PROCEEDINGS OF THE THIRD INTERNATIONAL SYMPOSIUM
ON MINE PLANNING AND EQUIPMENT SELECTION
ISTANBUL / TURKEY / 18 - 20 OCTOBER 1994

Mine Planning and Equipment Selection 1994

Edited by

A.G. PAŞAMEHMETOĞLU & C. KARPUZ
Middle East Technical University, Ankara, Turkey
Ş. ESKİKAYA
Istanbul Technical University, Turkey
T. HIZAL
Turkish Coal Enterprises, Ankara, Turkey

OFFPRINT

A.A. BALKEMA / ROTTERDAM / BROOKFIELD / 1994

Mine Planning and Equipment Selection, Paşamehmetoğlu et al. (eds) © 1994 Balkema, Rotterdam, ISBN 90 5410 327 2

Simulation of exploitation alternatives in marble quarries based upon a recovery index

J. Ribeiro & H. G. Pereira
CVRM/IST, Mining Department, Lisbon, Portugal

ABSTRACT : To perform the exploitation planning in marble quarries in the context of modern information technologies, it is needed to forecast the value of the blocks before extraction. To cope with this problem, a methodology, based on observable attributes in the working faces of the quarry and on expert information, was developed to obtain an index that summarises the expected local recovery. Once obtained this index by Correspondence Analysis, its estimation in unknown blocks by Kriging allows to produce an economic model of the quarry, based on which the exploitation planning may proceed. The simulation, by a Monte Carlo based technique, of the quarry development provides sequences of extraction for each exploitation alternative, compared on the grounds of the Discounted Cash Flow (DCF) statistical distribution. The application of this methodology, adjusted to specific economical/environmental conditions, entails obviously an improvement on productivity, reducing to a minimum the non-economical waste blocks that damage the environment. A case study regarding a Portuguese marble quarry is presented, for the purpose of illustrating the proposed methodology.

1. INTRODUCTION

The economic viability of ornamental rocks exploitation depends strongly upon the minimum dimensions of "Good" blocks that it is possible to be extract, taking into account the downstream transformation processes and the intrinsic commercial value of the stone. The reduction of waste blocks is another requirement (intimately related with the minimisation of production costs and environmental damage), which also contributes to the rational exploitation of the deposit. The success of the venture depends strongly upon the procedure by which the exploitation plan is performed. The basic problem of that procedure is the difficulty to know the expected *in situ* material value, prior to its exploitation.

Indeed, as opposed to the other mineral resources, whose value is straightforward to define by the ore quotation and concentration (expressed by only one number - ore grade), in the case of ornamental rocks the management must establish, somehow subjectively, the value of each unit submitted to exploitation planning. This value is based upon a set of intrinsic and extrinsic factors.

Given the impossibility of controlling clearly the extrinsic factors that give rise to an extremely volatile market, the research effort reported in this paper focus on the intrinsic factors. In this respect, the formulation of mathematical models, which combine descriptive geological methodologies and analytical methods, constitutes a sound basis for the mathematical characterisation of rock deposits, since they permit an objective analysis of discontinuities' properties and the integration of subjective information, through appropriate codification.

In the case of ornamental rocks, the quality of the material is not expressed by only one number, but depends upon a set of attributes of different types - Boolean variables, as presence/absence of veinlets; nominal variables, as colour and texture; ordinal variables, as granulometry; real variables, as density of fractures.

Thus, the intrinsic characteristics must be synthesised in a single quantitative parameter, which constitutes the basis for exploitation planning and economic evaluation. The definition of this parameter, denoted quality index of the ornamental rocks (or recovery index, in a particular formulation, depending only upon fracture attributes, *cf.* Albuquerque (1993) and Ribeiro (1994)), is based upon an innovative methodology supported by an algorithm of Correspondence Analysis (CA), applied as a discriminant procedure (Benzécri (1980), Pereira (1988)) and modified to fit the specific features of that problem (Pereira *et al*. (1993)).

That methodology consists essentially of combining the measured and observable attributes in the working faces of the quarry, and projecting them in a scale fixed by two poles or archetypes, which materialise the extremes ("Good" and "Bad") of the classes in which the attributes are categorised. The application of that methodology (described in Pereira *et al.*(1993)) to fracture attributes - length, curvature, number of intersections, presence of veinlets, dip and fracture density - measured in the marble quarry of Rosal - located in south-east Portugal - allows to obtain a regionalized variable (RV), denoted recovery index, which gives the ranking order of each experimental "support" (non-overlapping window that sweeps the working faces of the quarry) where the attributes are observed and digitised.

This index combines in a single measure the geological features that govern economical recovery, and can be used as the basis for value assignment to blocks, prior to their extraction, being therefore part of the objective function that allows the comparison of alternative design solutions for exploitation planning.

Obviously, the index, once estimated by kriging in a grid of unknown blocks of the quarry, gives only an arrangement of the blocks in an arbitrary quality value scale. Hence, an economic function, transforming the index values into Portuguese currency (PTE[1]), should be adjusted on the basis of past experience, in order to proceed the economical analysis of exploitation alternatives.

2. ESTIMATION OF THE RECOVERY INDEX

The experimental values of the index, viewed as a RV, are used in a geostatistical study that gives the estimated values in unknown blocks. Through the variogram function, it is possible to evaluate the spatial continuity of that RV in each level of the quarry.

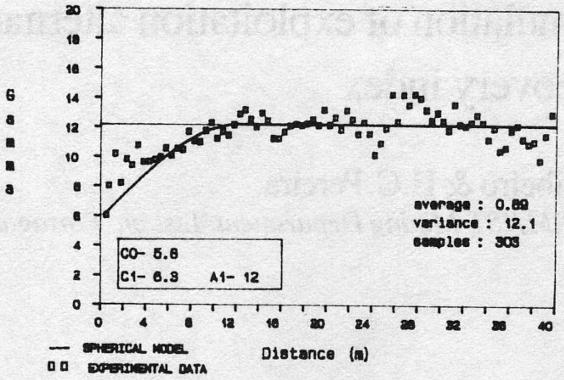


Fig. 1 - Variogram of the index (level 1)

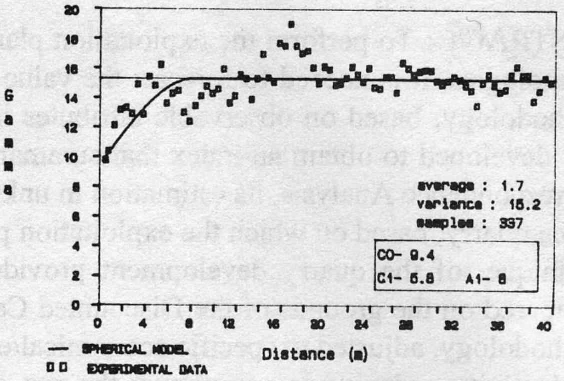


Fig. 2 - Variogram of the index (level 2)

Figures 1 e 2 show, for each level of the quarry, the omni-directional variograms of experimental supports and the fitted theoretical models. Both variograms exhibit basically the same structure, being modelled by spherical schemes of 12 and 8 m ranges, respectively.

Since the index is calculated by an iterative process, its value depends upon some controlling parameters (weight of each attribute, dimension of the sampling window and classes of attributes), which can be modified during the algorithm.

Indeed, the presented variograms (obtained after a set of trials conducted after modification of the above mentioned parameters) show a good structural representativeness of the index. The variographic study gives rise to a structural validation, which complements the expert validation performed further with the results of the estimation.

Figures 3 and 4 show the maps of each level where the index was estimated by kriging in a 1.5 x 1.5 m grid. The zone where the index is predicted is bounded by the variogram range, ensuring extrapolation.

An overall analysis of the maps of figures 3 and 4 permits to validate the model in global terms, since the higher expected recovery of level 2 (50 % of

---

[1] 1 $US ≅ 175 PTE

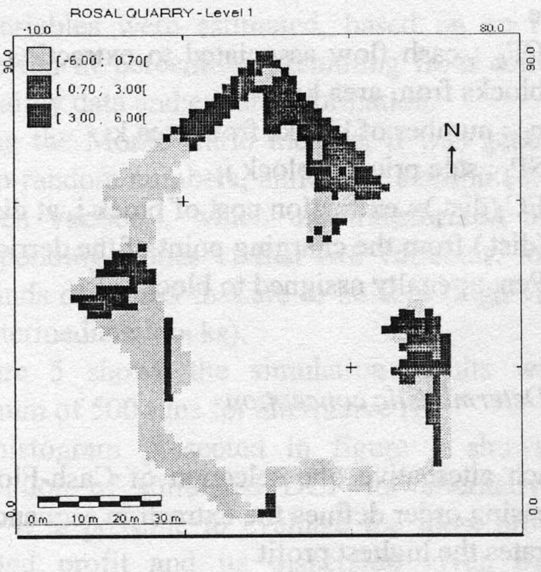


Fig. 3 - Map of kriged blocks (level 1)

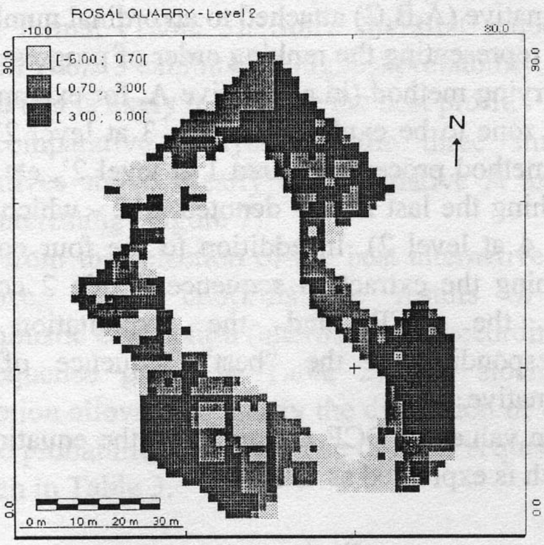


Fig. 4 - Map of kriged blocks (level 2)

good blocks, approximately) matches the historic information provided by the enterprise management, as opposed to a lower recovery predicted and observed in level 1 (20 % of good blocks, approximately).

3. ECONOMIC EVALUATION

3.1 Basic hypotheses, definition of exploitation alternatives and cash flow calculation

In order to perform the economic evaluation by calculating an objective function based on the Discounted Cash Flow (DCF), a set of hypotheses, given below, must be established :

- absence of investment, because the two levels are currently in exploration, and additional workings and/or acquisition of equipment are not required;
- sale price time invariant, depending only on the category of the material and on the index, as follows :

$$\text{- high valued blocks} = 80\,000 \text{ PTE/m}^3 \text{ x V x } \frac{\text{Index} - 1.5}{3}$$

$$\text{- intermediate blocks} = 50\,000 \text{ PTE/m}^3 \text{ x V x } \frac{\text{Index} + 0.45}{2.3}$$

$$\text{- low valued material} = 0 \text{ x V x Index}$$

- extraction costs time invariant, depending only on the distance between the location of each block and the charging point of the derrick;
- input penalties to each kind of blocks, in order to account for environment damage, as follows:

$$\text{- high valued blocks} = 0 \text{ x V x Index}$$

$$\text{- intermediate blocks} = 7\,500 \text{ PTE/m}^3 \text{ x V x } \frac{\text{Index} - 4.15}{-2.3}$$

$$\text{- low valued material} = 15\,000 \text{ PTE/m}^3 \text{ x V x } \frac{-\text{Index} + 4.05}{6.7}$$

- average production rate of 50 blocks/month;
- capital opportunity cost time invariant equal at 12%/year;
- time of stock different to each kind of blocks, as follows :

- high valued blocks = 15 days
- intermediate blocks = 30 days
- low valued material put in the waste disposal area

- absence of depreciation.

The technique of Discounted Cash Flow (DCF) was used as a quantitative support to permit the selection between three alternatives of exploration (A, B, C), and to define the best exploration sequence in each of them.

The different alternatives were based on a division of each level in four equal areas (1 to 4), and are described below :

- Alternative A - Step 1 : exploration of blocks from level 2, without overlying blocks (level 2'); Step 2 : exploration by areas (first the blocks of level 1 and after the blocks from level 2);
- Alternative B - extraction by areas (first the blocks from level 2', then the blocks from level 1 and then the last blocks from level 2);
- Alternative C : Step 1 : extraction of blocks from level 1; Step 2 : extraction of blocks from level 2.

Table 1 - Cash-flows of each area from each level

Areas	Characteristics	Level 1	Level 2	Level 2'
1	Average Index	1.57	3.12	2.62
	Cash-Flow (10^3 PTE)	55260	188782	58479
2	Average Index	0.69	2.25	1.80
	Cash-Flow (10^3 PTE)	19225	132463	48964
3	Average Index	-0.29	3.01	2.40
	Cash-Flow (10^3 PTE)	-13522	189451	87439
4	Average Index	0.52	1.58	1.56
	Cash-Flow (10^3 PTE)	18535	88820	18807

Table 2 - Extraction sequences

Level	Areas				DCF (10^3 PTE)	Time (months)
	1	2	3	4		
1	A5	A7	A9	A11	307620	198
2	A6	A8	A10	A12		
2'	A2	A3	A1	A4		
1	B2	B8	B5	B11	278078	198
2	B3	B9	B6	B12		
2'	B1	B7	B4	B10		
1	C1	C2	C4	C3	232577	198
2	C8	C10	C6	C12		
2'	C7	C9	C5	C11		

Table 3 - Extraction sequences obtained by simulation for alternative A

Level	Areas				Probability* (%)
	1	2	3	4	
1	A5	A7	A9	A11	77.6
2	A6	A8	A10	A12	
2'	A2	A3	A1	A4	
1	A5	A7	A11	A9	13
2	A6	A8	A12	A10	
2'	A2	A3	A1	A4	
1	A5	A9	A7	A11	7.4
2	A6	A10	A8	A12	
2'	A2	A3	A1	A4	

*For the other sequences, the probability is 2 %

The equation [1] allows the calculation of cash-flows of each area in each level, and its results are synthesised in Table 1.

$$CF_k = \sum_{j=1}^{n_k} \left[SP_j - EC_j\left(dist_j\right) - Pen_j \right] \qquad [1]$$

where :

- CF_k : cash flow associated to extraction of all blocks from area k;
- n_k : number of blocks from area k;
- SP_j : sale price of block j;
- $EC_j(dist_j)$: extraction cost of block j, at distance ($dist_j$) from the charging point of the derrick;
- Pen_j : penalty assigned to block j.

3.2. Deterministic conception

In each alternative, the selection of Cash-Flows in decreasing order defines the extraction sequence that generates the highest profit.

These results are summarised in Table 2 under a matrix format, where the extraction sequence of each area at each level is symbolised by a code for the alternative (A,B,C) attached to an ordinal number (1-12), representing the ranking order of progress of the quarrying method (in alternative A, for example, the first zone to be exploited is area 3 at level 2', then the method proceeds to area 1 at level 2', etc., until reaching the last zone - denoted A12 - which is the area 4 at level 2). In addition to the four columns defining the extraction sequence, Table 2 contains also the DCF and the exploitation time corresponding to the "best" sequence of each alternative.

The values of DCF are given by the equation [2], which is expressed as follows :

$$DCF_k = \sum_{j=1}^{na_k} \sum_{t=1}^{T} \frac{CF_j}{(1+i)^t} \qquad [2]$$

where :

- DCF_k : discounted cash flow of alternative k;
- na_k : number of areas from alternative k;
- T : exploitation and stock period;
- CF_j : cash flow from area j;
- i : capital opportunity cost;
- t : time of extraction and stock of area j.

The analysis of results of the deterministic conception leads to the conclusion that a maximum DCF is obtained in alternative A, according to the sequence given in Table 2.

3.3. Stochastic conception

Due the great uncertainty associated to the sale price of the blocks and to the respective time of stock, the cumulative density functions of probability for that two variables were estimated, based on an rough calculation of percentiles, stemming from collected uncertainty data and expert information.

Using the Monte Carlo method, it was generated pseudo-random numbers, uniformly distributed, (one by each variable), which are transformed in the corresponding values of that two variables, for the two kinds of blocks that are to be sold (high valued and intermediate blocks).

Figure 5 shows the simulation results with a minimum of 500 runs for alternative A.

The histogram presented in figure 6 shows the distribution of simulated DCF for alternative A, where it is possible to evaluate the most probable expected profit and its dispersion given by the standard deviation.

The stochastic conception also allows to obtain the histogram of the extraction sequences, given under a matrix format (Table 3). Since the first sequence given in Table 3 exhibits the highest probability, it is the one that is likely to produce the best profit.

The comparative analysis of the three studied alternatives shows clearly the alternative A as the most interesting (Figure 7).

Apart from the selection of the best alternative and sequence, which confirms the results of the deterministic conception (alternative A, according to the sequence given in Table 2), the stochastic conception allows to quantify the dispersion of DCF and the probability of occurrence of other sequences, as given in Table 3.

4. CONCLUSIONS

The proposed methodology, based on the establishment of a quality index that combines the observable attributes, permits to quantify the value of the material in marble quarries, prior to the extraction. Once estimated that value by kriging, an economic analysis by DCF can be performed, leading to a decision on the best exploitation alternative and extraction sequence. A stochastic Monte Carlo simulation based on the economic model allows to quantify the dispersion of the DCF and the probability of occurrence of plausible extraction sequences using the same basic methodology.

Further work is being conducted on the improvement of the index, in order to account for all observable attributes on to match accurately the commercial value of the material.

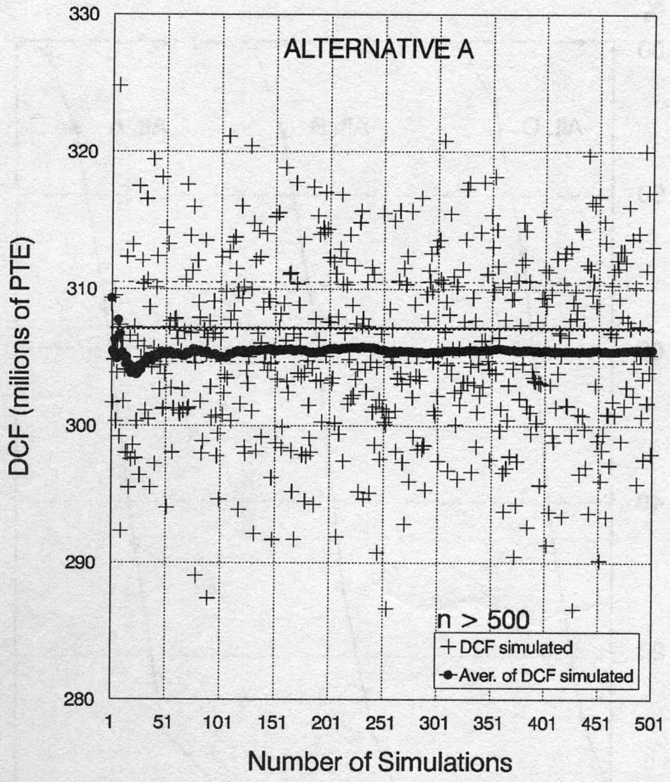
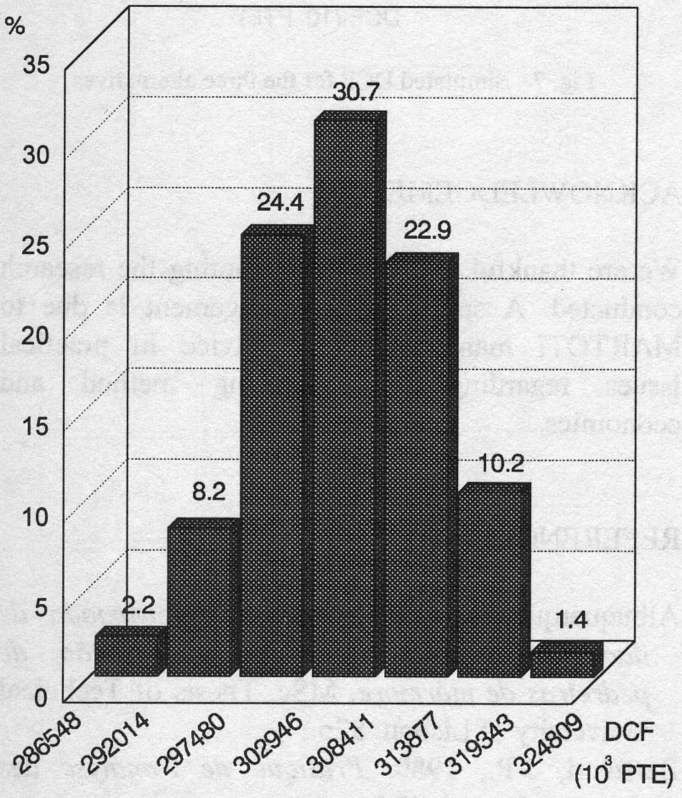


Fig. 5 - DCF simulations for alternative A



Deterministic DCF = 307 620 . 10^3 PTE
DCF simulated :
average = 305 550 . 10^3 PTE
standard deviation = 6 627 . 10^3 PTE

Fig. 6 - Histogram of simulated DCF for alternative A

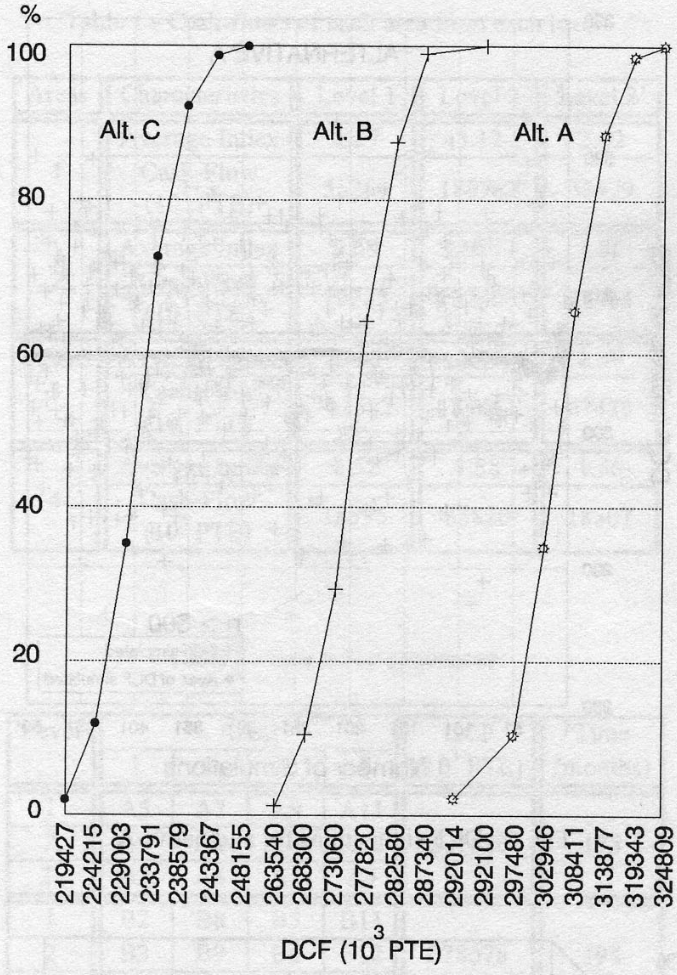


Fig. 7 - Simulated DCF for the three alternatives

ACKNOWLEDGEMENTS

We are thankful to JNICT for granting the research conducted. A special acknowledgement is due to MARTOTI management for advice in practical issues regarding the quarrying method and economics.

REFERENCES

Albuquerque, T., 1993. *Análise multivariada de dados e geoestatística da recuperação de pedreiras de mármore*. MSc. Thesis of Technical University of Lisbon. 82p.;

Benzécri, J-P., 1980. *Pratique de l'analyse des données*. Dunod, 424 p.;

Pereira, H.G., 1988. Case study on application of qualitative data analysis techniques to an uranium mineralization, in C.F. Chung *et al.* (eds.). *Quantitative Analysis of Mineral and Energy Resources*, Reidel, p. 617-624;

Pereira, H.G.; Brito, G.; Albuquerque, T.; Ribeiro, J.; 1993. Geostatistical estimation of a summary recovery index for marble quarries, in Amílcar Soares ed. *Geostatistics Tróia '92*, Kluwer Academic Publishers, vol. 2, p. 1029-1040.

Ribeiro, J., 1994. *Planeamento da exploração de pedreiras de mármore com base em um índice de recuperação*. MSc. Thesis of Technical University of Lisbon, 121 p.

FROM THE SAME PUBLISHER:

Bawden, W.F. & J.F.Archibald (eds.) 90 5410 325 6
Innovative mine design for the 21st century – *Proceedings of the international congress on mine design, Kingston, 23-26 August 1993*
1993, 25 cm, 1054 pp., Hfl.230 / $130.00 / £85
A state-of-the-art on technology, innovative mining practices, & anticipated evolutionary trends in the various fields of mining engineering. *Topics*: Slope stability & rock mechanics; Underground support & backfill; Grade estimation & mine feasibility; Open pit planning & design; Underground planning & design; Machinery, materials handling, & mine maintenance; Mine environment; Mine management; Research & development. Editors: Queen's Univ., Kingston.

Kidybinski, A. & J.Dubinski (eds.) 90 5410 040 0
Effect of geomechanics on mine design – *Proceedings of the 12th plenary scientific session of the International Bureau of Strata Mechanics, World Mining Congress, Leeds, 8-13 July 1991*
1992, 25 cm, 184 pp., Hfl.135 / $75.00 / £50
20 papers on effect of geomechanics on mine design. Geodynamic phenomena associated with mining, longwall face technology, permanent mine workings & tunnels, ground subsidence, yield pillars & water inflows to mines. Editors: Central Mining Inst., Katowice.

Almgren, G., U.Kumar & N.Vagenas (eds.) 90 5410 314 0
Mine mechanization and automation – *Proceedings of the second international symposium, Luleå, Sweden, 7-10 June 1993*
1993, 25 cm, 827 pp., Hfl. 250 / $140.00 / £93
Innovative mining systems: Non energy minerals (metals), industrial minerals; Innovative mining systems: Solid fuel minerals; coal, etc.; Mechanization & automation of drilling operations; Mechanized rock fragmentation; Material handling & data communication; Machine automation & control; Computer applications; Human factors and safety, miscellaneous; Reliability and maintenance of mining systems.Editors: Luleå Univ. of Technology.

Hustrulid, W. & M.Kuchta (eds.) 90 5410 173 3
Fundamentals of open pit mine planning and design
July 1994, 25 cm, c.850 pp., 2 vols, Hfl.245 / $125.00 / £90
(Student edn. 90 5410 183 0, 2 vols, Hfl.125 / $65.00 / £46)
The books is divided into two parts. Part 1 consists of six chapters in which the basic planning & design principles are presented: Mine planning; Mine revenues & costs; Orebody description; Geometrical considerations; Pit limits; Production planning. Much of the actual calculation involved in the design of an open pit mine is done by computer. Two professional computer programs CSMine & VarioC have been specifically developed with the university undergraduate learning environment in mind. These programs, their related tutorials & user manuals, together with a data set for the CSMine Property, are subject of part 2 of this book. Six chapters involved are: Introduction; CSMine property description; CSMine tutorial; CSMine user's manual; VarioC tutorial & user's guide; VarioC reference manual.

Singhal, Raj K. & Marion Vavra (eds.) 90 6191 159 1
Mine planning & equipment selection 1990 – *Proceedings of the second international symposium, Calgary, 7-9 November 1990*
1990, 25 cm, 544 pp., Hfl.230 / $130.00 / £85

Singhal, Raj. K. (ed.) 90 6191 819 7
Mine planning & equipment selection – *Proceedings of an international symposium, Calgary, 3-4 November 1988*
1988, 25 cm, 548 pp., Hfl.305 / $175.00 / £113

Szwedzicki, T. (ed.) 90 5410 321 3
Geotechnical instrumentation and monitoring in open pit and underground mining – *Proceedings of the Australian conference, Kalgoorlie, 21-23.06.1993*
1993, 25 cm, 562 pp., Hfl.185 / $105.00 / £69
Displacement monitoring; Stress measurement & monitoring; Groundwater monitoring; Blast monitoring; Seismic activity monitoring; Environmental monitoring; & Instrumentation as tool for numerical modelling. Editor: W.A.School of Mines, Kalgoorlie.

Chugh, C.P. 90 6191 477 9
High technology in drilling and exploration
1992, 24 cm, 789 pp., Hfl.135 / $75.00 / £50 (No rights India)
Reviewes the principles of operations, methods, techniques, related economics, optimisation & formulation of specifications of drills deployed in mining, groundwater & petroleum industries. Rotary & percussive methods are still the basis of all conventional drilling techniques. Rotary drilling covers a wide range of applications, including oil well drilling, prospecting drilling, water well drilling, blast hole drilling, soil stabilisation drilling, grout hole drilling, & drilling for drifts & tunnels. The topics discussed are diverse & cover several different aspects of operations ranging from diamond drilling through to the full oil field applications.

Hartley, J.S. 90 5410 159 8
Drilling: *Tools and programme management*
1994, 25 cm, 192 pp., Hfl.85 / $45.00 / £31
(Student edn., 90 5410 160 1, Hfl.45 / $25.00 / £17)
Types of drills; Rod strings; Holemaking tools; Rock drillability and stability; Downhole drilling problems; Drill hole deviation; Drillhole deflection; Selection of drilling method for exploration; Preparation for drilling programme; Managing the drilling programme; Downhole surveying; Oriented coring; Downhole logging and inspection; Sampling; Appendices.

Ghose, A.K. (ed.) 90 5410 231 4
Small-scale mining – *A global overview*
1994, 24 cm, 380 pp., Hfl.135 / $75.00 / £50 (No rights India)
The perspective - Policies & prospects; Geological parameters; Small-scale mining worldwide - Reviewing the current status; Small-scale mining in Saarc; Economic & technological parameters; Keynote addresses, short contributions & recommendations; 35 papers. Editor: Indian School of Mines, Dhanbad.

Jeremic, M.L. 90 5410 113 X
Rock mechanics in salt mining
1994, 25 cm, 544 pp., Hfl.175 / $99.00 / £65
(Student edn., 90 5410 103 2, Hfl.95 / $55.00 / £35)
5 chapters consider general geology, folding & faulting structures composition of salt & form of salt bodies with the simplifications. 3 chapters deal with the exploration & opening of salt deposits with the aspect of design of safe & stable mine structures, and risk of water inflow into the mine. 3 chapters analyse deformation & failure of the salt due to elasto-plastic, creep & outbursts loading conditions. 5 chapters discuss strata mechanics & control for different mining systems of flat, inclined & massive salt bodies, as well as solution mining & excavation for storage. The last chapter presents the stability analyses to the mine structures in regard to salt mining subsidence. Author: Laurentian Univ., Sudbury, Canada.

All books available from your bookseller or directly from the publisher:
A.A.Balkema Publishers, P.O.Box 1675, Rotterdam, Netherlands
For USA & Canada: A.A.Balkema Publishers, Old Post Rd, Brookfield, VT, USA