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IN-SITU MONITORING AND COMPUTER MODELING OF A CEMENTED SILL MAT AND CONFINES DURING A TERTIARY STAGE PILLAR RECOVERY

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ABSTRACT

This report outlines a diamond drilling technique, developed to extract relatively undisturbed core samples of weakly consolidated hydraulic mill tailings backfill, together with results from in situ and laboratory material quality tests. Work using a numerical model for simulation of an underground backfill structure is also reported.

In the process of this study, backfill coring techniques were developed at Falconbridge's Lockerby Mine. Material quality determinations were then done on the backfill core samples to obtain the value for: Dry bulk density, moisture content, cohesive strength, angle of shearing resistance, uniaxial compressive strength and pressure modulus. The resulting drill holes in the fill were then used to accommodate soil extensometers, geophones and Glotzl cells. These instruments were used to monitor the backfill's behaviour as mining progressed adjacent to the fill. An ultrasonic measuring device was also used to help profile the fill failure that resulted. The data obtained from the material quality determinations and in situ instrumentation was used to numerically model the backfill behaviour when subjected to loading due to adjacent mining.

The results of this work indicate that it is possible to obtain up to 95% undisturbed core samples from even weakly consolidated backfills. It was also shown that, with accurate calibration of presently available numerical models, representative modeling of backfill structures within an active mining environment can be carried out.

RÉSUMÉ

Ce rapport présente une technique de forage au diamant développée pour extraire des échantillons de carottage relativement intacts d'un remblai hydraulique composé de résidus de concentrateur peu consolidés. On présente aussi les résultats d'essais de qualité des matériaux in-situ et en laboratoire, ainsi qu'une modélisation numérique pour simuler une structure souterraine de remblai.

Au cours de cette étude, les techniques de carottage pour remblai furent mises au point à la mine Lockerby de Falconbridge. Les mesures de qualité des matériaux furent prises sur les échantillons de carottage de remblai, dans le but de déterminer les paramètres suivants: poids volumique sec, taux d'humidité, force de cohésion, angle de résistance au cisaillement, résistance uniaxiale en compression et module de pression. Les trous ainsi forés furent utilisés pour l'installation d'extensomètres, de géophones et de cellules Glotzl. Ces instruments ont alors permis de suivre le comportement du remblai, parallèlement à la progression des travaus miniers adjacents au remblayage. On se servit également d'un appareil de mesure ultrasonique pour aider à l'établissement du profil de rupture qui en résulta. Les données obtenues par les mesures de qualité des matériaux, et par l'appareillage "in-situ", servirent à la modélisation numérique du comportement du remblai soumis au chargement par les activiés adjacentes des travaux miniers.

Les résultats de ces travaux indiquent qu'il est possible d'obtenir des échantillons de carottage jusqu'à 95 pour cent intacts même dans un remblai qui est peu consolidé. On démontre aussi qu'en calibrant avec précision les modèles numériques qui sont présentement disponibles, on peut accomplir une modélisation représentative des structures de remblai dans un environnement minier dynamique.

SUMMARY

The main purpose of this study was to develop a method for in situ sampling of backfill and use the physical property data and monitoring information obtained to simulate backfill behaviour using computer modelling. The field work was originally scheduled at Falconbridge's Strathcona Mine but was shifted to Lockerby Mine due to ground problems at Strathcona. The project was carried out under a Department of Supply and Services (DSS) Contract Number 0SQ85-00292.

A blasthole pillar at Lockerby Mine (31-176 Stope) was selected for the project as it was being recovered against two backfill walls, approximately 70 meters high, using a vertical crater retreat (VCR) mining method. Diamond drilling, performed by Trow Limited, Sudbury Divison was conducted with a Craelius Diamec 251 drill and a split tube core barrel. Core recoveries with backfill were as high as 95%. The stope was instrumented using extensometers, pressure meters and geophones to study the static and dynamic effects of mining on backfill. The monitoring data, together with the physical property strength information obtained from in situ samples, was used to develop a number of two-dimensional numerical simulations using FLAC (a finite difference computer modelling code) and MUDEC (a distinct element computer modelling code). Both the codes have been developed by the Itasca Consulting Group in Minneapolis, Minnesota, and have been used by Falconbridge since 1986. A large slough of backfill, which unexpectedly occurred during mining of the 31-176 Stope, provided an excellent opportunity to calibrate the computer models with in situ results. Computer model results showed good correlation with in situ fill behaviour.

Finally, a limited number of computer simulations of a sill mat were conducted, using physical property data obtained from Lockerby, to study sill mat behaviour at one of Strathcona's mining blocks. The models indicated that the current sill mats in use at Falconbridge are stable. This aspect requires further investigation.

The results of this study will be of significant benefit to the mining industry in Ontario and the rest of Canada. An alternative technique for undisturbed sampling of backfill has been developed that resulted in higher recoveries. In addition, good calibration was established between the computer models used and in situ fill behaviour. This information will enhance backfill design in Canadian mines and lead to further optimization of placement of backfill.

It is recommended that the Canada Centre for Mineral & Energy Technology (CANMET) consider developing backfill sampling techniques further to make them more cost effective. This will encourage mines to regularly sample backfill and, over time, a large data base on backfill properties, strengths and in situ behaviour can be collected and used in future mine design. Consideration should also be given to broader distribution of the Itasca computer codes (FLAC and MUDEC) because of their capability to accurately simulate backfill behaviour.

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APPENDICES

1.0 INTRODUCTION

This report presents the results of a study on "In Situ Monitoring and Computer Modelling of a Cemented Sill Mat and Confines During a Tertiary Stage Pillar Recovery." The project was completed for the Department of Supply and Services (DSS) through the Canada Centre for Mineral & Energy Technology (CANMET) under contract serial number 0SQ85-00292. The main objectives of the contract are defined in the statement of work as follows:

1) Review previous investigations of backfill monitoring and backfill failures by literature survey, site investigations and interviews throughout the hardrock mining industry. Analyze previous approaches to the monitoring and computer modelling to guide the proposed research.

2) Establish drilling techniques, probably using a soils engineering sub-contractor to obtain maximum recovery of core while producing a precision hole in the fill for the insertion of instrumentation.

3) Select a test site with adequate access and control.

4) Procure and install suitable instrumentation for the characterization of backfill in situ.

5) Develop and/or adapt computer models to the generally expected range of test values and to the geometry of the test site.

6) Gather data for input to the models. Review data to determine any changes necessary to improve the quality of the input.

7) Validate/calibrate the model and predict the convergences/stresses etc. to be expected during a subsequent planned extraction.

8) Repeat the process of instrumentation and monitoring to demonstrate the capability of the model.

9) Produce a paper for delivery at an industrial seminar appropriate to the topic.

The original field work was scheduled at Falconbridge's Strathcona Mine under a large sill mat. As the project progressed, however, Strathcona experienced serious rockbursting problems and a large proportion of the area scheduled for testing had to be temporarily closed down. In discussions with the CANMET Scientific Authority, Mr. Charles Graham, it was decided to move the initial drilling and testing program to Falconbridge's Lockerby Mine, where pillar recovery against backfill in blasthole stopes was in progress. Pillar mining at Lockerby provided an ideal opportunity to develop appropriate drilling techniques for sampling of backfill and to monitor their static and dynamic behaviour. Once the sampling was completed, the in situ properties and instrumentation data were used to develop and calibrate computer models and eventually simulate in situ sill mat behaviour.

The present state-of-the-art numerical modelling software, the FLAC and MUDEC codes developed by Itasca Consulting Group Incorporated, were used for the numerical modelling. The models were calibrated with instrumentation data and a backfill failure that unexpectedly occurred in the test stope. Finally, a cemented sill mat, of a design recently in use at Falconbridge's Sudbury Operations, was modelled to confirm the mat's structural integrity and demonstrate MUDEC's ability to accurately model cemented sill mats.

2.0 CONCLUSIONS

1. A number of drilling techniques were evaluated to assess the most suitable method for obtaining high percentages of undisturbed backfill recovery. The Diamec 251 diamond drill was modified using a low rpm/high torque unit with a split inner tube core barrel to obtain the desired recovery levels. Core recoveries were as high as 95%, even in extremely weak cemented hydraulic backfill. This is a significant improvement over typical core recoveries of approximately 15% using conventional methods.

2. The diamond drilling equipment used is relatively expensive and is unlikely to be used by mining companies on a routine basis. In addition, the operation of the diamond drill requires a highly qualified operator. Further work is, therefore, necessary to develop more cost effective drilling techniques in backfill.

3. The use of a co-polymer flushing agent can significantly enhance overall core recovery when drilling through cemented hydraulic backfill. After testing a number of agents, a granular co-polymer of sodium acrylamides/acrylates, supplied by Westcoast Drilling Services Limited, appeared to be more suitable. In addition, the agent appeared to have minimal effect on the moisture content of the samples.

4. A number of instruments were used to monitor the in situ behaviour of backfill during mining. These included Glötzl cells (flatjacks), soil extensometers, an ultrasonic void measuring device developed by the U.S. Bureau of Mines, a Texam pressure meter used in boreholes, and penetration cones. Most of the instrumentation worked successfully but required careful installation and a qualified technician on the site to monitor the equipment. Future development of instrumentation for cemented backfills should be encouraged and should focus on more rugged equipment at an attractive cost.

5. The physical properties of backfill were evaluated in the laboratory from samples obtained with diamond drilling and through in situ monitoring. The results are summarized below:

	Strongly Cemented (Tailings to Cement Ratio less than 10)		Weakly Cemented (Tailings to Cement Ratio over 25)	
	In Situ	Laboratory *	In Situ	Laboratory*
Pressure Meter Modulus	400-600 MPa		40-200 MPa	
Uniaxial Compressive Strength	2000-4000 kPa	1050-1600 KPa	200-1000 kPa	250-600 KPa
Cohesive Strength	1000-1500 kPa		100-400 kPa	
Moisture Content	14.3%	12.5%	16.8%	15.0%
Angle of Shearing Resistance	10-15 degrees		35-50 degrees	
Dry Bulk Density	2113 kg/m^3	1946 kg/m^3	2113 kg/m^3	1946 kg/m^3

* Laboratory results were obtained from Falconbridge lab tests-1983-present

The above results are more representative of in situ backfill than those typically obtained from samples prepared in the laboratory and reflect the variety of cemented backfills that can be encountered underground due to segregation. Fill segregation depends on the placement method, drainage techniques employed, the size of the stopes and the pour density. Further in situ physical property data needs to be obtained at a number of mines in Ontario and Canada to allow adequate assessement of the variability in backfills and to develop a broad data base on in situ fill properties for use by the mining industry.

6. The dynamic effects on backfill were studied by conducting a blast vibration monitoring program as mining was in progress in the 31-176 Stope. Four geophones were installed at approximately 15 meters from the blast and the peak particle velocities (P.P.V.) measured with each blast. Results indicated that P.P.V.'s of up to 53 centimeters per second were encountered at this distance. These velocities are obviously high and the slough of backfill on one side of the pillar may well have been caused, at least partially, by blasting. The impact of blasting

on backfill, and how to minimize it, needs to be studied further in a separate project.

7. Two computer models, FLAC (a finite difference code) and MUDEC (a distinct element code), were selected to simulate static and dynamic fill behaviour during mining. Both these programs have been developed by the Itasca Consulting Group based in Minneapolis, Minnesota and represent the present state-of-the-art in two-dimensional numerical modelling. The programs have been used by Falconbridge over the last three years. The results of the simulation indicated extremely close correlation between in situ fill behaviour and that predicted by the computer model. The MUDEC model was also used to simulate the dynamic effects of blasting on backfill and showed that large peak particle velocities in the backfill may well have triggered the failure that was encountered during mining. It may, therefore, be concluded that current computer modelling techniques are capable of simulating in situ backfill behaviour provided good input data is available.

8. Once confidence was gained in the computer modelling, one of the recent sill mats at Falconbridge's Strathcona Mine was evaluated. Results indicated that the current sill mat design at Falconbridge is acceptable under conditions of static loading. Time constraints did not allow modelling of the effects of dynamic loading on the sill mat, but the ability of MUDEC to simulate such loading was successfully demonstrated by the backfill modelling. Further follow-up work using the results of this study, should be carried out on sill mat design.

3.0 RECOMMENDATIONS

1. The cost of equipment and level of operator expertise required for diamond drilling in backfill precludes its use as a routine tool in backfill sampling. Further work, possibly with the manufacturing company, is necessary to develop a reliable and relatively inexpensive method for coring and obtaining fill samples. Since the physical properties of backfill in stopes can vary significantly from those determined in the lab, it is essential that regular in situ sampling of fill be conducted at different mines in Canada. This will allow the establishment of a nation-wide data base for the mining industry for use in future backfill design.

2. Blast vibration damage in stoping appears to be a major cause of dilution from backfill. CANMET should conduct a follow up study on blast design and blasting practices at mines recovering pillars against backfill. The objective of the study should be to determine the optimum explosive charge, drilling patterns and firing sequence so that damage to backfill can be minimized. In addition, consideration should be given to developing methods for reinforcing backfills to better withstand dynamic loading. Since fill dilution is a major problem at most mines, this project should be given a high priority.

3. Further work needs to be carried out with computer models to simulate in situ backfill behaviour and improve calibration with observed fill behaviour. In addition, the present programs used by Falconbridge (FLAC and MUDEC) are proprietary and have to be purchased. CANMET should consider developing and/or obtaining these programs for broader distribution and to enable access for the mining industry at minimum cost.

4.0 IN SITU TESTING AND MONITORING OF BACKFILL

This chapter presents the result of all the field work carried out for this study. The in situ testing included experimentation and development of methods for obtaining acceptable core recoveries of undisturbed backfill samples. This drilling and core recovery program was carried out by Trow Limited, Sudbury Division under the supervision of Falconbridge Limited personnel. The test stope was instrumented using extensometers and pressure meters. Geophones were used for blast monitoring in the fill during each production blast. This information formed the basis for follow-up numerical modelling (discussed in section 5.0).

4.1 Technical Review

Prior to conducting any field work, a technical review on the current state-of-the-art in drilling and instrumentation in backfill was carried out. This review included a literature search, evaluation of previous work funded by DSS and CANMET on backfill and visits to selected mines in Canada. Since Falconbridge was completing a separate study for DSS under sub-contract to Dome Mines Limited (in situ determination of dewatered tailings fill properties in Ontario mines, serial #O6SQ.23440-5-9204) that involved visits to Europe and Australia, key aspects of backfill technology relevant to this study were also examined.

The technical review and site visits confirmed that very little work has been carried out on the in situ behaviour of hydraulic backfills. Most of the studies have either focussed on cemented waste rock fills (such as at Kidd Creek Mines in Timmins, Ontario and Mount Isa in Australia) or have been extrapolated from laboratory tests. A 1980 study by Trow Ontario Limited at Falconbridge's Strathcona Mine (sampling and testing of cemented backfill in underground mines, serial #OSQ79-00113) gave poor core recoveries in backfill and highlighted the need to develop better methods.

The technical review confirmed CANMET's assessment on the need to conduct more research in this area of backfill.

4.2 Test Site Selection

Careful selection of a suitable drill site within the five operating underground mines of Falconbridge's Sudbury Operations was essential in order to reach drilling objectives.
The following parameters were considered in site selection:

- Accessibility with drilling equipment.
- Direct access to exposed cemented backfill.
- Opportunity to drill in varying cement: tailings ratios.
- Access to sequential, rather than single bulk, backfill pours.

With these criteria in mind, the 31-176 stope overcut (O/C) on Lockerby Mines's 2950 level, was chosen as the drill site (Figure 1). Falconbridge's Lockerby Mine employs the blasthole mining method and produced about 612,000 tons of nickel-copper ore in 1987. The mine has been in production since 1978 and currently obtains a large proportion of its tonnage through pillar recovery against cemented backfill (cement to tailings ratios vary from 1:12 to 1:32). Further details of Lockerby Mine are found in Appendix A.

This specific drill site is situated between two previously backfilled stopes (Figure 2), 31-172 and 31-179 with the following relevant parameters:

	31-172	31-179
Backfill: cement	12:1	16:1
Designed strength (MPa)	0.69	0.46
Date of Pour	1982	1985

Lockerby's 31-176 stope was ideally suited to conduct the drilling and monitoring because it provided backfill exposures (Figure 3) and drilling sites within the project time frame. The data could then be used to conduct detailed computer modelling for sill mat design.

4.3 Drilling and Core Recovery in Backfill

4.3.1 Drilling Objectives

Present technology for drilling in cemented backfills to obtain undisturbed backfill samples and produce an accurate drill hole for instrumentation and monitoring is unacceptable. Typical core recoveries, using conventional diamond drilling methods, average 15% or less. Since in situ hydraulic backfill in stopes can vary greatly from that in the lab, in situ sampling of this material is essential to accurately quantify backfill behaviour in underground mine design. A reliable estimate of in situ material properties such as cohesion, density, stiffness, etc. could lead to further optimization of backfill design and a possible reduction in cement usage and overall backfilling costs.

One of the main drilling objectives is undisturbed sample recovery to enable the determination of key in situ material parameters of the backfill; these parameters are required to accurately incorporate backfill in numerical models. Although some of these values are available for various cemented fills from previous lab work or literature, they can fluctuate greatly from mine to mine. In addition, the placement and dewatering method used for cemented hydraulic backfill, leads to inhomogeneity and different settling rates, coarse and fine particle segregation, and varying cement content ratios. In situ undisturbed sampling and monitoring of fill behaviour are therefore essential.

Undisturbed samples provide a very valuable visual picture of in situ backfill. Although it is accepted that segregation occurs in most backfill pours (due to the method of pouring, draining, etc.), the actual pattern of this segregation is not well understood.

Segregation and cement content affect the economics and safety of fill and a better understanding of how this occurs in cemented backfill can be of value in future mine design.

The extent to which in situ backfill in mines can be monitored as mining progresses is somewhat limited because it is difficult to drill accurate holes for instrumentation. A key objective to the drilling program was also, therefore, to drill accurately in backfill.

4.3.2 Drill Selection

Drill selection for this project was based on field experience, both external and at the Falconbridge mines, and recommendations from diamond drill contracting firms familiar with this type of drilling.

In the past, Falconbridge has attempted to recover undisturbed fill samples using conventional diamond drills with single, double and split tube core barrels. None of these methods provided the drilling control required for suitable sample recovery. In many cases, recovery was less than 15% and, in other cases where recovery was higher, the samples were badly broken and/or often saturated with drilling fluid. With this experience, it was determined that the following drill performance criteria were required:

- Accurate control of drilling rotation in the 50 to 200 RPM range.
- Minimal sample contact with drilling fluids.
- Drill barrels that allow for easy core removal.

Discussions were held with various contract drilling firms. Talks with Craelius Division of Unicorn Abrasives of Canada Limited resulted in the final selection of the drill to be used. The following are the basic details of this unit. Specific drill data is contained in Appendix B.

Selected Drill - Diamec 251 (modified)
- Diamec 260 low RPM/high torque rotation unit.
- Diamec 260 rod holder
- Skid type frame
- 30 KW 550 V electric motor
- Craelius T6S 86 x 1500 mm core barrel (double tube, swivel head type)
- Split inner tube core barrel
- Surface set diamond drill bit - 20 SPC

This unit is also portable and easily assembled (Figures 4-6). The power unit and drill frame are quickly detached and easily transported underground in either a standard size cage or scooptram.

4.3.3 Drilling and Drill Core Recovery

4.3.3.1 Drill Hole Locations

Six boreholes in total were completed and varied in length from 5.9 m to 8.5 m (Appendix C). The holes were orientated as shown in Figures 7 and 8. The first of these boreholes was drilled solely to optimise drilling rotation, feed pressure, and feed rates, and was not used for sampling or instrumentation purposes. All boreholes were drilled horizontal or upgrade to facilitate drainage of the drilling fluid, and in doing so, minimize the effect of drilling fluids on recovered core samples.

4.3.3.2 Drilling Parameters

In addition to the general drill data for the Diamec 251 Drill mentioned in Section 4.3.2, the following are the specific drill settings used:

Feed Load	-	0.5	-	0.75 tonne
Water Pressure	-	200	-	400 kPa
Feed Rates	-	15	-	25 mm/min.
Rotation	-	50	-	150 RPM

These settings were varied within the ranges listed above in order to provide optimum penetration with minimum "flushing" requirements for acquiring undisturbed core samples in both weak and strong cemented fills. The use of experienced drillers allowed for adjustments to these drilling parameters while drilling was in progress, and as different strength fills were encountered. These parameters were also varied for deeper boreholes.

4.3.3.3 Flushing Agents

Flushing agents used in drilling are important as they can affect the moisture content and physical integrity of core samples. These factors will, in turn, affect the physical properties of the cemented fill samples under examination. In order to minimize this sample deterioration, the following flushing methods were evaluated:

- Pressurized air
- Pressurized water
- Co-polymer mixed with pressurized water

The final flushing agent used during drilling operations was a concentrated, granular copolymer of sodium acrylamides/acrylates as supplied by Westcoast Drilling Supplies Limited. This solution appeared to work well and core samples were extracted fully intact in even the weaker cemented fill. Although it is difficult to determine the effect of the use of this copolymer on a sample's moisture content, it is felt that the increase in moisture level was minimal.

4.3.3.4 Sample Recovery and Handling

In order to obtain maximum core recovery of undisturbed cemented fill, inner split tube and standard NW solid tube (both using double tube core barrels) proved effective. Both core barrels worked equally efficiently in drilling and sample retrieval, although the split barrel design of the Craelius core barrel provided easier logging and handling of recovered samples.

Samples were placed on sample trays, sealed (to maintain their moisture content) and carefully transported to surface for analytical analysis (Figures 9 and 10). In the weakly cemented samples the core had to be handled carefully in order to maintain the samples in an undisturbed state.

4.3.3.5 Continuous Flight Augers

Backfill sampling with flight augers was also tried. This backfill sampling technique has the following advantages and disadvantages:

Advantages - No flushing agents required and thus moisture contents of samples remain unaltered.
- Faster drilling.
- Less expensive.
- Good hole tolerances for instrumentation.
- 100% sample recovery.

Disadvantages- Samples are fully disturbed
- Will not drill through rock, either in fill, or to access fill.

This method for cemented fill sampling was done using the same basic equipment as outlined in Section 4.3.2 and should be considered where sample moisture content, density, grain size distribution, and economical hole sizing for instrumentation are of primary importance (Figure 11).

4.3.4 Instrumentation

4.3.4.1 Selection

The following is a summary of the instrumentation that was selected for this project and the purpose for which it was selected.

SUMMARY OF INSTRUMENTATION

INSTRUMENTATION	NO. OF UNITS	INSTALLED BY	PURPOSE
Geophones *	4	Falconbridge	PPV Blast Wave Frequency
Glötzl Cells	4	Falconbridge	Fill Loading
Soil Extensometers	3	Falconbridge	Fill Failure Profile
USBM Ultra Sonic Measuring Device	1	Falconbridge	Fill Failure Profile
Texam Pressuremeter	5	Trow Limited	Modulus of Elasticity
Penetration Cone	N/A	Trow Limited	Fill Strength

* Discussed in Section 4.4 - Blast Vibration Monitoring Summary.

4.3.4.2 Installation

Glötzl Cells: Glötzl cells (flat jacks) were installed in the 31-179 (backfilled) stope on both the 29-1 sub-level and 3125 level horizons (Figures 12-13). One hole was drilled into the center of the fill at each location with two cells being installed in each hole, one vertically and one horizontally.

Soil Extensometers: Three soil extensometers were installed from the 29-183 crosscut and varied in length from 30 m to 44 m (Figures 14-15). Three to four anchors were installed (as shown) in each hole.

USBM Ultrasonic Measuring Device: This unit (Figure 16), on loan from the USBM (United States Bureau of Mines), was lowered, in increments of 3 meters, into the void created by mining 31-176 stope. This operation was performed for the top 25 m of the stope and a profile of the void taken at each horizon.

Texam Pressuremeter: This pressuremeter was used along the entire length of the five major cored holes outlined in Section 4.3.3.1. Unlike the Glötzl pressure tests, the readings obtained at these locations were sets of single readings. Once the individual hole was tested, the instrumentation was removed.

Penetration Cone: These tests were attempted on the exposed fill face at several locations in the 37-176 stope overcut (Section 4.2). Due to the stiffness of the fill and the light-weight nature of the Diamec 251 Drill, initial trials resulted in damaged and bent rods. These tests were discontinued at this point.

4.3.5 Physical Property Evaluation

4.3.5.1 Pressure Meter Results

Glötzl pressure cell results (Figures 17-18) indicate that a negligible amount of fill loading (in both vertical and horizontal directions) occurred after the adjacent 31-176 stope was mined out. This appears to support the theory that, because rock is extremely stiff compared with backfill, significant load transfer does not occur until the fill has undergone considerable compaction, which would perhaps require something of the order of 15% wall convergence. Detailed Texam pressure meter results are listed in Appendix C. A summary of the results, used in numerical modelling are listed below:

	Strongly Cemented (T:C < 10)	Weakly Cemented (T:C > 25)
- Pressuremeter Modulus (EM)	= 400 - 600 MPa	40 - 200 MPa
- Pressuremeter Limit Pres. (P)	= 10 - 20 MPa	5 - 15 MPa
- Em/P Ratio	= 30 - 40	8 - 15

4.3.5.2 Soil Extensometer and USBM Ultrasonic Measuring Device

Results from the extensometers (Figures 19-21) and the USBM Ultrasonic Measuring Device provided the necessary details to map the outline of a fill wall failure which occurred during mining. This profile was compared to a numerically generated failure surface to calibrate the computer model (see Section 5). The void profiles are shown in Appendix D.

4.3.5.3 Drill Core Mapping

An example of the core log is shown in Figure 22. This mapping provides a visual record of the fill segregation and quality, and the core itself provides undisturbed fill samples for laboratory determination of physical properties. The complete core mapping is in Appendix E and indicates the widely varying size distributions and cement contents.

4.3.5.4 Laboratory Evaluation and Test Work Summary

Cemented fill core samples were subjected to various laboratory tests to obtain the in situ physical properties of the material. This work was carried out by Trow Limited on sub-contract. The following is a list of the laboratory tests and a summary of all test work results.

Laboratory Tests	- Uniaxial compressive tests
	- Triaxial compressive tests
	- Moisture contents
	- Cement determination tests
	- Dry bulk density

<u>Test Work Result Summary</u>	Strongly Cemented (T:C < 10)*	Weakly Cemented (T:C > 25)*
- Uniaxial compressive strength (Q)	2000 - 4000 kPa	200 - 1000 kPa
- Cohesive Strength (c)	1000 - 1500 kPa	100 - 400 kPa
- Moisture Content (%)	14.3	16.8
- Angle of shearing resistance (ϕ)	10 - 15°	35 - 50°
- Pressuremeter modulus (EM)	400 - 600 MPa	40 - 200 MPa
- Pressuremeter Limit pressure (P)	10 - 20 MPa	5 - 15 MPa
- Em/P	30 - 40	8 - 15
Dry bulk density	2113 Kg/M^3	

* T:C is the tailings to cement ratio

4.4 Blast Vibration Monitoring

4.4.1 Monitoring Objectives

Blast vibration monitoring was carried out to determine the following:

- Peak particle velocity (PPV)
- Wave frequency
- Blast duration time

The blast vibration monitoring parameters were used in subsequent numerical modelling to assess the impact of dynamic loading on backfill.

4.4.2 Equipment and Installation

Four geophones were installed in total, two on 29-1 sub-level and two on 3125 level (see Figures 23-24). On each of these horizons, one geophone was installed in each of the two backfilled stopes, 31-172 and 31-179, adjacent to the pillar to be mined. The installation locations were chosen to allow comprehensive blast vibration monitoring around the 31-176 pillar.

A Racal 7-channel FM tape recorder and/or two Instantel DS-200 collector units were used to record blast data.

4.4.3 Monitoring Results

From August 22 to October 10, 1986, the first ten blasts of 31-176 VCR stope were monitored. The following values, used in numerical modelling, were obtained.

- PPV *	53 cm/second
- Dominant Frequency	30 Hz
- Blast Duration * *	15 MS

* Measured 15 m from the blast

* * Blast duration for the hole adjacent to the fill wall

Details of this work are given in Appendix F.

5.0 NUMERICAL MODELLING

5.1 Introduction

Data collected from field instrumentation, Falconbridge files, literature, and work by Trow Limited have been incorporated into input data used to simulate the response of fill to adjacent mining. Numerical models were utilized in the examination of the effects on a cement sill mat and confines during tertiary stage pillar recovery.

An investigation was carried out using FLAC, a finite difference code, and MUDEC, a distinct element code. FLAC was used in the initial stages of modelling to simulate the backfill as a continuum material. This preliminary work gave direction in scoping some input parameters used in MUDEC, which was extensively used throughout this analysis. The MUDEC code was used to simulate the backfill as a discontinuum material.

It was originally planned to monitor the ground movement around a sill mat during the mining of an adjacent stope. However, Falconbridge's mining schedule precluded the availability of a suitable mat which would fall into the project schedule.

A test site was chosen at Lockerby Mine as described in Section 4.2. The recovery of a tertiary pillar mined by the vertical crater retreat method (V.C.R.) was monitored. The philosophy in choosing such a test site was based on the premise that if a tertiary pillar recovery could be modelled successfully, then a sill mat could equally be simulated.

The instrumentation around 31-176 stope would verify the response of the MUDEC model. The successful response of the model to duplicate observations made underground would give us the confidence to try to simulate the reaction of a sill mat to the mining being carried on around it.

5.2 The Numerical Models

Flac is an explicit finite difference code which solves the equations of motion in difference form. "Explicit" refers to the nature of algebraic equations used in the numerical solutions. In the explicit method, all quantities on one side of all equations are known, and each equation is simply evaluated to produce the results on the other side. Explicit formulations differ from implicit formulations, ie. boundary elements, where known quantities exist on both sides of the equation. Implicit problems require the solution of simultaneous equations by some technique such as Gauss elimination.

The stope and confines to be simulated are divided into a number of elements with intervening grid points as in any continuum differential code, such as the finite element code. The equations of motion are then solved in a time stepping algorithm at each grid point. For each step in time, the out-of-balance forces at each grid point are determined. These, in turn, are used to determine the velocities at each grid point and the associated strain components. These strains are used in the stress-strain law chosen for the particular zone to determine the corresponding stress components. This cycle is repeated until the user is satisfied that an equilibrium state has been reached.

MUDEC is an explicit, time marching distinct element code which also solves the equations of motion in difference form. Unlike finite elements, distinct elements may interact with any of the other elements and may experience large-scale rigid body translations and rotations. The geometry of distinct elements is defined by the spacing and orientation of joints in the material mass being modelled, with each element corresponding to an individual block of material.

The code is based on force displacement relations which specify the forces between blocks, and a motion law which specifies the motion of each block due to unbalanced forces acting on the block.

Numerical integration of Newton's Second Law is used to determine translation of each block and rotation of each block about its centroid.

The distinct element method has three distinguishing features:

1) The rock mass is simulated as an assemblage of blocks which interact through corner and edge contacts.

2) Discontinuities are regarded as boundary interactions between blocks; joint behaviour is prescribed for these interactions.

3) The method utilizes an explicit timestepping (dynamic) algorithm which allows large displacements and rotations and general non-linear constitutive behaviour for both the material mass and the joints.

In summary, the FLAC code was used in the preliminary analysis to investigate the importance of induced stresses and gravity on the cemented hydraulic fill, as modelled as a continuum. The MUDEC code enabled the effects of blasting to be simulated enhancing its significance on the timing and mechanism of failure on fill.

5.3 Summary of Test Site Data and Observations

Figure 28 shows the location of the test stope 31-176. The dimensions of the stope are approximately 11 meters wide by 14 meters on transverse longditudinal with a height of 58 meters. The stope was mined from late August until late October 1986 by the V.C.R. method. A total of 14 cuts were taken including the blasting of the sill. The length of time between lifts varied from two to seven days.

The mining of stope 31-176 left the adjacent backfilled stopes unsupported to a height of about 70 meters. The west stope, 31-172, was filled in 1981 with 12:1 tailings to cement, and the east stope, 31-179, was filled in 1984 with 22:1 fill. During mucking of the stope, a significant amount of fill was noted by scooptram operators in their buckets. Based on these accounts of loose fill in the muck pile, it became evident that fill was peeling off the sidewalls.

The extensometers provided a first estimate of the spacial extent of the fill failure of the east sidewall. Figures 29 and 30 illustrate the magnitude and locations of movement in the x and y directions. It was estimated that the x = 0.025 meter contour indicated the failure surface. As a means of checking the accuracy of this estimate, a sonic void measuring device was lowered into the stope from the overcut (Appendix D). Only the top one third of the stope was surveyed; however, results of the survey showed that the x = 0.025 meter contour aligned reasonably well with the limited survey results. It also showed that the extent of fill failure from the east sidewall was more than double that of the west. On average, the surveyed location of the blastholes showed that the nearest row of holes to the east sidewall was 1.5 meters while the nearest holes to the west sidewall was 2.0 meters. Also, the east stope had ± 3.0% less cement in its fill than the west stope. Based on the blasting pattern and the cement contents of the fill, it seems not surprising that 31-179 failed more extensively than 31-172.

Of note in Figure 29 is the shape of the failure (0.025 m) surface. It is largely vertical near the top of the stope while at the bottom it curves towards the undercut. Such a surface suggests an initial slump at the bottom which progressed horizontally to a vertically orientated weakness plane extending to the surface. The large displacement of the initial slumped material removed the footing that gave direct support to overlying fill.

5.4 Preliminary Analysis

As outlined in Section 4.3.5.1 pressure cell results were obtained (Figures 17-18) and showed that little change in load occurred during and after the mining of 31-176. No change of load indicates that the fill was not transferring any load from the adjacent pillars. This phenomenon was also noted by Sinclair et al (1981) who noted that because the rock is very stiff compared with the backfill, transfer of stress is negligible. This is valid until the fill experiences significant compaction, requiring perhaps 15% wall convergence, which never occurred in this instance.

A FLAC model simulating stope 31-179 was examined under static loading conditions. A Mohr-Coulomb constitutive relation with and without tension cut-off was chosen. FLAC also accommodated an "interface". The interface allows grids on either side of it to slide past one another. Thus, for example, a slip plane could be simulated. The interface was situated at the rock fill interface furthest from mining.

Results of the analysis showed that without the tension cut-off a massive slump type failure progressed well into the fill stope. This failure surface was very different from the skin of fill that peeled off in 31-179 stope. However, the tension cut-off model produced a failure that extended ± 2 m into the fill stope and extended up much of the height of the stope. The surface observed in this failure was very similar in shape to that observed underground. In both cases examined, the entire collapse occurred after several cuts had been made. Observations underground showed that fill collapse occurred on several different occasions following production blasting. Thus the model failed to get the timing of the collapse right. However, this timing is strongly related to the blasting schedule and this analysis was strictly a static one.

The preliminary analysis indicates that boundary effects caused by stress transfer through the fill pillar are of little significance thus making gravity important. A Mohr-Coulomb constitutive model with a tension cut-off successfully reproduced the failure surface and further, indicated the peeling nature of the exposed fill wall.

5.5 Mudec Simulation

Based on the shape of the failed surface and, because backfill physically peeled away or separated from the fill mass, the distinct element code MUDEC was chosen to simulate the fill failure. The blocks indicated in Figure 31 represent 39-179 stope. The model has dimensions 76 meters x 14 meters. The larger blocks represent an area 4 meters x 2 meters. Two columns of blocks have diagonals through the corners and have been further discritized by splitting the blocks in half. The leftmost column of blocks have been assigned material properties equivalent to Falconbridge ore. The remaining eight columns of the model have been assigned material properties equivalent to the 22:1 backfill which is in place. Backfill in contact with, and adjacent to, the ore interface has been finely discritized in order to allow the failure surface to form its own course with as little dependence on block size as possible (failure can only occur along block interfaces).

The material properties used within the model were established by corroborating measured in situ values with data published in literature. Figure 32 lists all the input parameters pertaining to material properties. If a shear plane along a joint causes two blocks to separate from one another, the joint cohesion, joint friction, and joint tensile strength change. These changes can be found in Property Two of Figure 32.

Boundary conditions consisted of fixing the velocities in the x direction equal to zero on the right vertical boundary. The y velocity was fixed at zero at the bottom horizontal boundary. By fixing these two boundaries at zero, the model simulates the effect of fill resting against a solid rock interface. The other two boundaries were made viscous, allowing shock waves to pass through.

MUDEC simulates a dynamic event like a production blast by applying a force or a peak particle velocity to a given point or area in a sinusoidal manner. The duration of the blast and the frequency of the wave are additional data required to describe the event. By recording the actual seismic pulses resulting from the blasts, with the aid of geophones and vibration analysis equipment, reliable data pertaining to this site was extracted (see Section 4.4 and Appendix F).

The simulation of the mining consisted of the following steps. A 4 metre x 2 metre block was removed to simulate the undercut, Figure 33. A blast was simulated in the two blocks immediately overlying the undercut, Figure 34. The model was then cycled for a period of time such that the effects, ie. ground movement, created by the blast, were fully realized. These two blocks were then deleted from the model (Figure 35). This deletion simulates the extraction of the blasted ore. Again, the model was allowed to adjust to the new conditions. Another blast was repeated in the next two blocks overlying the previous two. This simulation was continued until the top of the model was reached. At this stage, the simulation was stopped. The resulting effects are shown in Figure 36.

5.6 Discussion of Modelling Results

Figure 36 illustrates the model after backfill blocks have peeled away from the exposed fill sidewall. The blocks left standing are those in stable equilibrium.

Figure 37 compares the measured failure surface to the predicted surface computed by the numerical model (Figure 36). The two failure surfaces are similar in shape and in dimensions. The MUDEC model was able to reproduce the failure that was known to occur in a well monitored backfilled stope adjacent to a full production stope.

The blasting simulation demonstrated a shock wave propagating outwards from the source location in the form of velocity vectors. After only a couple of meters of propagating outwards some of the wave is reflected back towards the open stope. The reflected wave creates planes of tension between adjacent blocks causing them to separate and peel off into the open stope. The timing of such a collapse occurred immediately after each blast. Consequently, not only the shape of the failure surface was reproduced, but the timing of its occurrence was also duplicated.

5.7 Sill Mat Model

A section of Falconbridge's Deep Copper Zone at Strathcona Mine has been used to illustrate the following example. The Deep Copper Zone is located below the Strathcona Mine main ore body. The ore zone has been folded and dips at 60° near the top and 35° near the bottom. It averages 400 meters in strike length. Mining widths vary from 5 to 15 meters.

Figure 38 illustrates, in a transverse section, the geometry of a MUDEC model simulating cut and fill mining in a 5 meters wide stope at a depth of 1200 meters. The timberless sill mat in the model consists of a 2 meter bed of 8:1 fill followed by a 2 meter bed of 16:1 fill which overlie the final two cuts of ore from the sill. The remainder of the fill is 30:1.

The two remaining cuts were extracted one at a time, Figures 39 and 40. Figure 40 shows the principal stresses at equilibrium. The stress vectors have been scaled in length proportional to the longest one, located 5 meters into the hanging wall and measuring 97 MPa. Stresses in the fill measure 0.2 MPa (in the 30:1 fill) and the maximum wall convergence is about two percent. The 8:1 fill beam only deflects several centimeters and, more importantly, remains stable with regard to gravity loading.

In the model, the 8:1 fill was given a friction angle of 36° and cohesion of 0.5 MPa. Time has not permitted a thorough investigation of the sill mat stability for varying friction angles and cohesion. However, critical friction angles and cohesions could be determined and related to cement:tailings ratios. The impact of seismic loading could additionally be examined with such a MUDEC model.

With mining reaching to greater and greater depths, the need to aid our design with predictive models is becoming more evident. We are no longer able to draw on past experience. Stresses have increased and, in some cases, mining induced seismicity must be accounted for in a thorough design. This illustrative example, along with the previous back analysis, demonstrates the capabilities of current software.

6.0 IMPLICATIONS FOR THE MINING INDUSTRY.

The results of this study are likely to be of significant benefit to the mining industry in a number of key areas:

1. Core recoveries in weakly cemented hydraulic backfills have been improved significantly. With the techniques developed and established as a result of this project, drilling programs can be performed with a high degree of confidence and good undisturbed samples of in situ backfill can be obtained for laboratory testing.

2. The diamond drilling equipment is also capable of drilling accurate long holes in backfill. Instrumentation can, therefore, be placed in these boreholes and fill behaviour monitored as mining progresses. Although instrumentation in backfill has been used in the past, this is one of the few projects where a detailed instrumentation program for backfill monitoring has been conducted.

3. Blast vibration monitoring results demonstrated that fill behaviour, under dynamic loading conditions, can lead to sloughing and instability of the fill walls. Blasting, obviously plays a key role in fill stability and this entire aspect needs to be examined. The mining industry should reevaluate blasting methods during pillar recovery against backfill.

4. Numerical modelling techniques historically have not been able to reliably simulate backfill behaviour in situ. With the development of new distinct element codes, such as MUDEC, both the static and dynamic behaviour of fill can be reliably simulated. The two-dimensional MUDEC results are in good correlation with in situ fill behaviour. These, and similar programs, can now be acquired by the mining industry and, provided reliable input data is available, used for evaluating fill stability and behaviour in future mine design.

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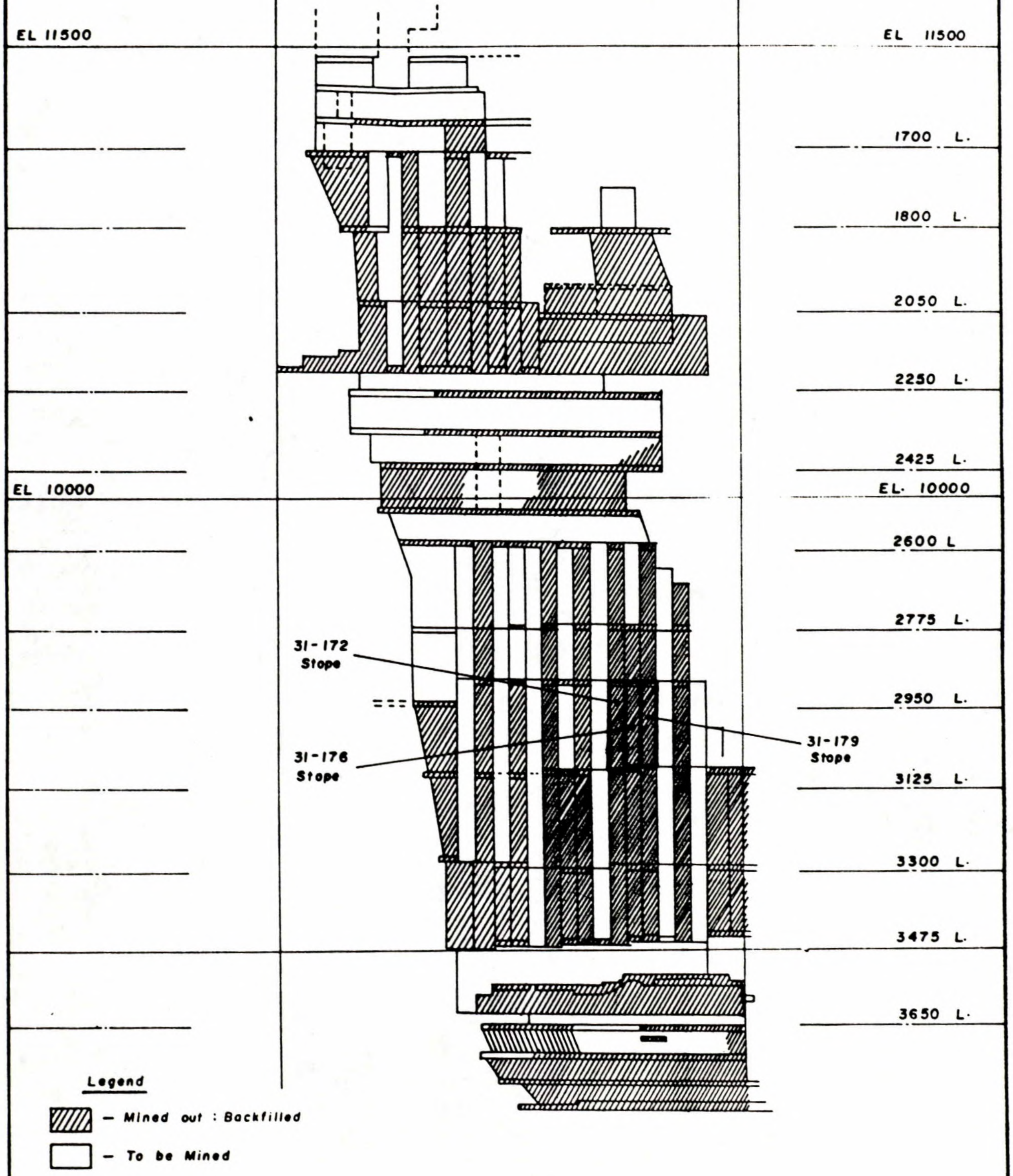
M. Scoble, L. Piciacchia, J.M. Robert, "In Situ Testing in Underground Backfilled Stopes", in C.I.M. Bulletin (Canada, 1987), p.33.

G. Herget, "Borehole Dilatometer for Backfill Studies", in CANMET Minerals Research Program (Canada, 1981), p. 3.

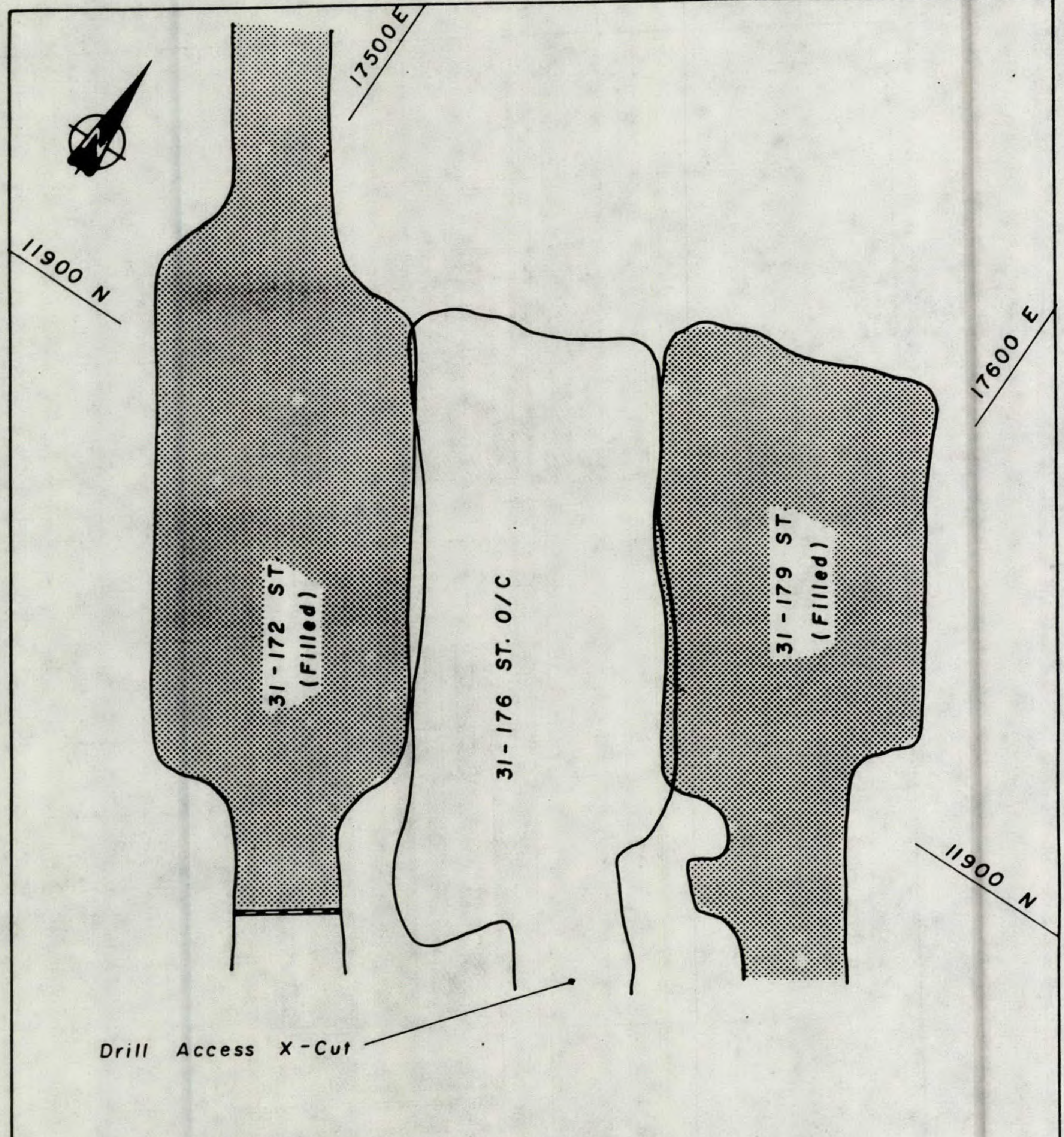
L. Friel, E. VanEexkhout, K. Stout, "Stiff-Backfilled Stope - Instrumentation Plans with Initial Results", in Geomechanics Applications, Underground Mining (U.S.A., 1985), p. 141.

LIST OF FIGURES



Longitudinal Section of Lockerby Mine

FIG : 1

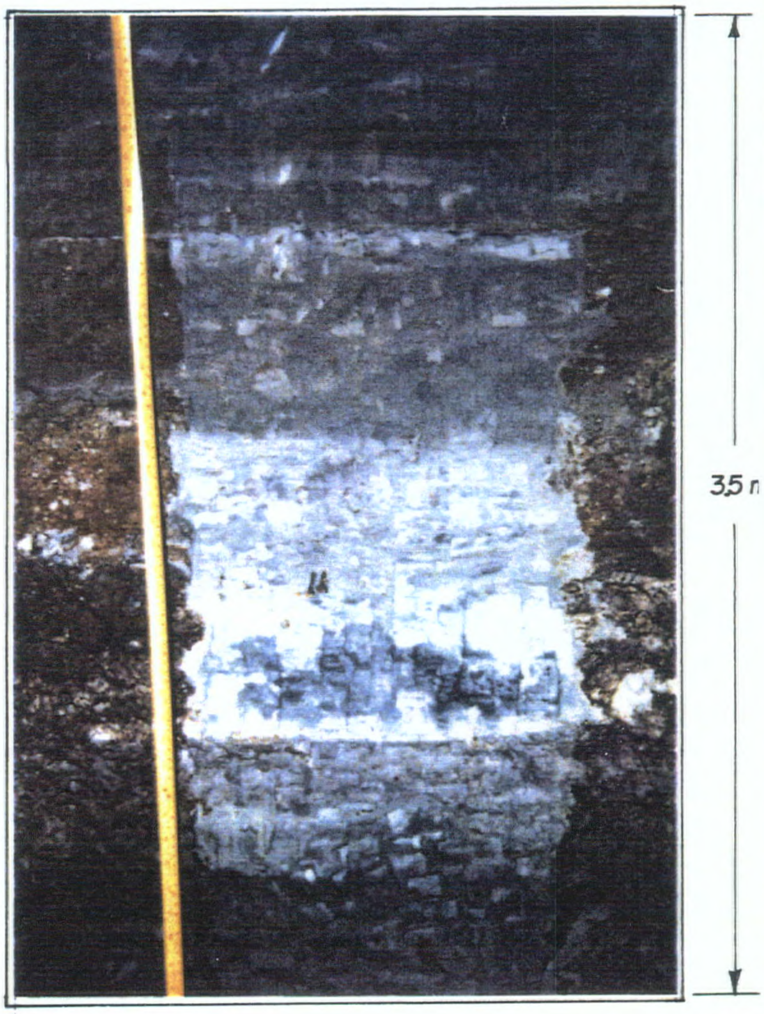


31- 176 Stope — Plan View

FIG : 2

Center of Stope

North End of Stope



In-Situ Mine Fill Stratification

31-172 Stope

Figure 3

Craelius 251 Drill Unit

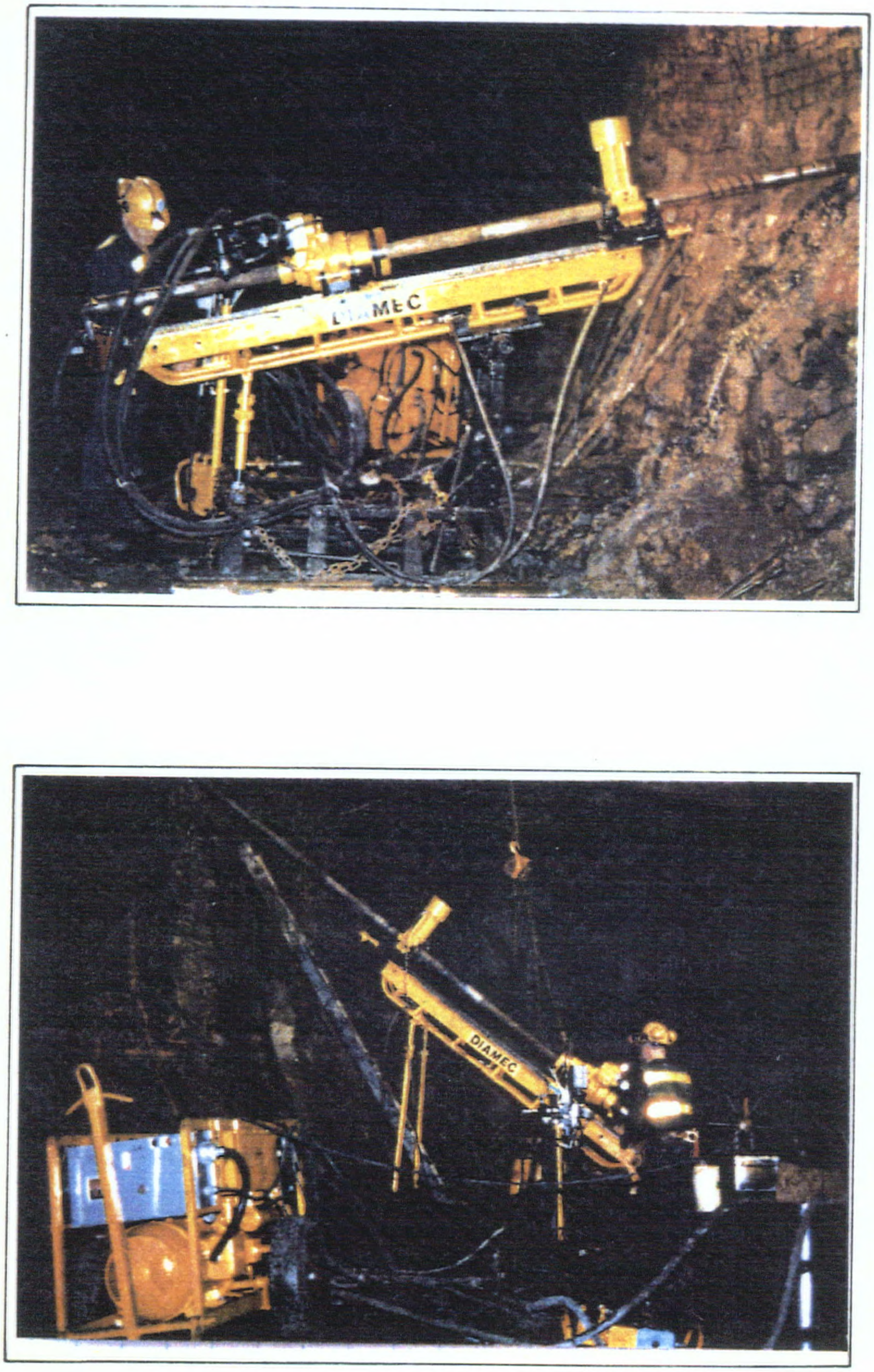
Model 30 E Power Unit

Underground Transportation of The Craelius Drill

Figure 4

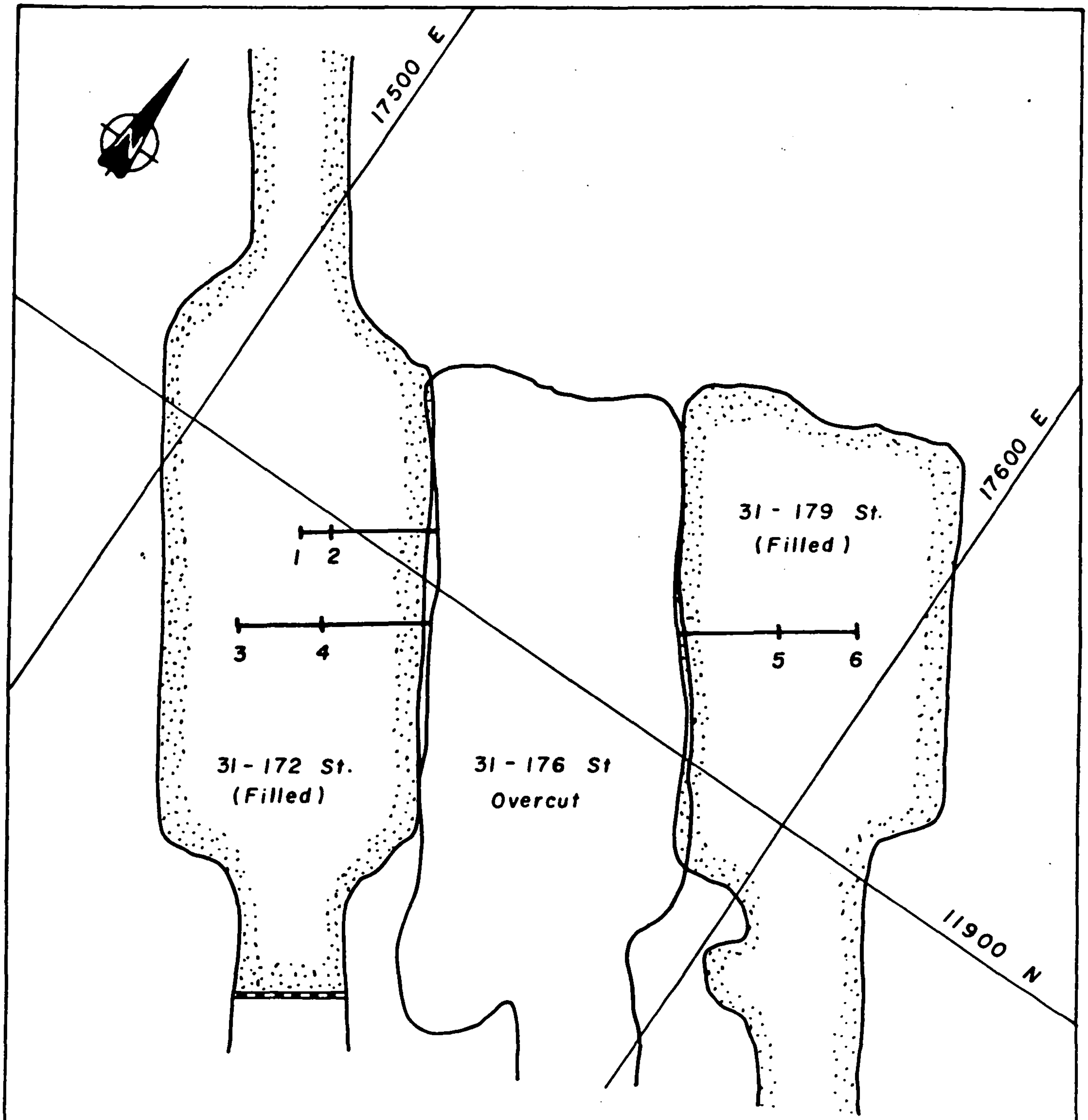
Assembly of Drill Feed Frame

Figure 5



Typical Drill Set Up and Operation

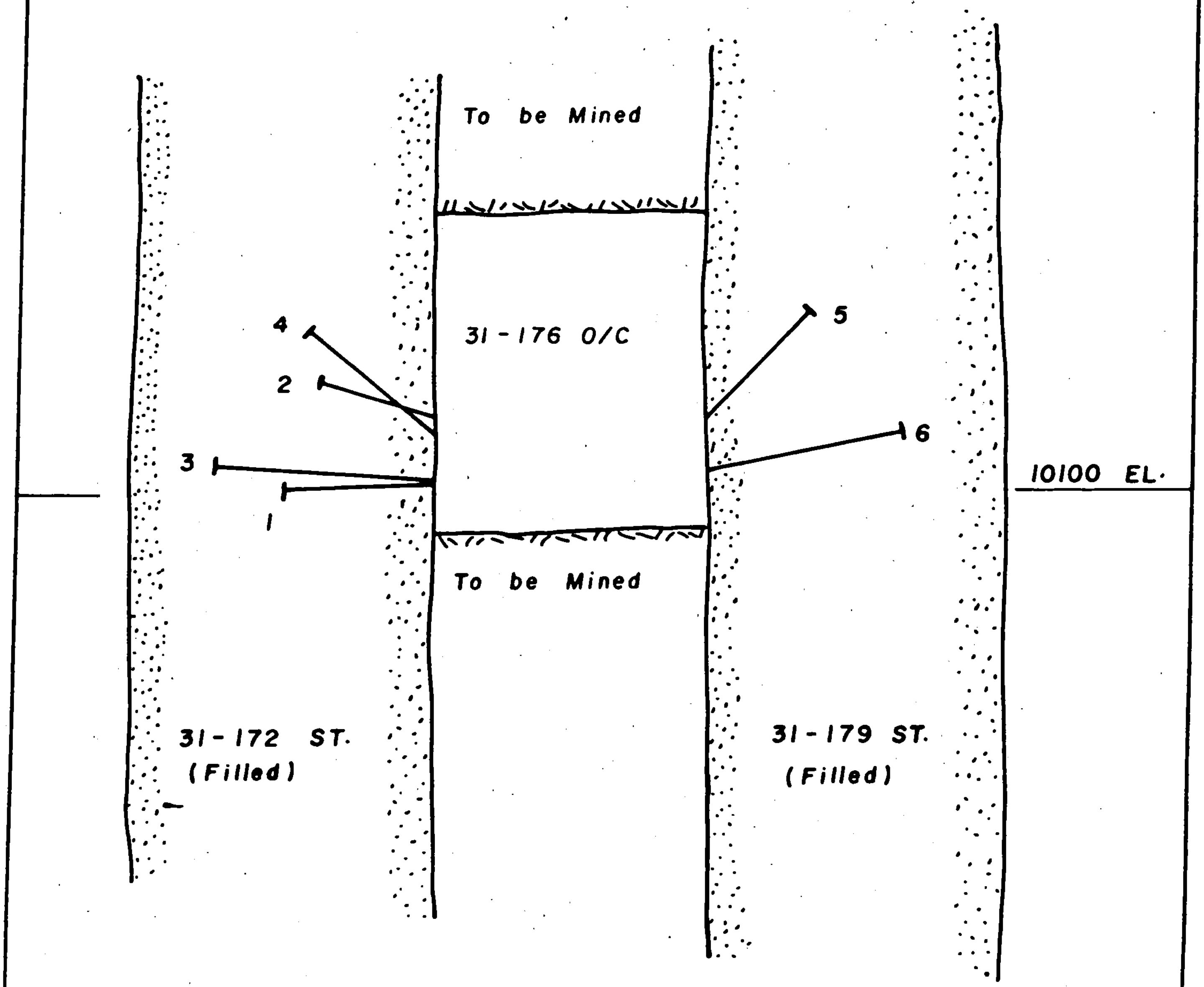
Figure 6



Drill Hole Locations

Plan View

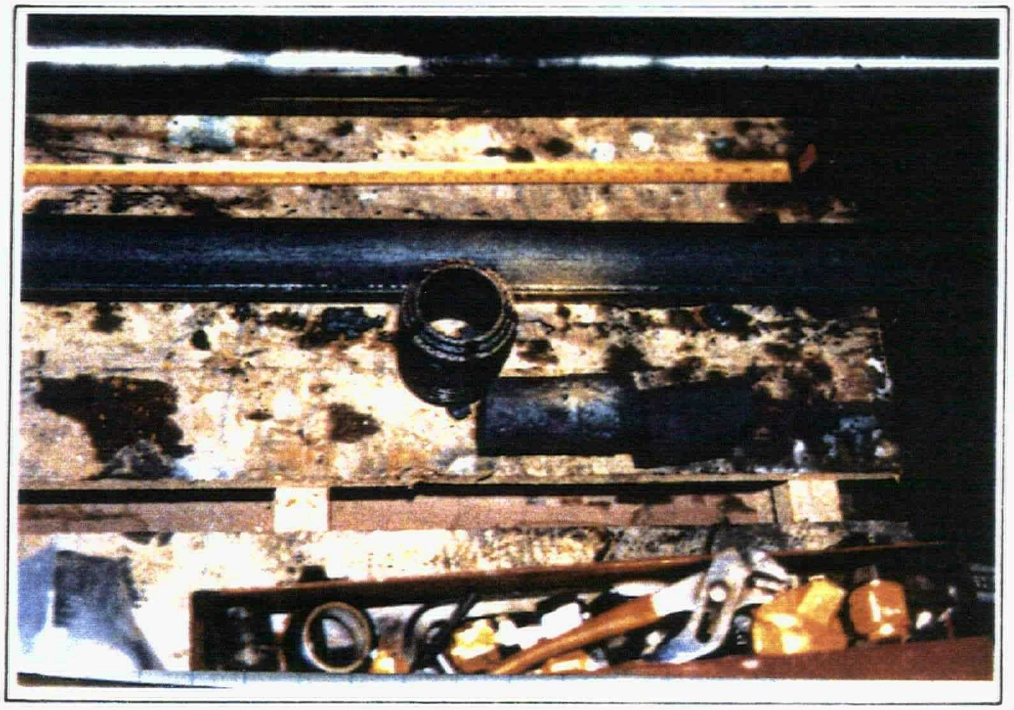
FIG : 7



Drill Hole Location

Section View

FIG : 8



Typical Core Recovery Using Craelius Split Inner Tube Core Barrel

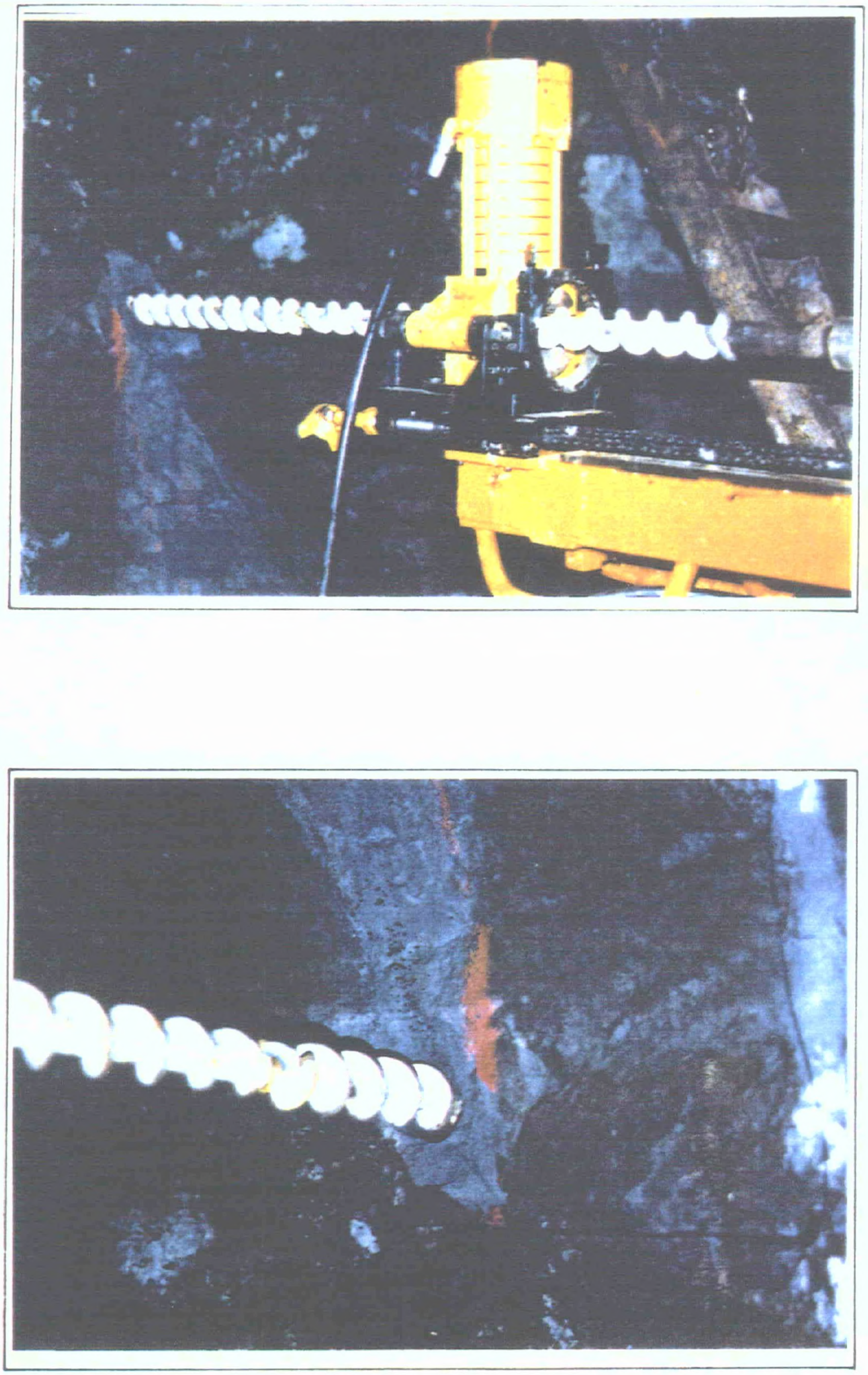
Core Recovery With Craelius Core Barrel

Split Inner Tube and Standard Core Barrels Figure 9

Core Recovery Using NX Solid Inner Tube Core Barrel Samples Are Displayed in a Sample Tray

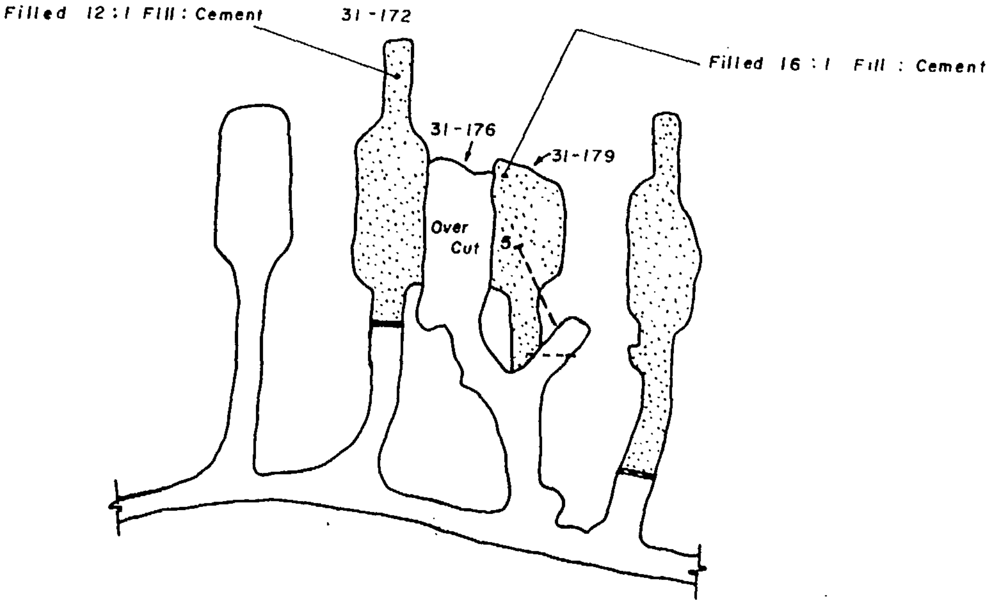
Example of Core Recovery
In Solid Inner Tube Core Barrel

Figure 10



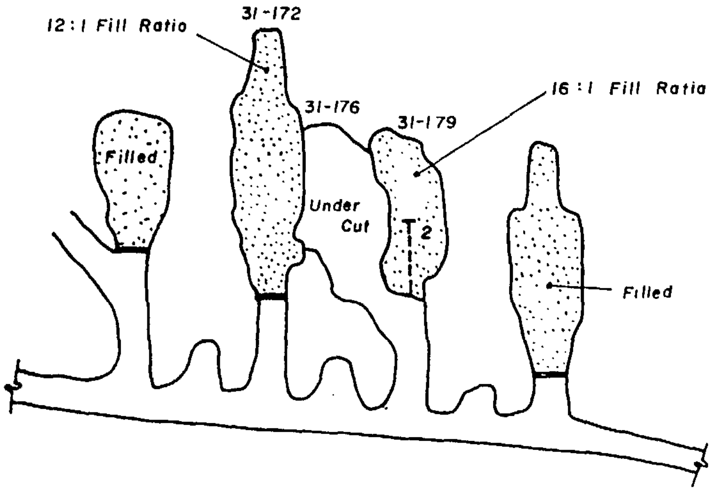
Auger Drilling in Mine Backfill

Figure 11



Note: Two Glotzl Cells Are Installed in Each Hole

Plan of 29 - 1 Sub - Level

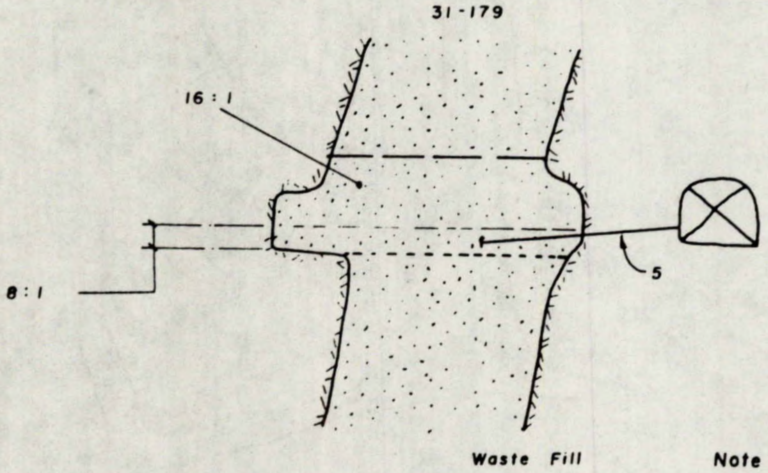


Plan of 3125 Level

Glotzl Cell Installation

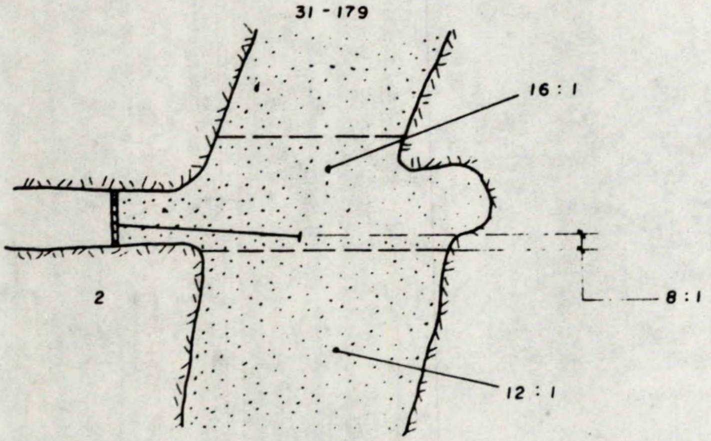
Plan View

FIG : 12



Note : Two Glotzl Cells Are Installed in Each Hole

Section

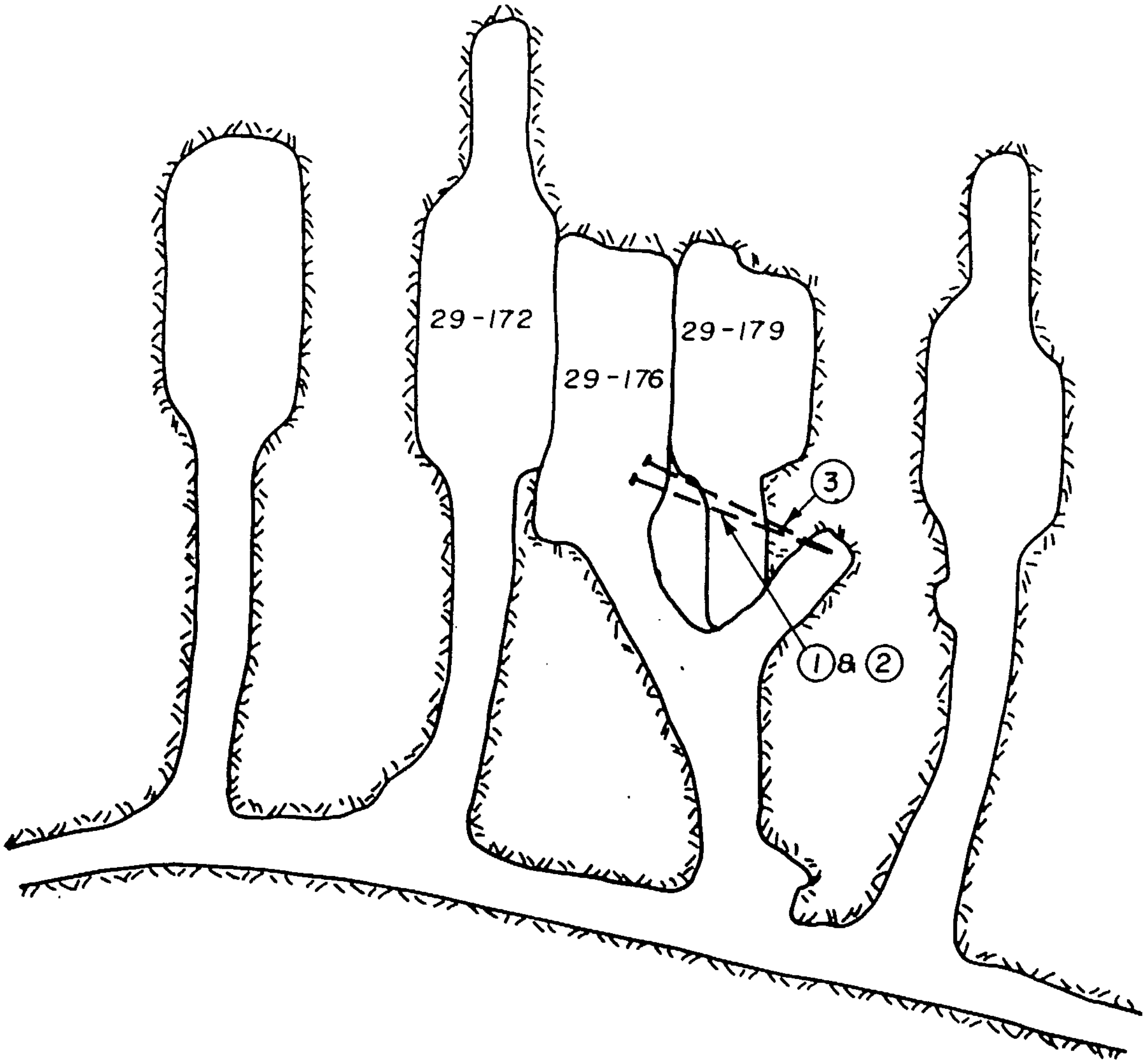


Section

Glotzl Cell Installation

Section View

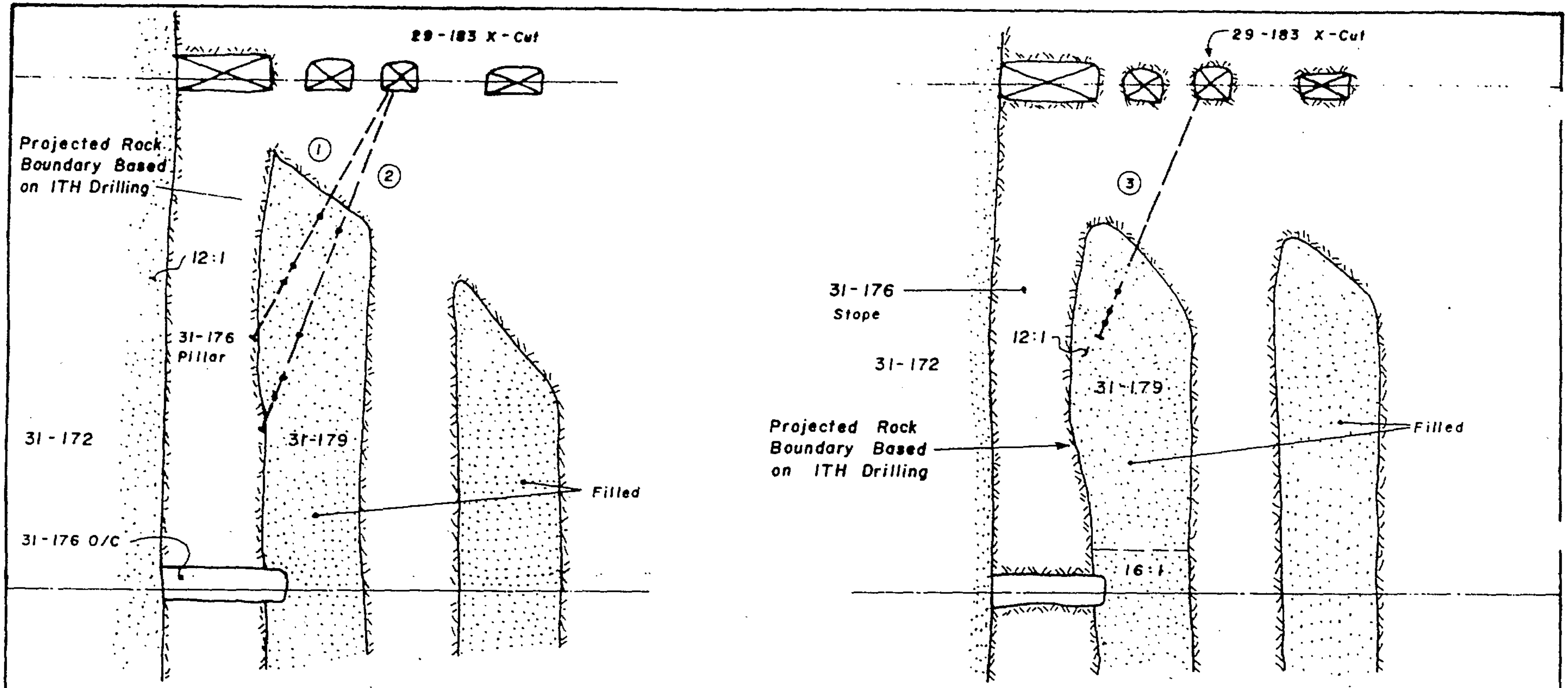
FIG : 13



Extensometer Installations

Plan View

FIG: 14



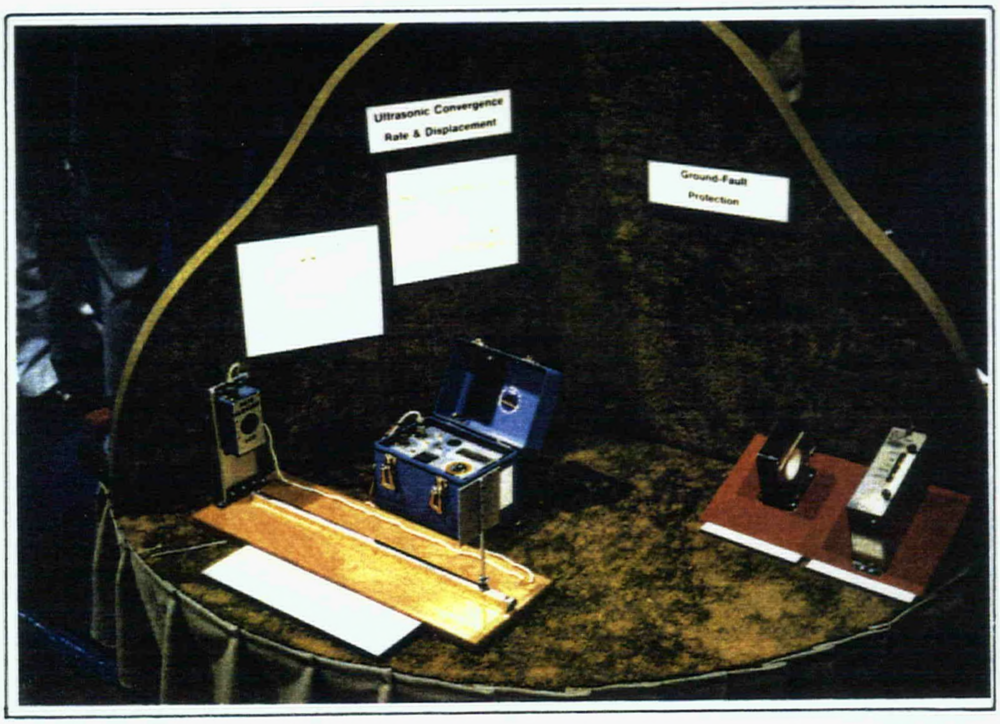
Hole No.	Length			Dip	Az.	Hole O
	Rock	Fill	Total			
E1	48	46	94	-62°	259°	T6S - 86mm
E2	47	93	140	-71°	259°	NX - 75·6mm
E3	76	24	100	-[illegible]°	250·5°	T6S - 86 mm

Hole No.	Anchor Depths			
	4	3	2	1
E1	16·7	23·7	25·9	-
E2	17·3	31·1	36·8	39·0
E3	24·4	27·4	28·9	-

FIG: 15

Extensometer Installations — Section View

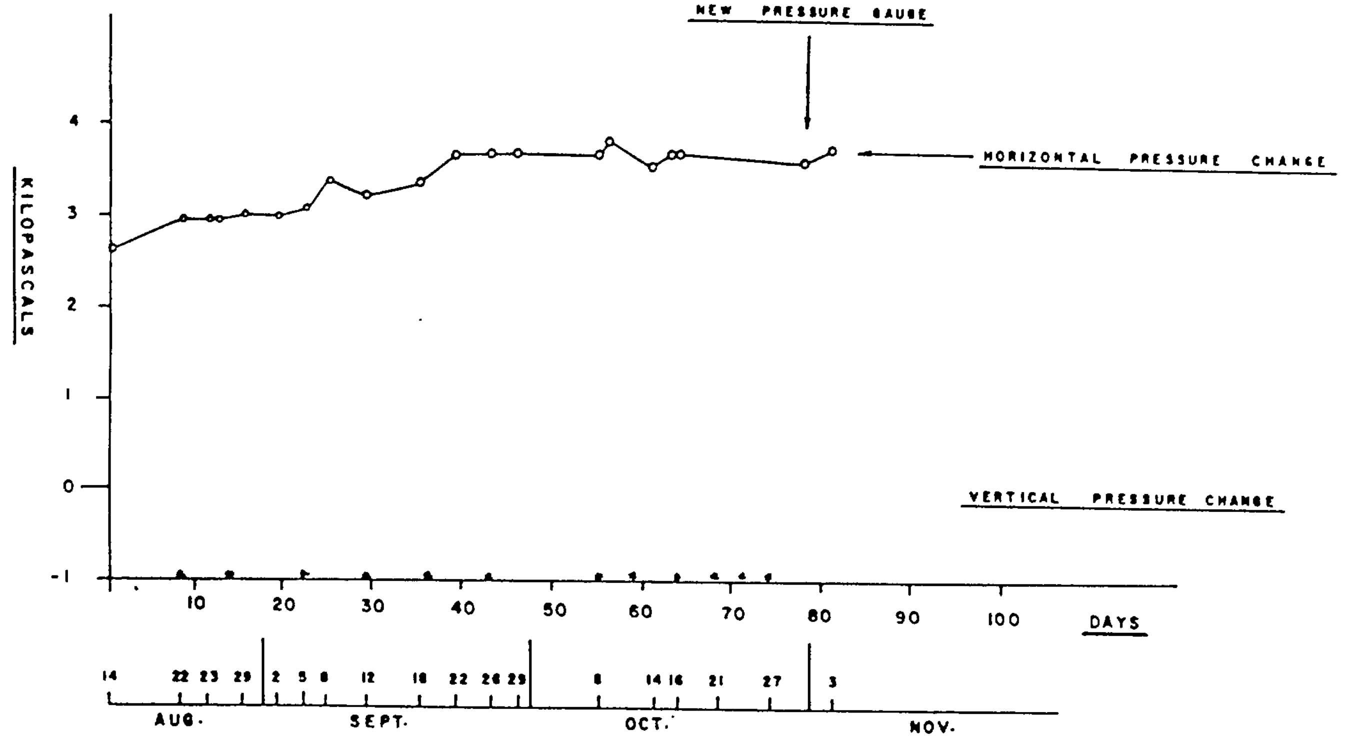
FIG : 15



(USBM) United States Bureau of Mines

Ultrasonic Measuring Device

FIG : 16



LOCKERBY MINE

LEVEL PRESSURE CELL — LOCATION 33-179 in 16:1 FILL

FIG: 17

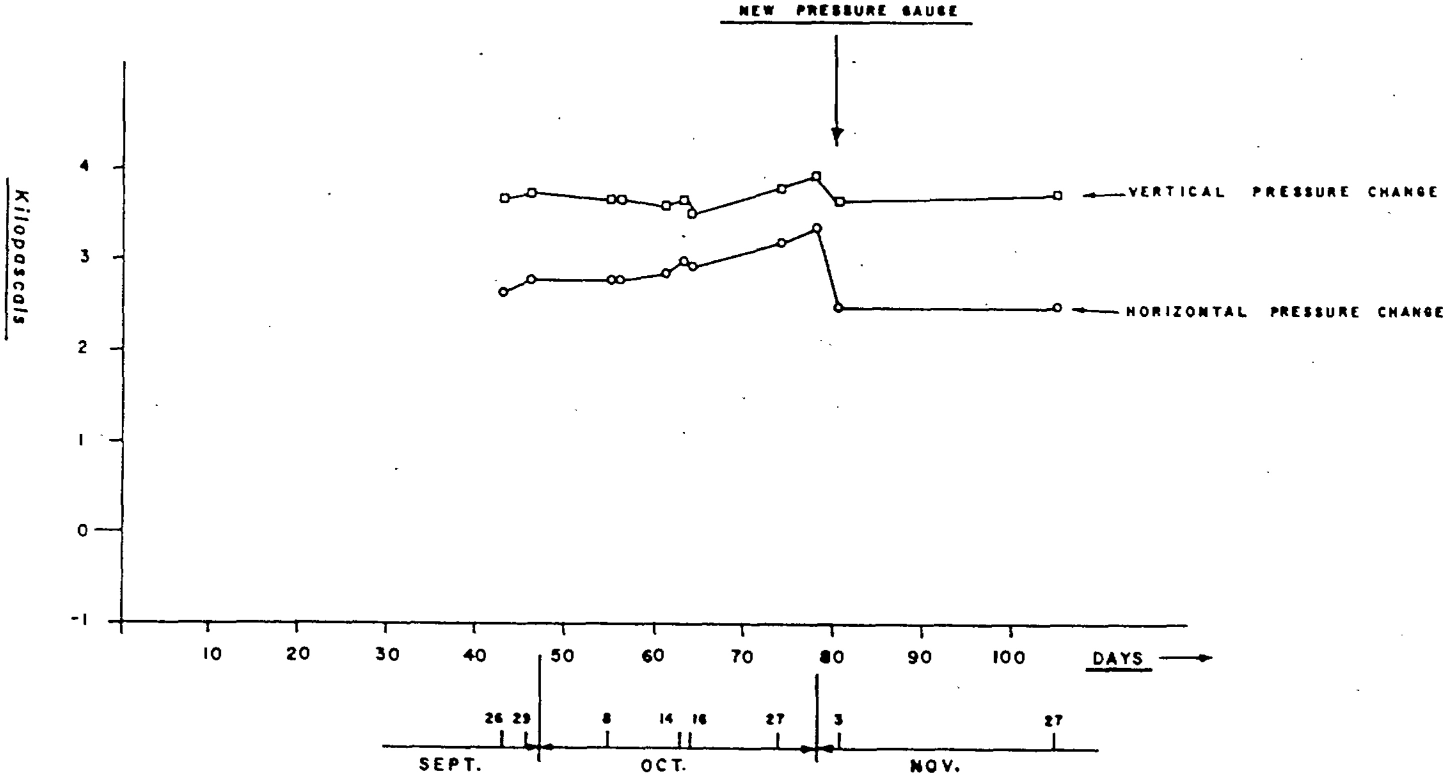
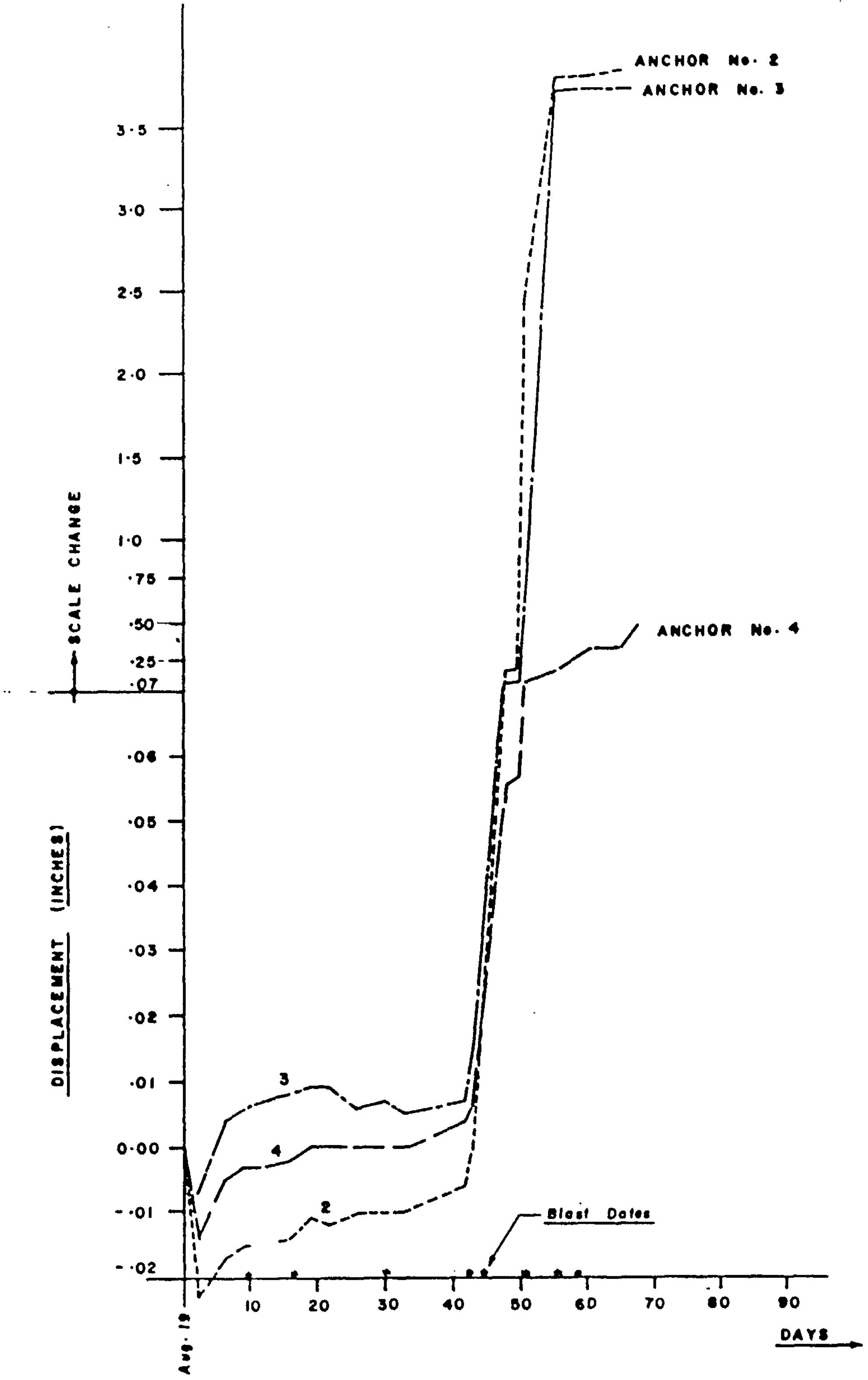


FIG : 18

LOCKERBY MINE

29-1 Sub LEVEL PRESSURE CELL — LOCATION 31-179 in 16:1 FILL

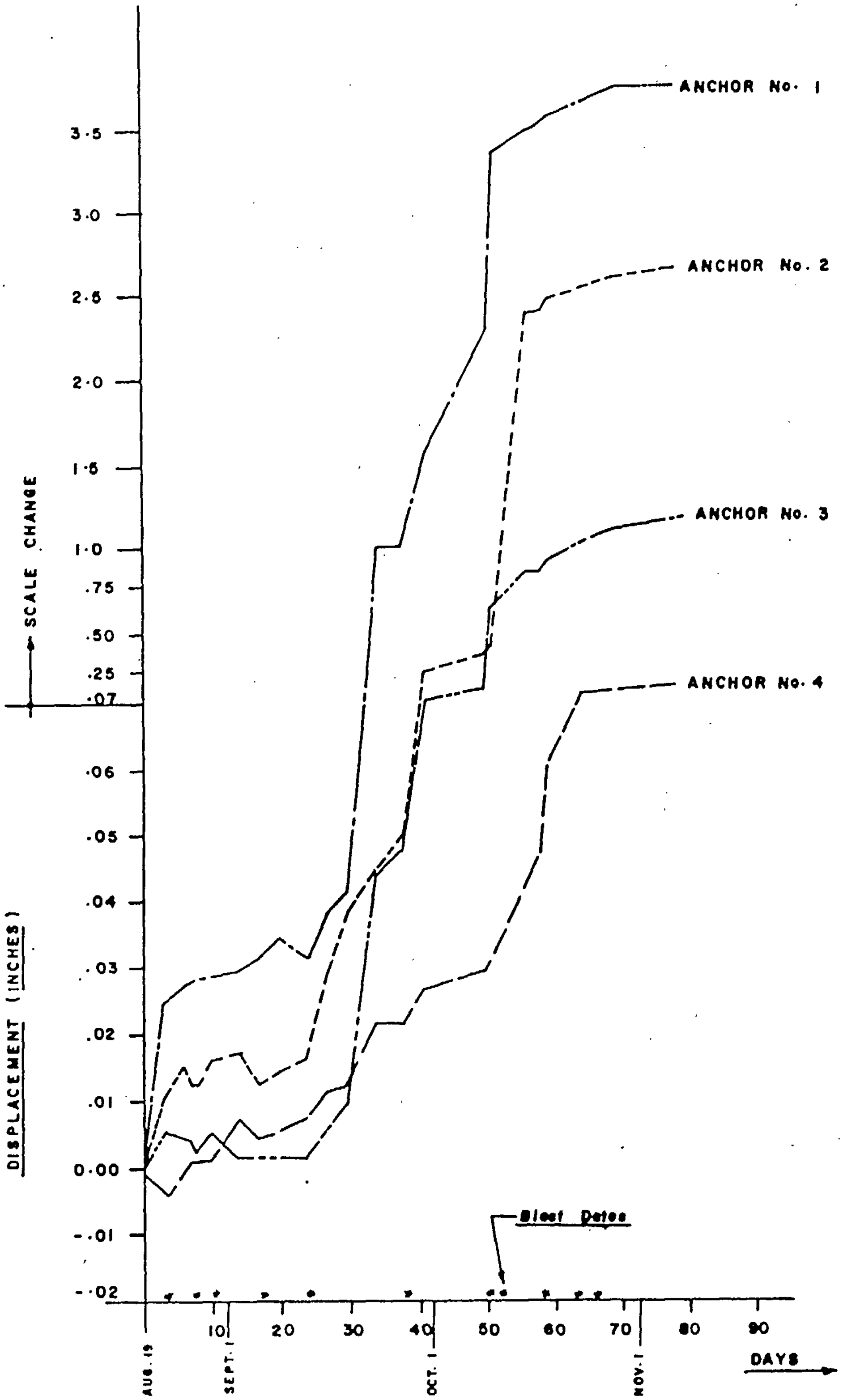
FIG : 18



EXTENSOMETER READING

LOCKERBY MINE — 2900 LEVEL — HOLE E - 1

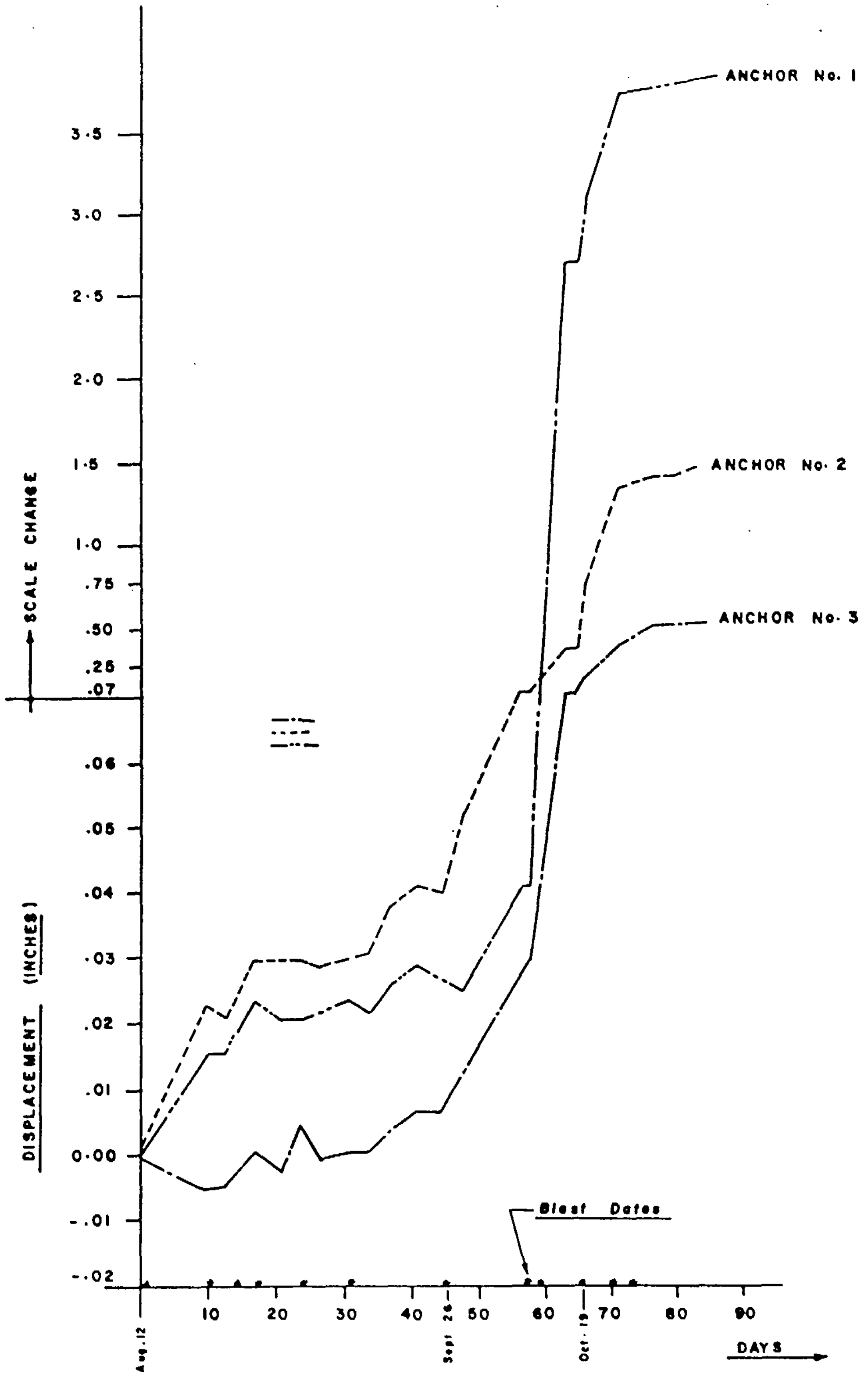
FIG: 19



EXTENSOMETER READING

LOCKERBY MINE — 2900 LEVEL — HOLE E-2

FIG: 20



EXTENSOMETER READING

LOCKERBY MINE — 2900 LEVEL — HOLE E-3

FIG: 21

FALCONBRIDGE MINE BACKFILL CANMET SILL MAT PROJECT	DIP 0° AZIMUTH 352°	LOGGED BY: A. BRADFIELD SEPT. 23, 1986	BOREHOLE NO G3
LOCKERBY MINE 3125 LEVEL	DRILLED BY CRAELIUS DIAMEC 251/260		SHEET 1 OF 1

SAMPLE NO.	FOOTAGE (FT.)	DESCRIPTION	REC. (%)	COMP. STR. (psi)	TAILS: CEMENT	MOIST (%)
		Grey, clay size, high moisture & cement, med. strength all loose	5			
	5					
258		Grey, silt size, high strength, med. cement & moisture no loose	100	130:3	17:1	16.0
	10	Light grey, clay size, high strength & cement, low moisture, all loose				
257		Very light grey, clay to silt size, very high strength & cement, low moisture, no loose	95	521.1	8:1	12.0
	15					
		Very light grey, clay size, very high strength & cement, low moisture, 10% loose	95			
	20	Very light grey, clay to silt size, very high strength & cement, low moisture, no loose	98			
259				448.7	11:1	12.7
	25	Very lt. gr. ,cl. to silt size, very high str. cem., low moist., 10% loose. At approx. 26.5ft, drk. med. moist., sand size for 6".	90			
	END30					
		OVERALL RECOVERY	81			

REMARKS: PERSONAL CONVENTIONS USED

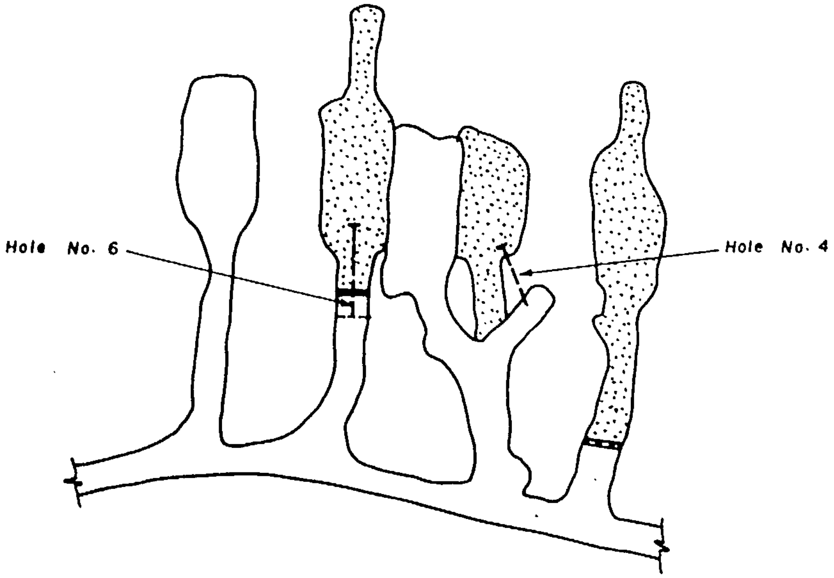
AVG.RANGES FOR COMP.STR. LOW 0 - 50 psi
MED. 50 - 100 psi
HIGH > 100 psi

SIZES: Low tails, high cement = clay size
Med tails, med. cement = silt size
High tails, low cement = sand size

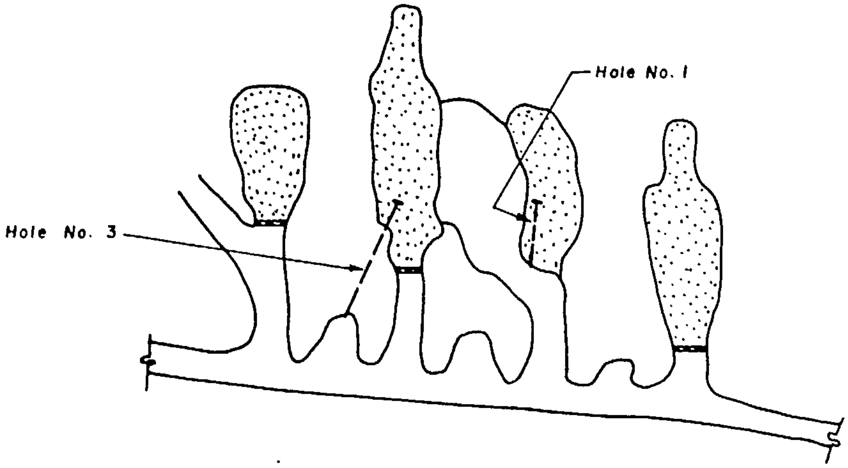
86-24B

Drill Core Mapping — Example

FIG : 22



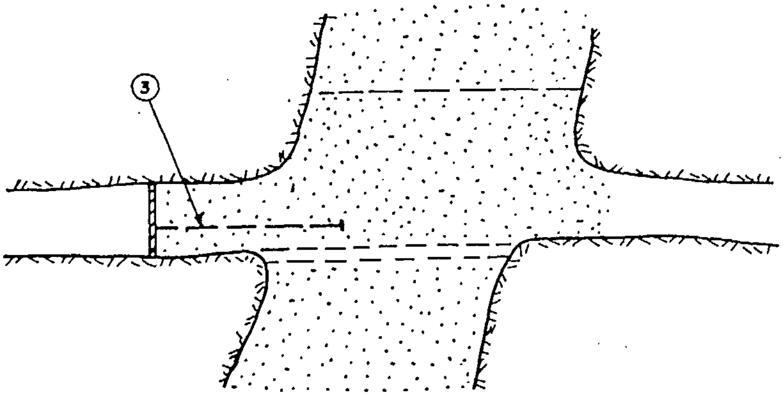
Plan of 29-1 Sub-Level



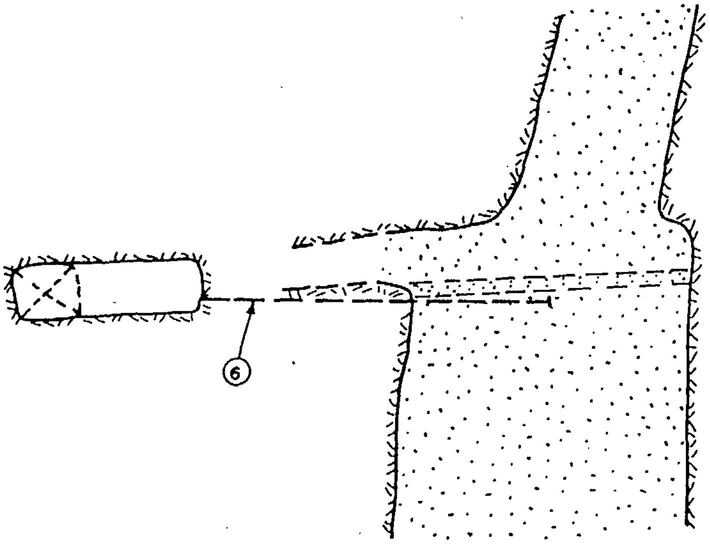
Plan of 3125 Level

Geophone Installations — Plan View

FIG: 23



Section



Section

Geophone Installations — Section View

FIG: 24

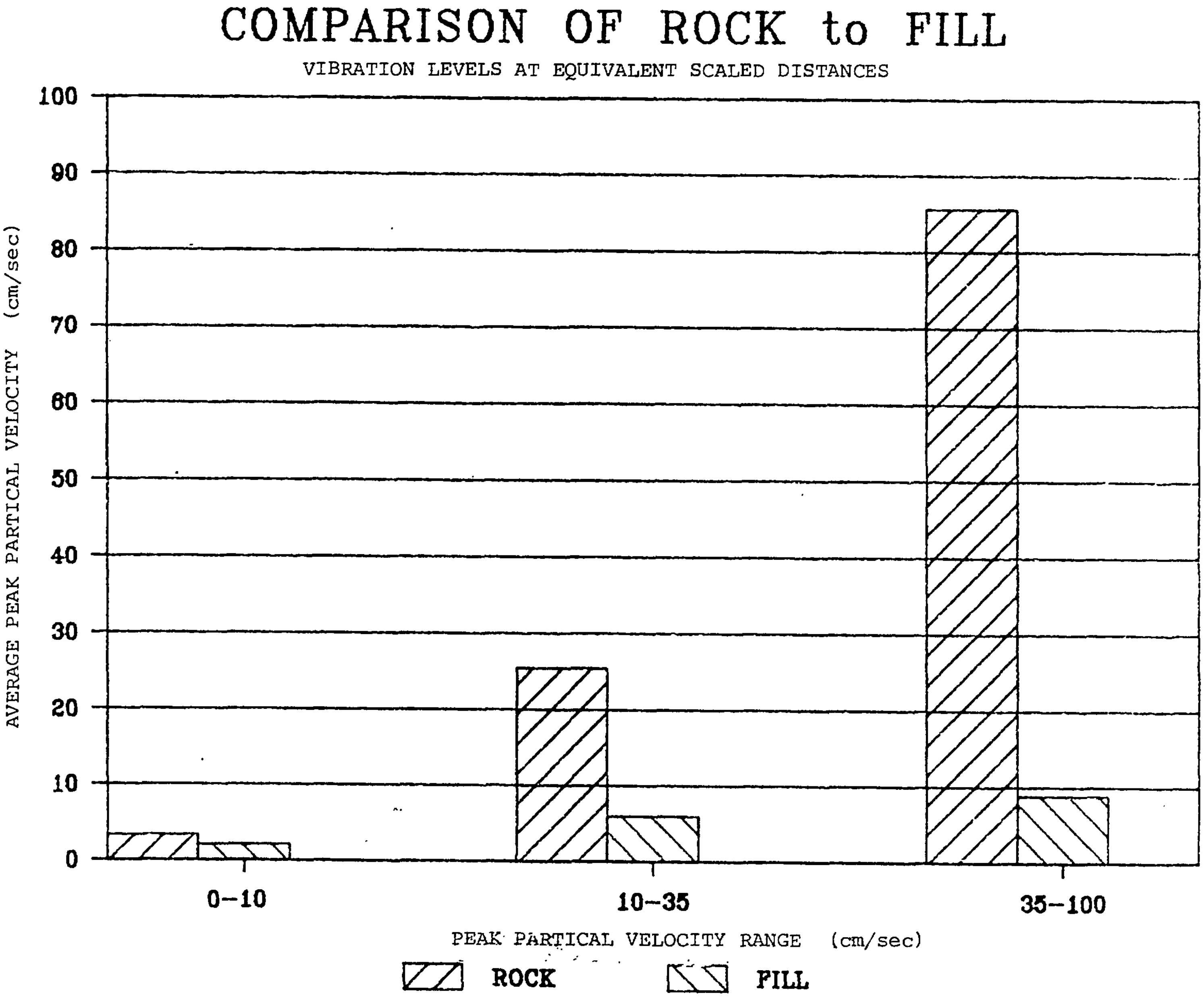
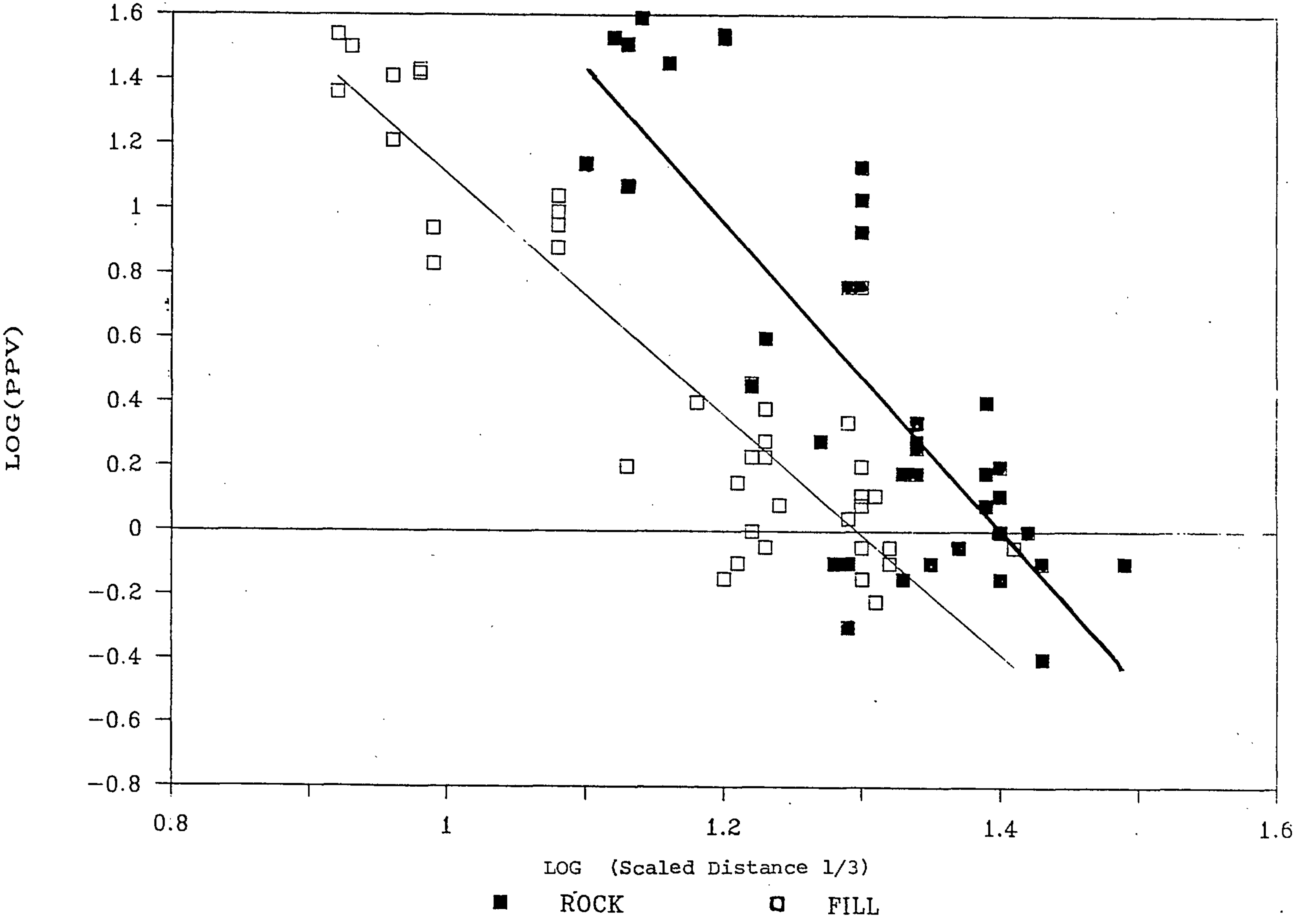

COMPARISON OF ROCK to FILL
VIBRATION LEVELS AT EQUIVALENT SCALED DISTANCES
AVERAGE PEAK PARTICAL VELOCITY (cm/sec)
100
90
80
70
60
50
40
30
20
10
0
0–10
10–35
35–100
PEAK PARTICAL VELOCITY RANGE (cm/sec)
ROCK
FILL

FIG: 25



VIBRATION ATTENUATIONS--- ROCK vs FILL

Blast Vibrations VS Scaled Distance

FIG: 26

CEMENT CONTENT ⁕⁕⁕ 22:1 vs 12:1 ⁕⁕⁕

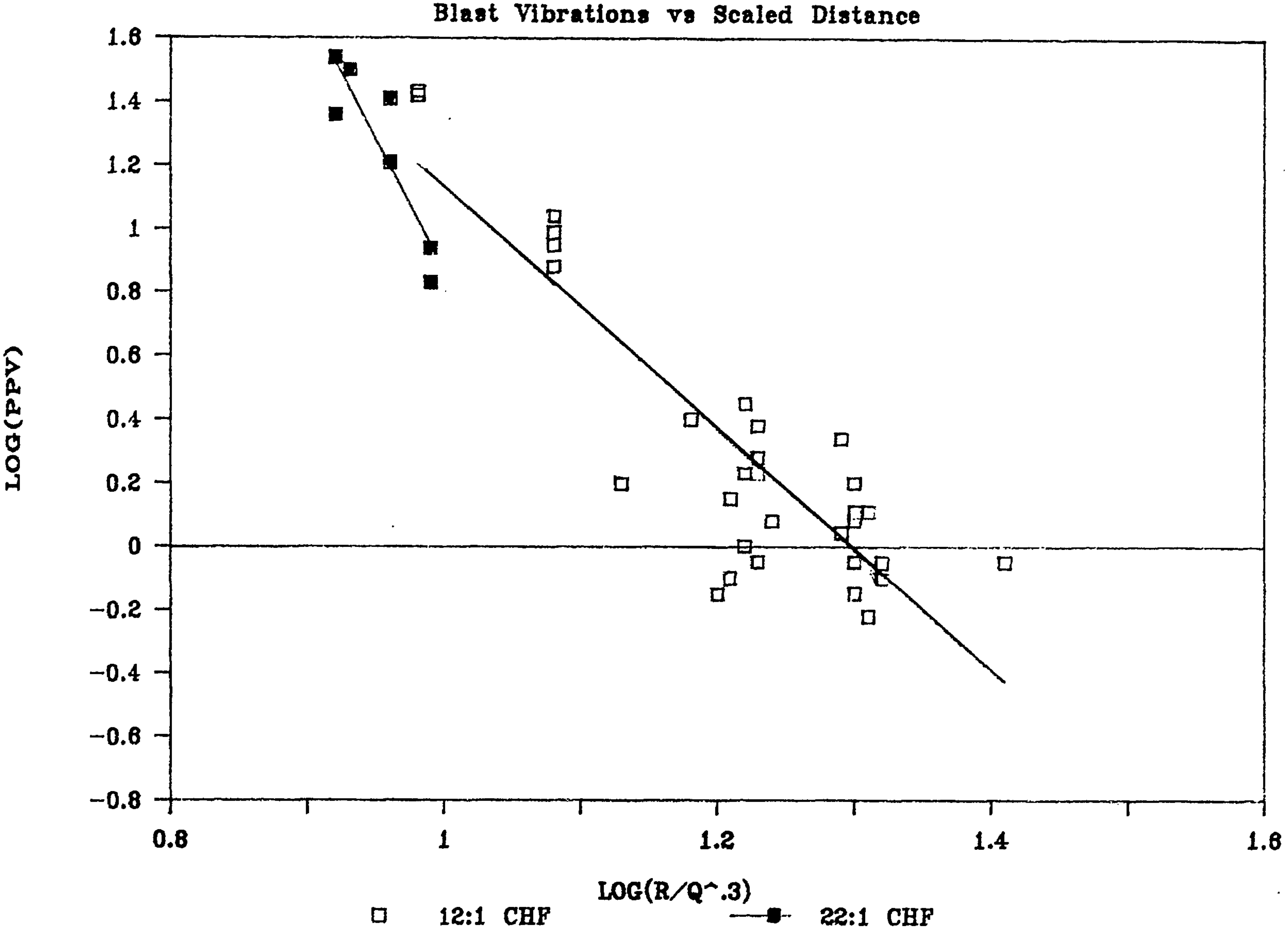
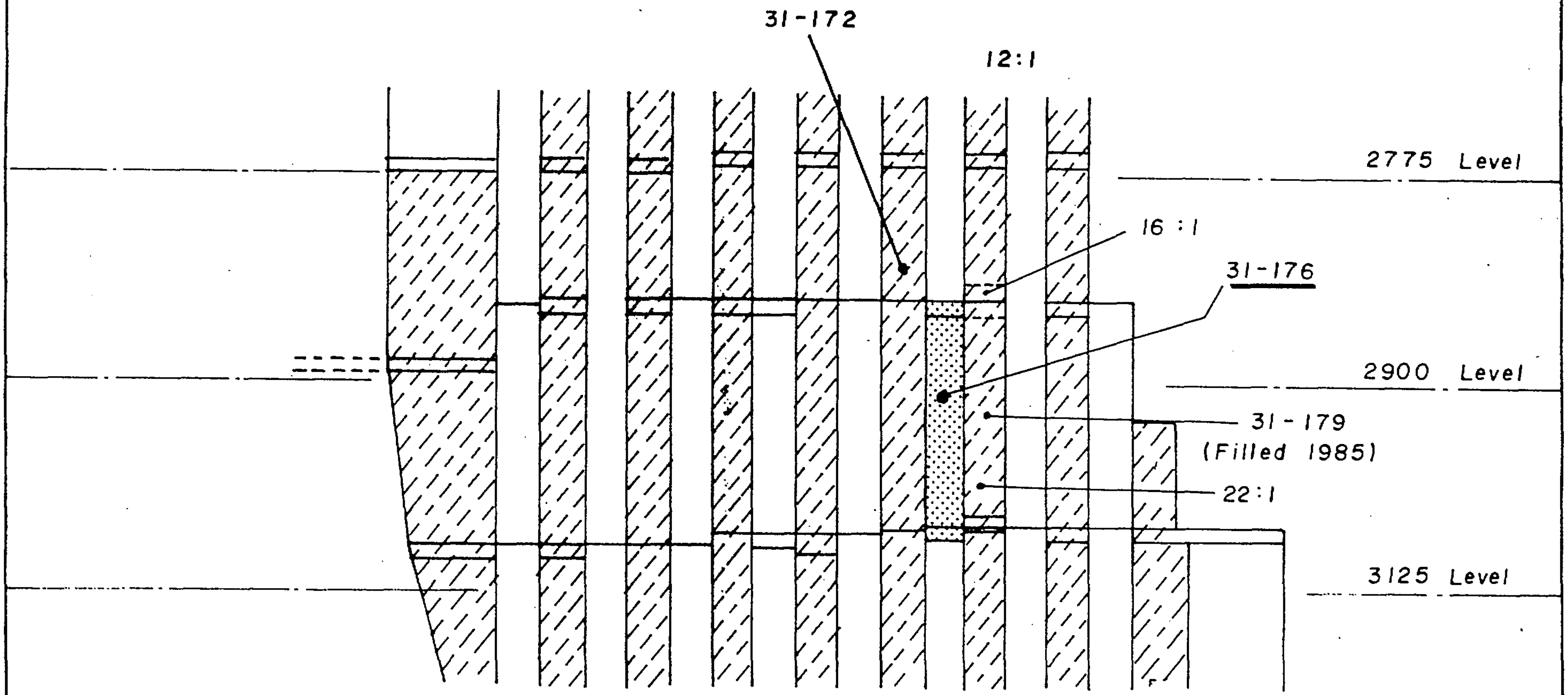


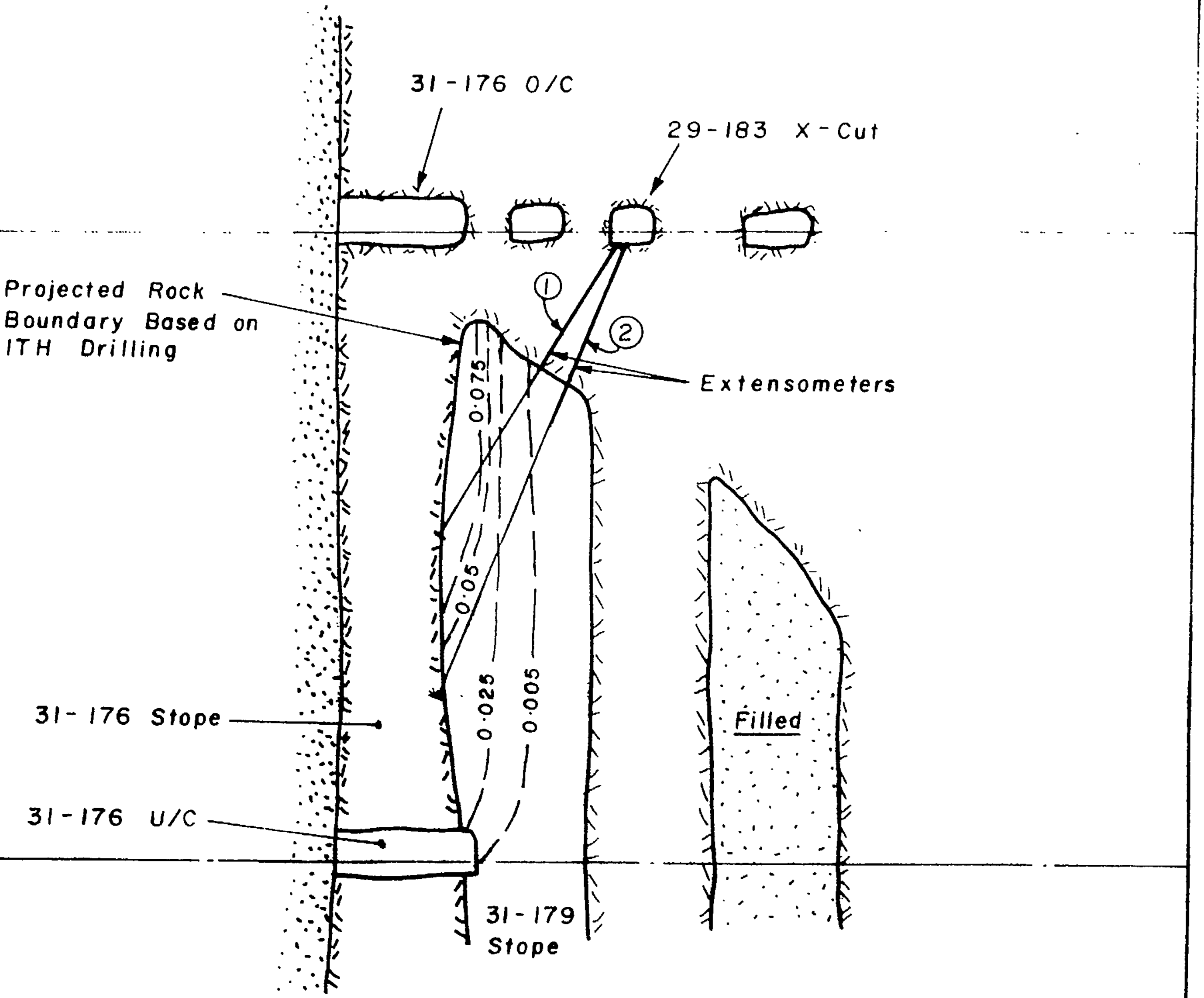
FIG: 27



31 - 176 Stope — Longitudinal Section — Stope Location

FIG : 28

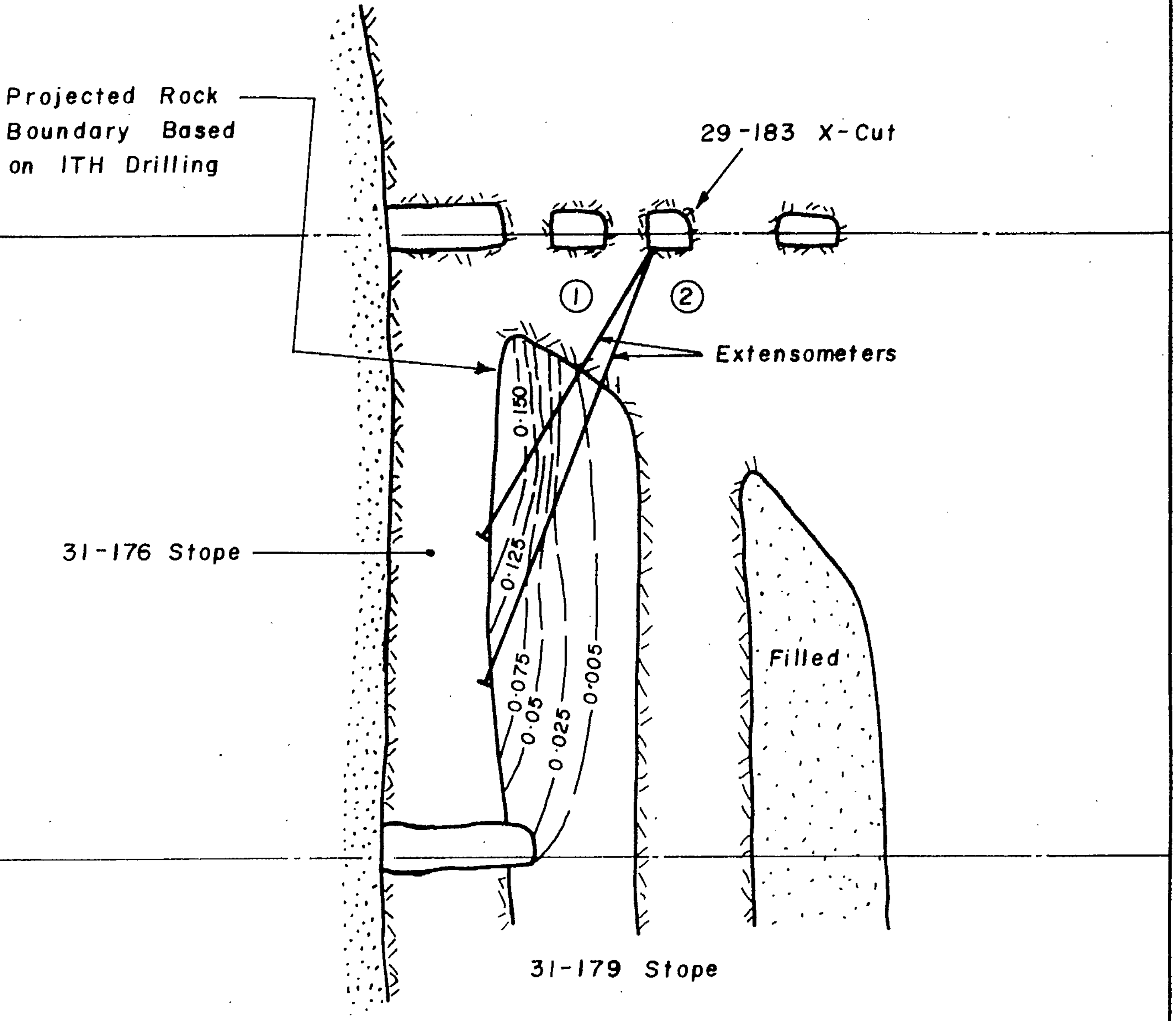
FIG : 26



Backfill Displacement Contours

X - Direction

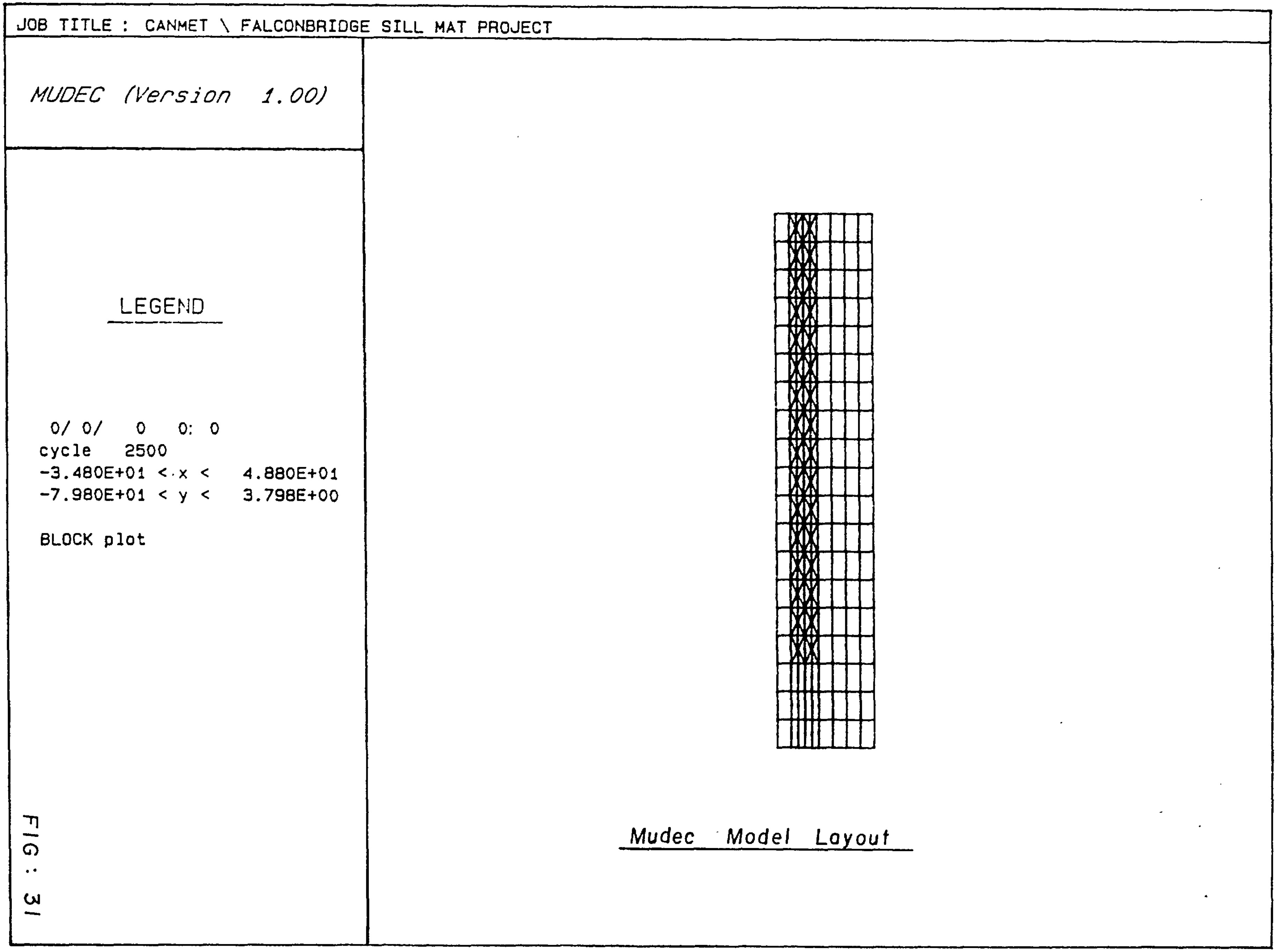
FIG : 29



Back Displacement Contours

Y - Direction

FIG : 30



JOB TITLE : CANMET \ FALCONBRIDGE SILL MAT PROJECT

MUDEC (Version 1.00)

LEGEND

0/ 0/ 0 0: 0
cycle 2500
-3.480E+01 < x < 4.880E+01
-7.980E+01 < y < 3.798E+00

BLOCK plot

Mudec Model Layout

FIG: 31

FILL MATERIAL PROPERTIES USED AS MUDEC INPUT

PROPERTY ONE	PROPERTY TWO
Bulk Modulus = 50E6 Pa	Bulk Modulus = 50E6 Pa
Shear Modulus = 37E6 Pa	Shear Modulus = 37E6 Pa
Cohesion = 0.2E6 Pa	Cohesion = 0.0 Pa
Friction (Joints) = 35 deg	Friction (Joints) = 20 deg
Tensile Str. (Joints) = 1E3 Pa	Tensile Str. (Joints) = 0.0 Pa
Density = 2100 kg/m*m*m	Density = 2100 kg/m*m*m

CONSTITUTIVE RELATION

Blocks = Elastic   Joints = Mohr Coulomb

FILL MATERIAL PROPERTIES

FIG: 32

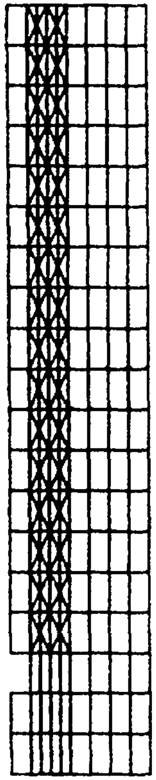
JOB TITLE : CANMET \ FALCONBRIDGE SILL MAT PROJECT

MUDEC (Version 1.00)

LEGEND

```
 0/ 0/   0   0:  0
cycle   5000
-3.481E+01 < x <   4.879E+01
-7.980E+01 < y <   3.798E+00

BLOCK plot
```



Mudec Model Layout

Undercut Removed

FIG : 33

JOB TITLE : CANMET \ FALCONBRIDGE SILL MAT PROJECT

MUDEC (Version 1.00)

LEGEND

0/ 0/ 0 0: 0
cycle 5200
-3.481E+01 < x < 4.879E+01
-7.980E+01 < y < 3.798E+00

BLOCK plot
XX-stress contours
Contour interval= 2.500E+05
Number of contours/color= 3
Min=-3.000E+06 Max= 0.000E+00

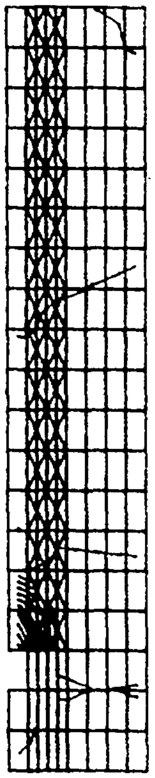


FIG: 34

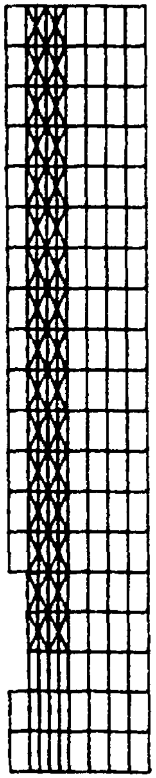
JOB TITLE : CANMET \ FALCONBRIDGE SILL MAT PROJECT

MUDEC (Version 1.00)

LEGEND

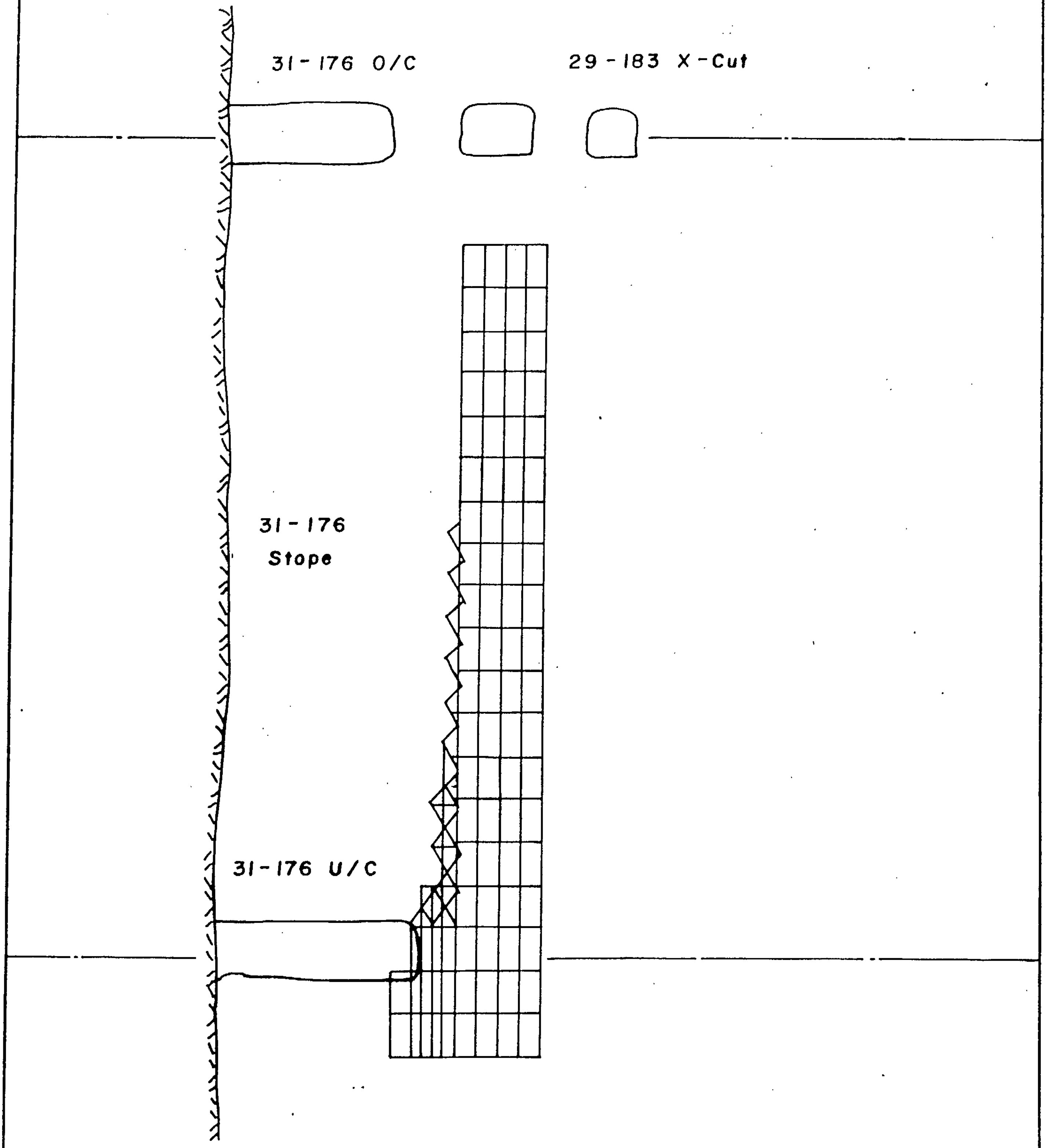
```
 0/ 0/   0   0:  0
cycle  16000
-3.481E+01 < x <   4.879E+01
-7.980E+01 < y <   3.798E+00

BLOCK plot
```



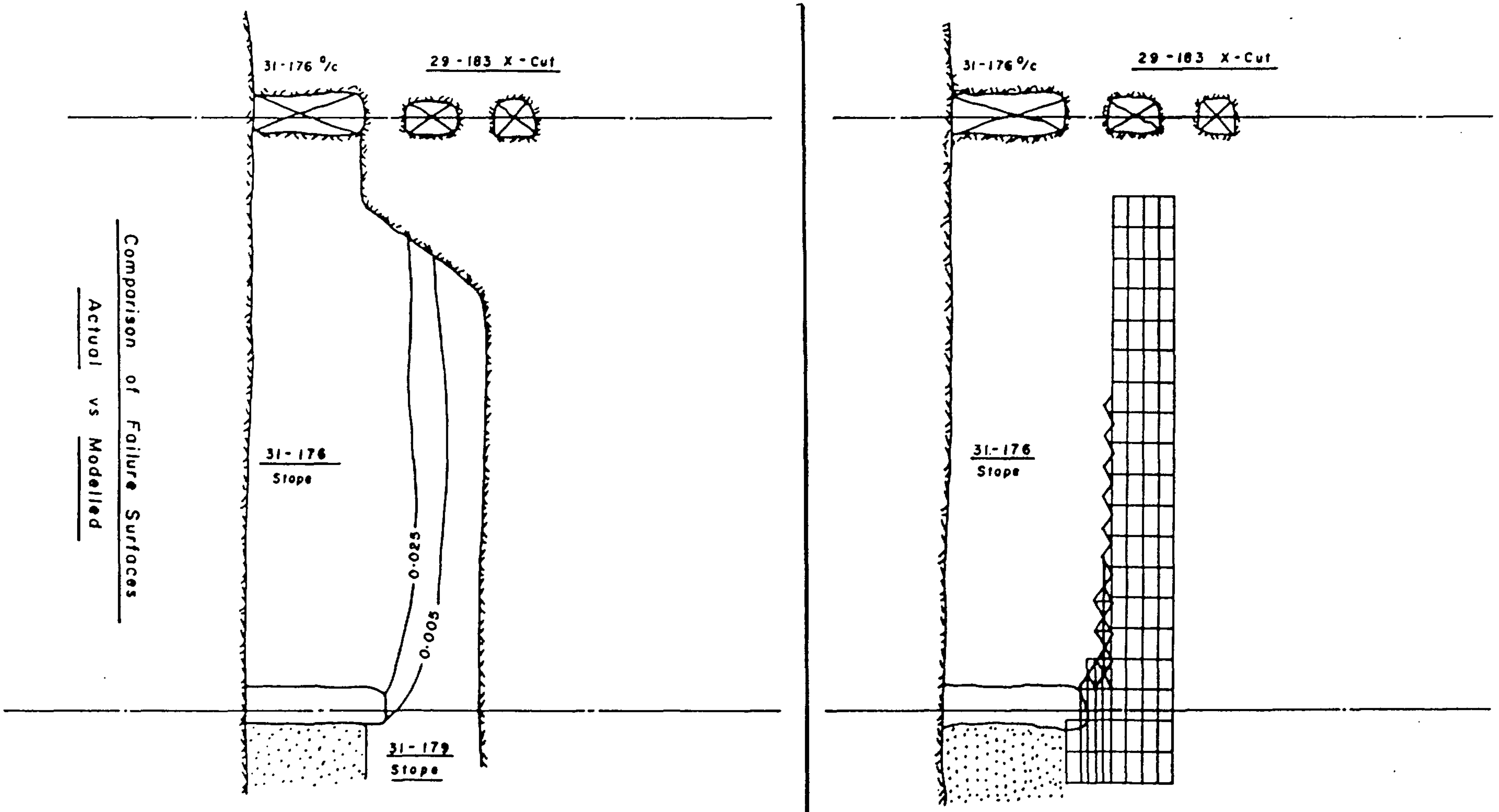
Mudec Model — Mining Cycle

FIG: 35



Model Final Profile

FIG : 36



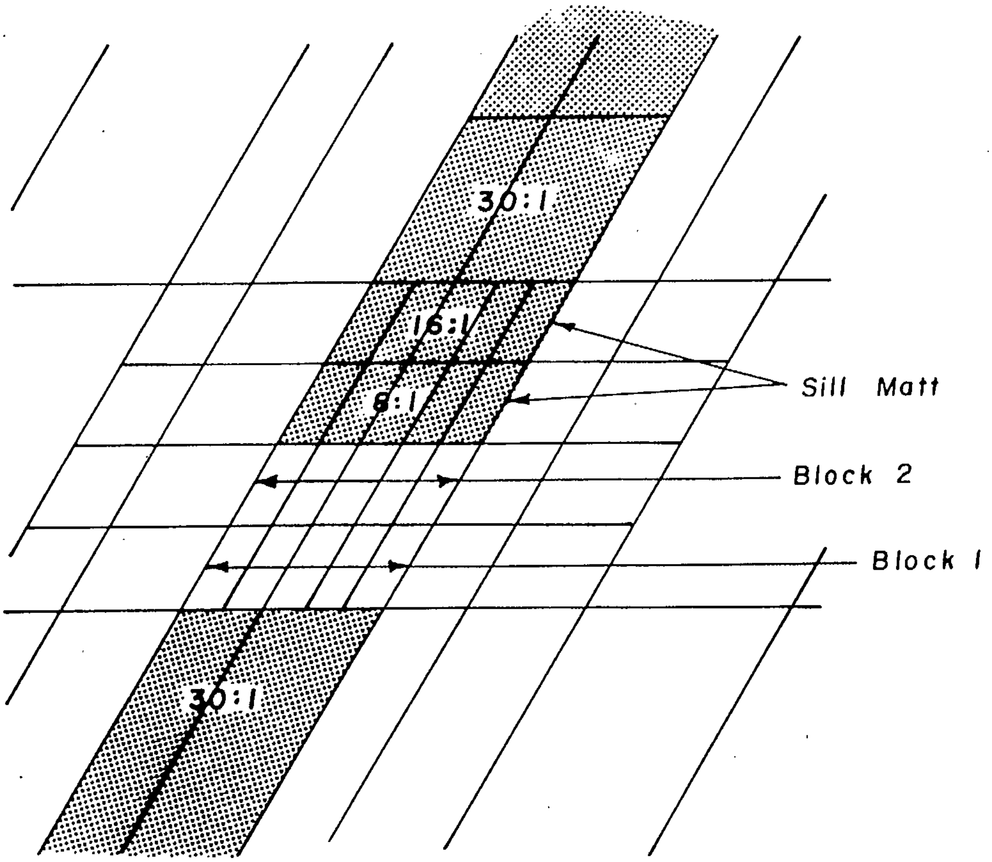
Failure Surface Measured By Instrumentation

Failure Surface Generated By Model

Comparison of Failure Surfaces

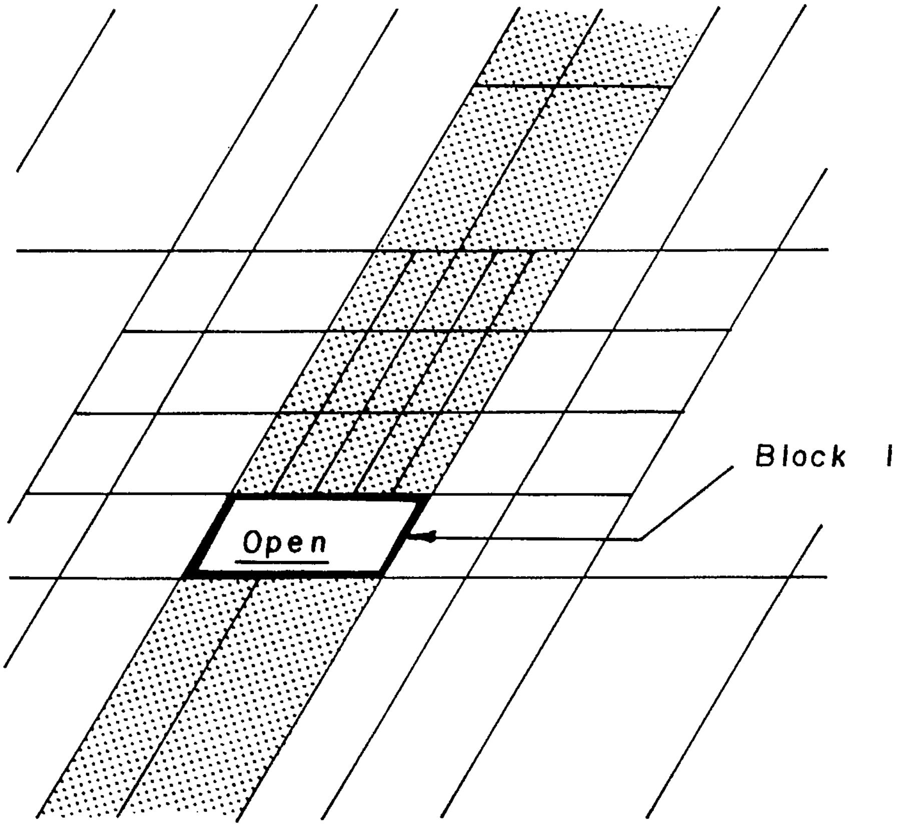
Actual vs Modelled

FIG: 37



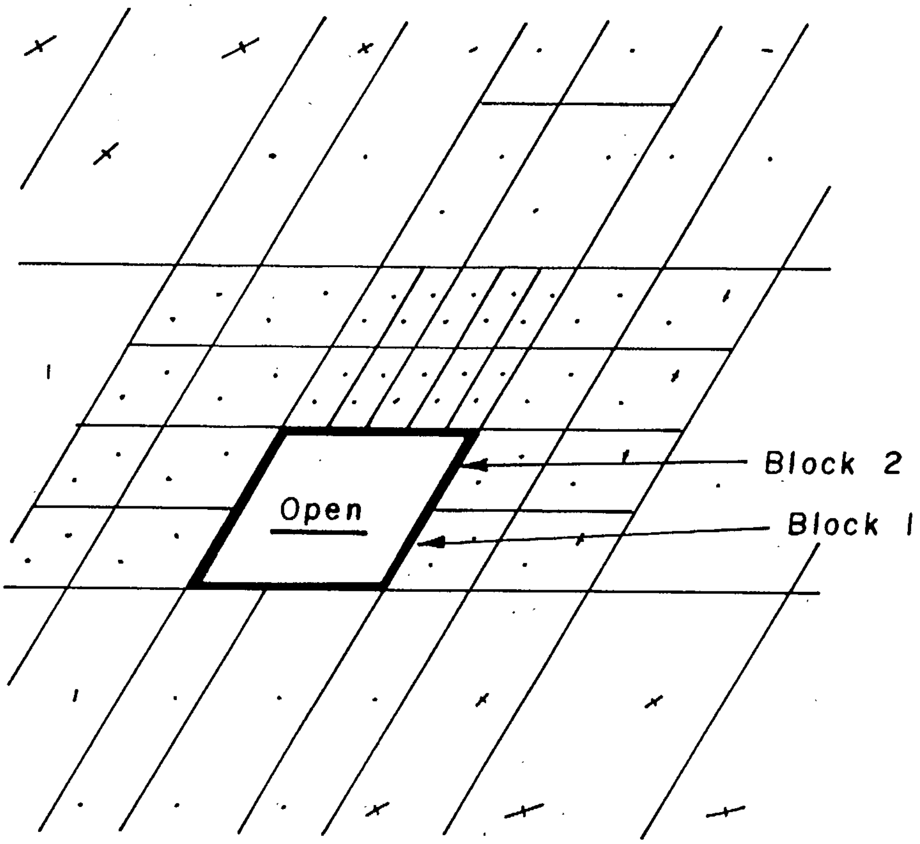
Mining Below a Sill Mat

FIG : 38



Removal of Second Last Cut

FIG : 39



Removal of Final Cut

FIG : 40