold mine he continued his education at McGill University, Montreal, Canada. Based on laboratory research into the shear strength of Witwatersrand quartzites a masters degree was awarded magna cum laude, in 1957.

After a further short spell as miner and shift boss, he commenced applied research studies into strata movement with Rand Mines Ltd. Some 6 years later an important formative period of his career commenced with his appointment as the Rock Mechanics Engineer on East Rand Proprietary Mines which involved him largely with the underground operations of what was then the deepest and largest deep mine in the world. After 8 years on ERPM he became the Group Rock Mechanics Engineer for Rand Mines Ltd. He later spent 5 years with Anglo American Corporation in a similar capacity. He had then acquired 33 years of experience in deep and ultra-deep mining. During this long period of involvement with deep level rock mechanics he documented and studied, to greater or lesser degree, some 130 rockbursts.

During a brief spell as lecturer at the Witwatersrand Technikon he joined Steffen, Robertson and Kirsten as an associate consultant in 1990, a position he still holds. This association afforded valuable opportunities to continue his studies ofrockburst problem in Australia Canada Chile and the USA.

In 1995 he was awarded the MDG Salamon Prize by the South African National Group on Rock Mechanics (SANGORM).