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Some Conditional Simulations Compared with Later Results in the Hardcoal Industry

M. KANNENBERG*, W. SKALA* and V. WEBER†

**Mathematische Geologie, Institut für Geologie, Freie Universität, Berlin (W), Federal Republic of Germany*
†Bergbau-Forschung GmbH, Essen, Federal Republic of Germany

When coal properties are estimated geostatistically for mine planning in the hardcoal industry, there is one important supposition which influences the reliability of prediction of economically profitable parts of the deposit. This is the fact that activities in hardcoal exploration and mine planning are characterized by distinct levels of information and knowledge upon which decisions of economic import must be based, for example, whether exploration should proceed or not, or which methods and strategies should be used to maximize search efficiency.

To get more reliable results for mine planning, in particular, advanced kriging methods (e.g. conditional simulation) have to be introduced and checked for their reliability in historical analyses (post-mortem studies). By using this feedback, kriging results from underground samples or production data can be compared with results gained by advanced geostatistical methods from exploration boreholes.

Introduction

Exploration for hardcoal is a sequential procedure subject to repeated interruption phases for planning and decision-making. The basic job of planning is to decide on what coal volumes of a given quality and by what means, viz. at what cost, coal can be extracted from clearly localized areas. At this juncture the reliability of such statements will be of great economic relevance.

Unbiased planning is possible only if any and all available information is used optimally. During the early exploration phases only relatively scarce information will be available from widely spaced borehole patterns. To explore the deposit in the Ruhr coalfield, for example, and determine its geological reserves, there are boreholes as widely spaced as 1 or 2 km which are completed by seismic profiles. In this context geological reserves mean those coal reserves which are contained in seams of minimum 0.6 m thickness, of maximum 50% by wt waste, down to a depth of max. 1500 m.

For the construction of a colliery and its subsequent exploitation the decision-taking levels of exploration ahead of face areas as well as lay-out and

planning of mining operations are the crucial items. Whereas for exploration ahead of face areas the planning targets, such as determination of the mineability of individual seams or seam sections, location of the planned extraction shaft, solution of transport issues etc., play a major part. During layout and extraction planning such issues as the sequence of seams to be worked under consideration of varying marginal conditions also come to bear.

In hardcoal mining the seam thickness is the most important quantitative parameter. Reliable knowledge on seam thickness is not alone a criterion of the mineability of seams and seam sections but is also decisive for the dimensioning of face support systems and safety issues. Of particular significance is also the identification as early as possible of those areas which owing to their seam thicknesses justifiy inclusion in the production planning, both from a safety and a technical and economic point of view (i.e. cut-off thicknesses).

At this juncture - in all of the said planning and decision-making phases - specific problems of forecasting the anticipated reserve losses will arise. Such reserve losses are categorized into two types:

(a) Reserve losses because of tectonic conditions occur whenever owing to the configuration of geological faults bigger parts of the exploration area must be excluded from exploitation either for technical, economic or safety reasons.

(b) Reserve losses due to seam configurations occur whenever bigger zones must a priori be excluded from exploitation because they contain coal seams below a defined cut-off thickness which is dictated by the mining technology available.

The present study deals with the issue of reserve losses due to seams below cut-off thickness. Identification of seam sections remaining below a set cut-off thickness should be done as early as possible, i.e. in the exploration phase, in order to permit mine planners to react adequately and in time to safeguard the economic interests of the mining industry. Practical relevance of thickness prediction in the hardcoal industry will thus reside not so much in the capability of exactly predicting local seam thicknesses but rather in the correct evaluation of potentially mineable reserves. Such global information provides critical decision-making aids for planners in hardcoal mining sufficiently ahead of time to allow them to draw an adequate layout of workings and procure the necessary face support and means of conveyance.

As shown by relevant preliminary studies carried out by our staff members Leonhardt & Skala,[1] Burger, Schürmann, Skala & Weber,[2] and Burger,[3] the use of advanced

geostatistical methods (e.g. conditional simulation) appears to be highly valuable in solving this type of problem since these methods take into account both the prevailing density of information and specific prediction requirements. Burger,[3] has already demonstrated, by means of examples from exploration on hardcoal, that conditional simulation provides probability information good enough to allow conclusions as to the distribution pattern of seam thicknesses.

Planning of mining activities in the Zollverein 8 seam, based on conditional simulation

Based on such preliminary knowledge it appeared logical to verify, from selected examples, what would be the degree of reliability and precision of predictions of seam thicknesses or coal reserves in the zone ahead of faces within the framework of layout and mine planning. Conforming to the set targets these studies had to be concentrated on delimitating, i.e. identifying of those areas beyond a cut-off thickness of 130 cm. To be able to verify the evaluation accuracies attained on the different planning levels it was imperative to have sufficient data available from any and all planning levels.

One take of the Zollverein 8 seam appeared to be especially appropriate for our studies as its exploration drilling-, roadway-, and face measuring data were available. Under a pilot study the data were to be evaluated both by simple kriging calculations and by conditional simulation. The following data from different planning levels were available for computing purposes:

(a) Data on thicknesses from 38 boreholes most of which were gathered during the early stage of exploration of zones ahead of face areas with a view at a take to be developed. The grid of boreholes (Figure 1) shows the average spacing of some 500 m for a large part of that area. It is only along the spine road that measurements are closer together.

(b) After layout planning the base roadways were driven so that other 65 access data became available (spaced mostly

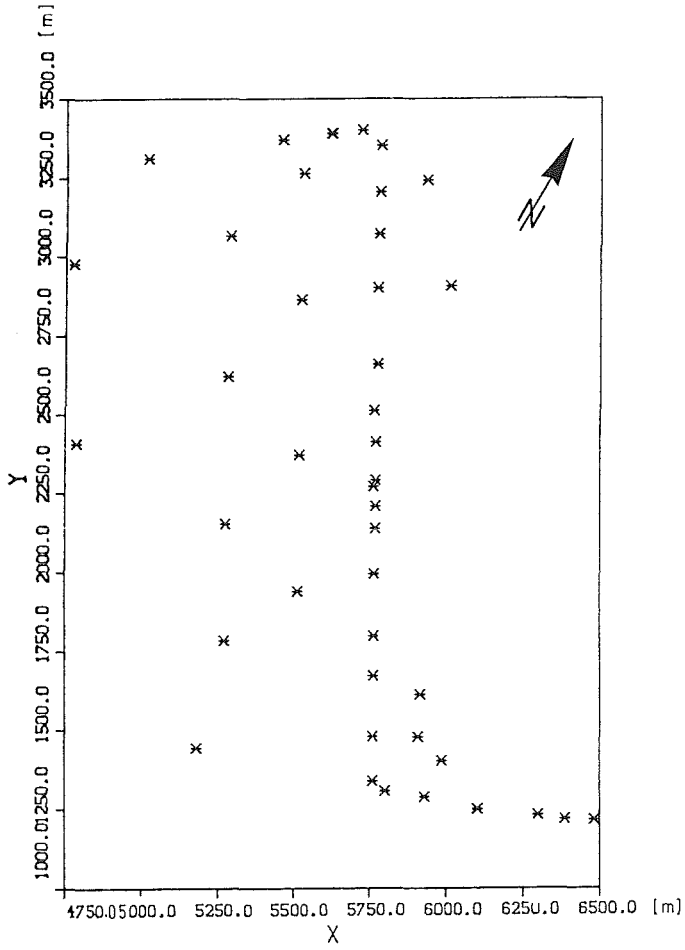

FIGURE 1. Grid of drilling data: Zollverein 8 seam

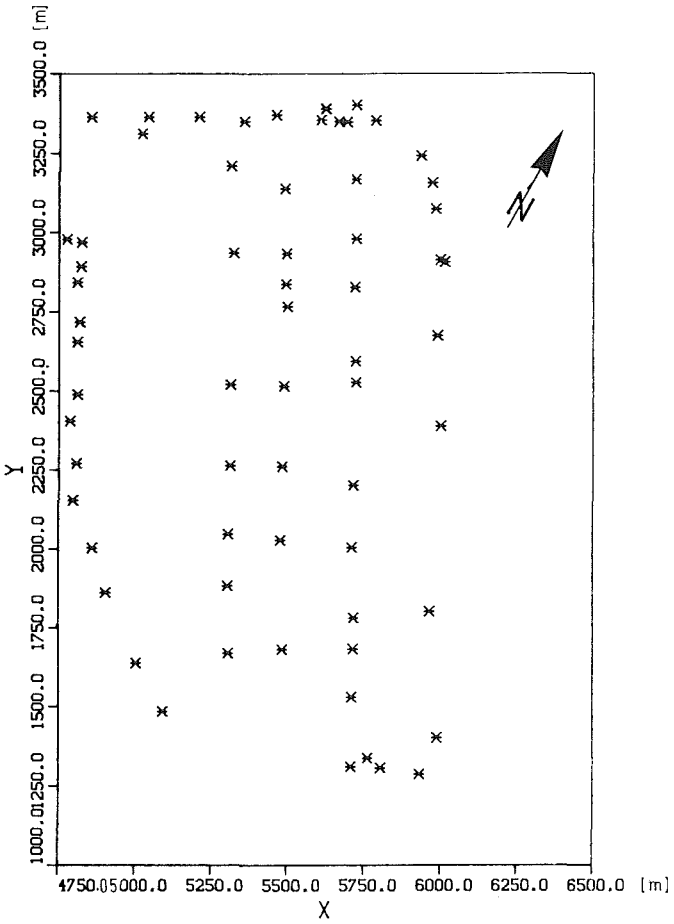

FIGURE 2. Grid of roadway data: Zollverein 8 seam

between 100 and 250 m (Figure 2).

(c) From a coal face started later on in the eastern part of that take face position measurements were carried out at irregular intervals. Face measuring points are spaced roughly between 5 and 10 m; spacings between the different face positions amount to 100 or 200 m (Figure 3).

The data were used to give an answer, in particular, to the following questions of geostatistic relevance:

1. What is the degree of reliability for delimiting, from borehole data, those seam sections with thicknesses beyond cut-off (in our case beyond 130 cm)? Special attention should be given to the percentage beyond cut-off of the take under examination.
2. What is the degree of reliability of obtaining critical information on the seam thickness profile by appropriate methods of interpolation or evaluation of roadway measurement data? From this planning phase, predictions are attempted of local cut-off fluctuations which are, in general, attainable only from a close network of face-measuring points.

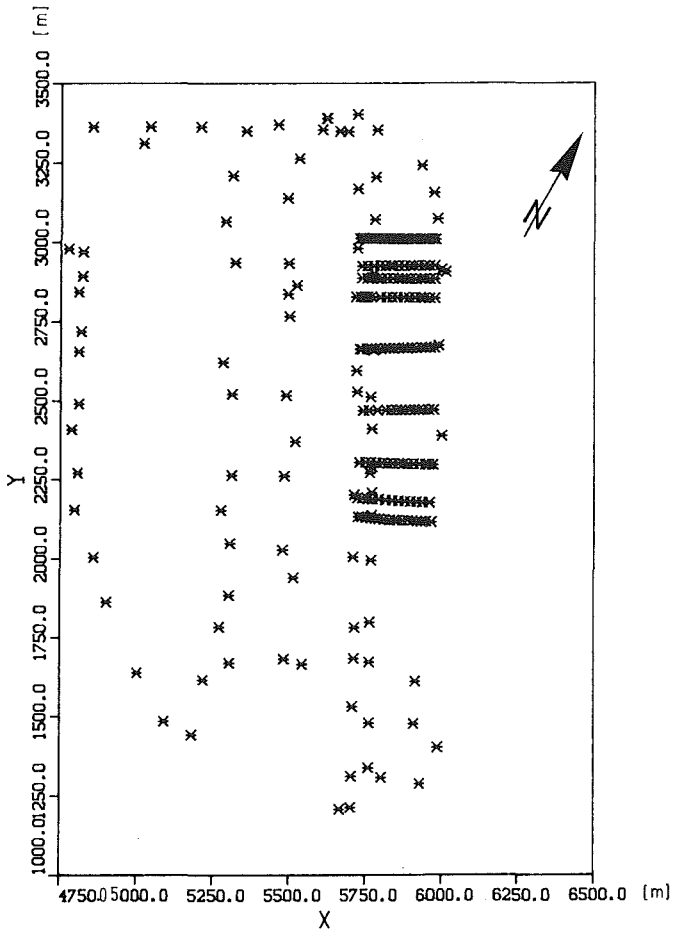

FIGURE 3. Grid of roadway and face data: Zollverein 8 seam

Exploration drillings — roadway measurements

To give an answer to the first question the results of interpolated roadway data (maximum spacing 250 m) were compared with the prediction results from borehole data (maximum spacing 500 m). This was done in the following way:

(a) Starting from the mining - related roadway measurements, interpolation on an equidistant grid of 250 m x 250 m was done by simple kriging. The interpolation grid of 250 m x 250 m was selected as this grid spacing roughly matches the face length of a panel. The roadway data interpolated to these grid points therefore largely correlate to the state of exploration of the panel at that moment.

(b) The same state of exploration was also to be predicted from the scarcer drilling data available. To this end we relied on the method of conditional simulation where for ease of comparison interpolation was, again, carried out using the same equidistant grid of 250 m x 250 m. When applying conditional simulation we reverted to an improved version of our program described by Burger, Schürmann, Skala & Weber.[2] We were able to adopt spherical models to the computed variograms (Figure 4). Anisotropies were not observed.

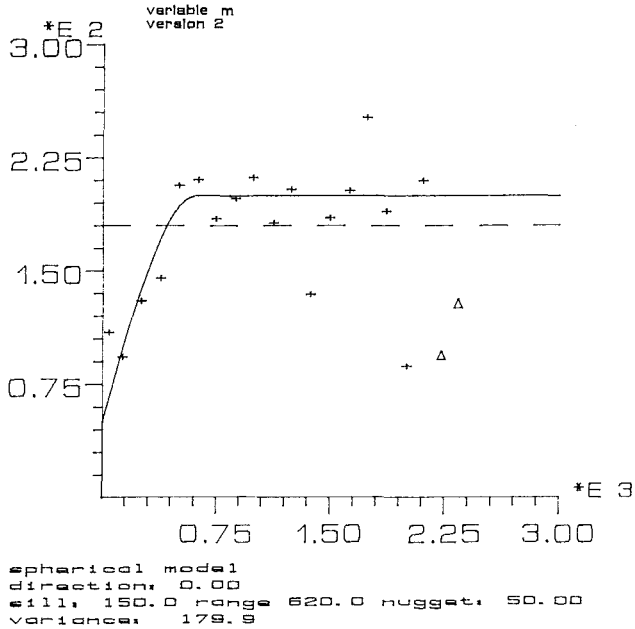

FIGURE 4. Spherical variogram of roadway data: Zollverein 8 seam

The outcome of our evaluations was:

1. Kriging of exploration drillings (about 500 m spacing, kriging grid 250 m x 250 m): Figure 5 shows the results of

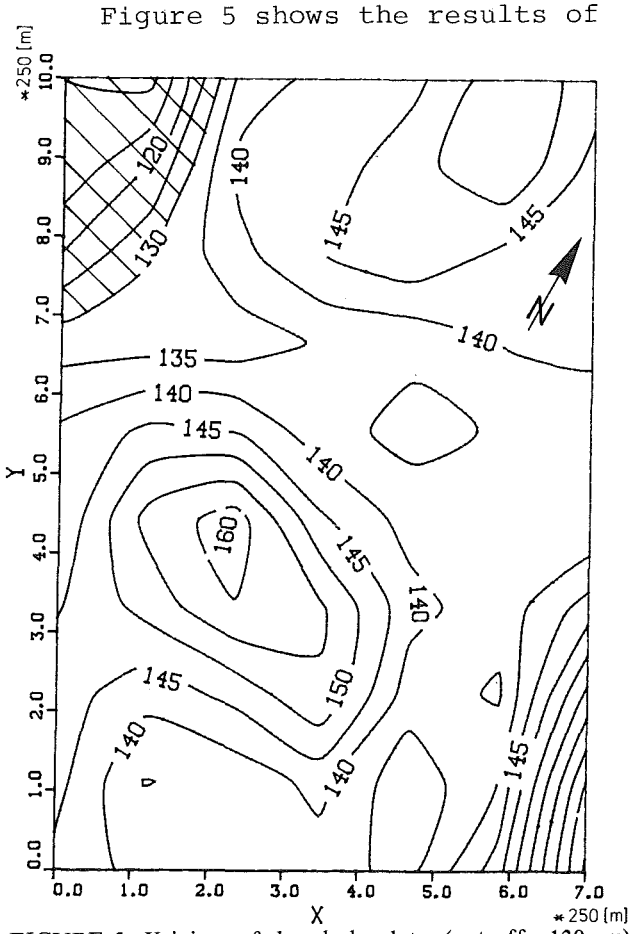

FIGURE 5. Kriging of borehole data (cut-off: 130 cm): Zollverein 8 seam

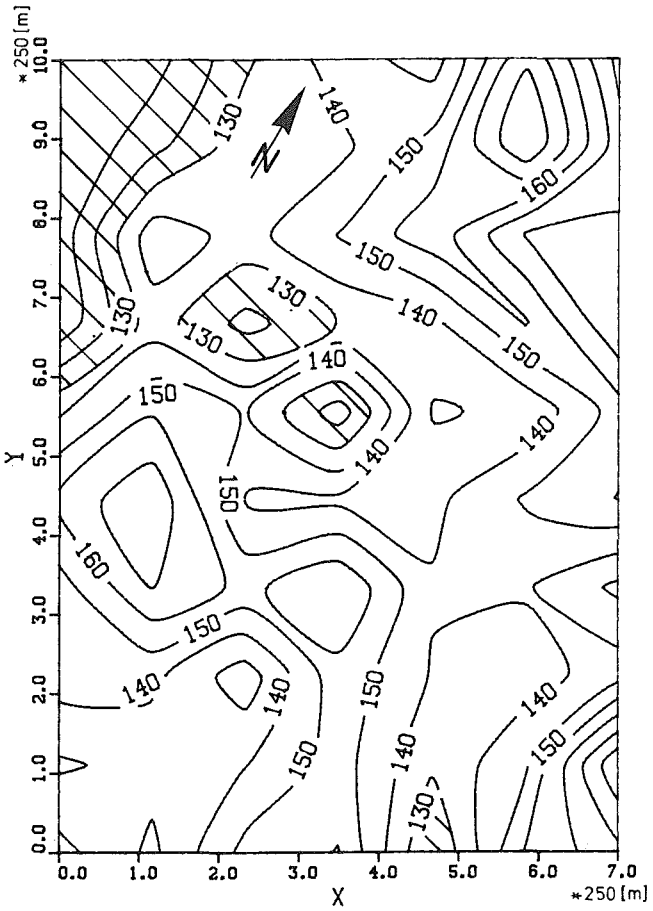

FIGURE 6a. Conditional simulation based on borehole data, run no. 1: Zollverein 8 seam

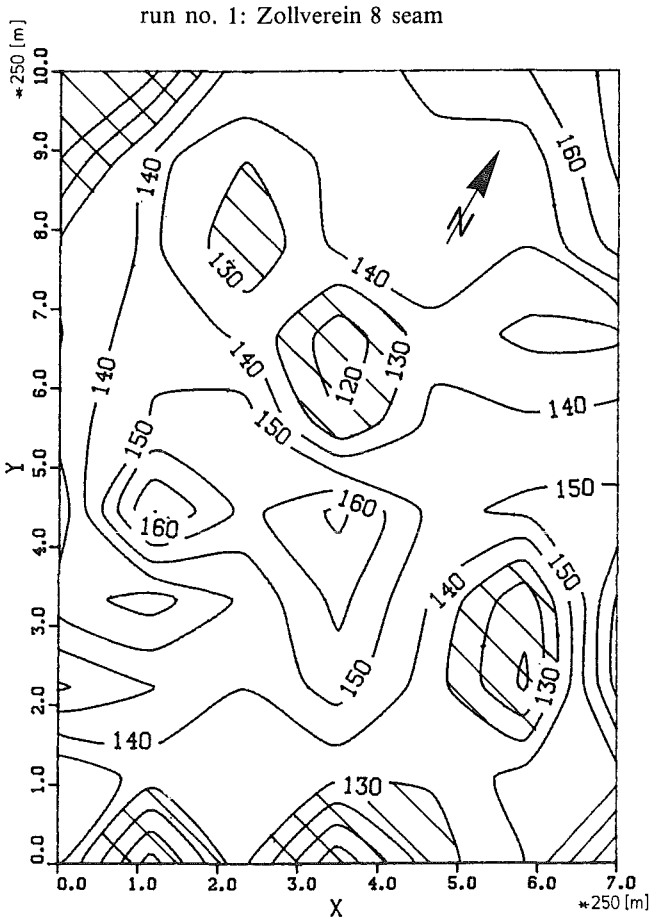

FIGURE 6b. Conditional simulation based on borehole data, run no. 2: Zollverein 8 seam

the interpolation. There is only a small area in the north-west of the take where seams stay below the cut-off thickness of 130 cm. It was found from the analysis of the accumulated frequency distributions of the kriging points that the proportion beyond cut-off as related to the total area was roughly 91%.

2. Conditional simulation relying on spherical variograms (Figure 4): On the representations of isolines (Figures 6a, 6b) seam sections of thicknesses below 130 cm can be distinguished not only in the north-west but also in other parts of the take. The outcome of evaluations of five simulation runs shows that when using this type of calculation one has to expect smaller proportions of areas beyond cut-off than could be reckoned with when relying on kriging interpolation. Against kriging (91%), the five simulation runs yielded 75, 68, 70, 68 and 71%. These assumptions were reconfirmed also by the kriging results from roadway measurements. Starting from the averagely spaced (about 250 m) measuring points, evaluations were based on the same equidistant grid of 250 m x 250 m (Figure 7). The 62% proportion beyond cut-off resulting therefrom as well as its distribution can much easier be compared to the

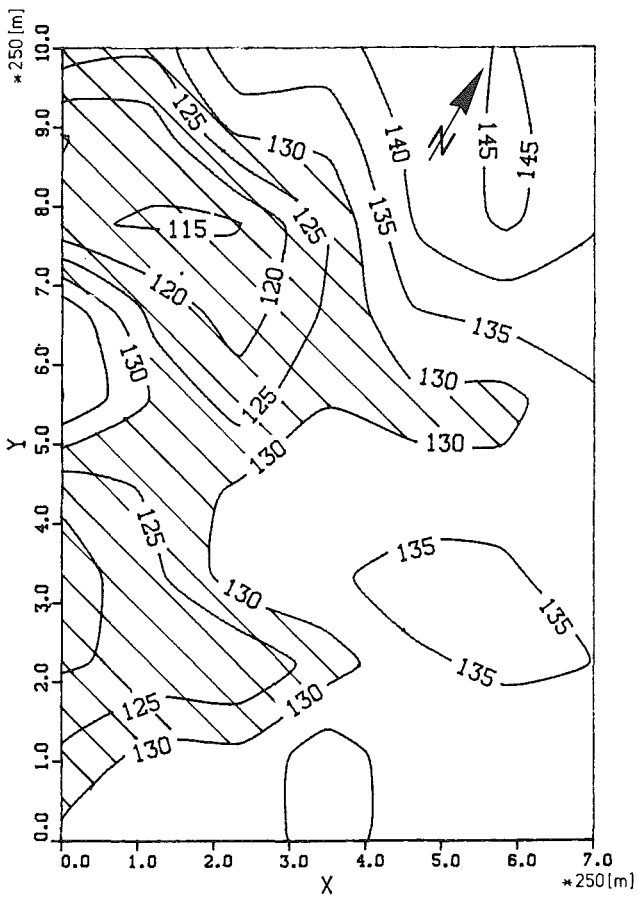

FIGURE 7. Kriging of roadway data (cut-off: 130 cm): Zollverein 8 seam

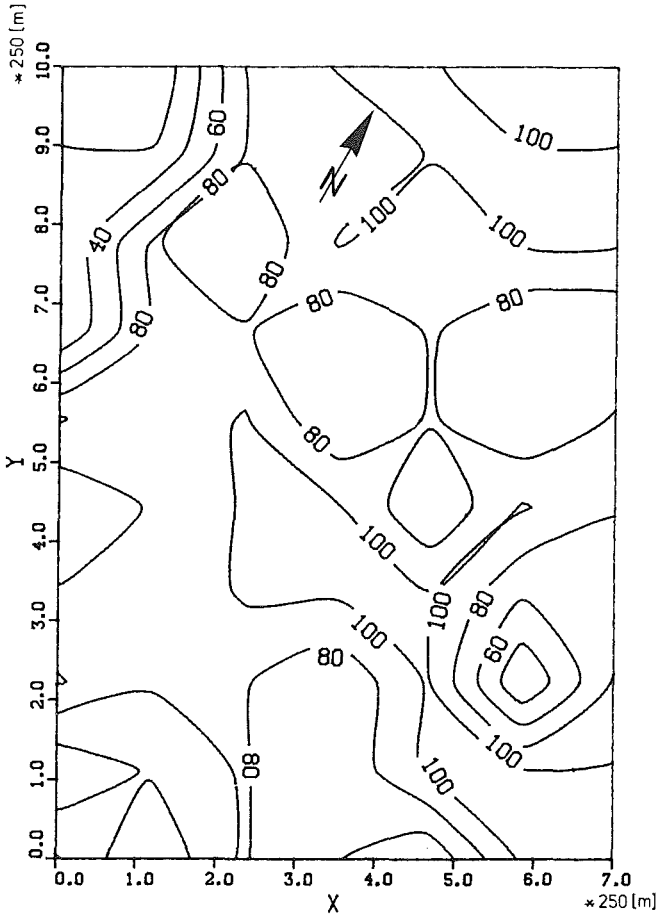

FIGURE 8. Representation of beyond cut-off (130 cm) probabilities by superposition of 5 simulation runs: Zollverein 8 seam

simulation runs than the kriging results of exploration boreholes.

Superposition of the results of simulation runs and subsequent averaging does not appear to make sense as in such a case one would ultimately obtain some representation comparable to the kriging results. In lieu of this we tried some superposition of the results of each individual run to arrive at an integrated representation (Figure 8) by determining the degree of probability at which the different grid elements of the simulation grid exceed the given 130 cm cut-off. This figure makes it obvious, inter alia, that the highest probabilities are encountered in the north-west and south-west of the area under review.

Roadway measurements — face measurements

In the second instance it was to be clarified how far thickness fluctuations in a face - as related to the cut-off - are predictable from roadway measurements. We selected part of a panel in the north-east of the take where the seam thicknesses of four face positions were measured (Figure 3). Using a spherical variogram model of any and all roadway data we proceeded to kriging of that panel section to a regular 25 m x 25 m grid (Figure 9). Assuming, as before, a cut-off thickness of 130 cm, the map of isolines

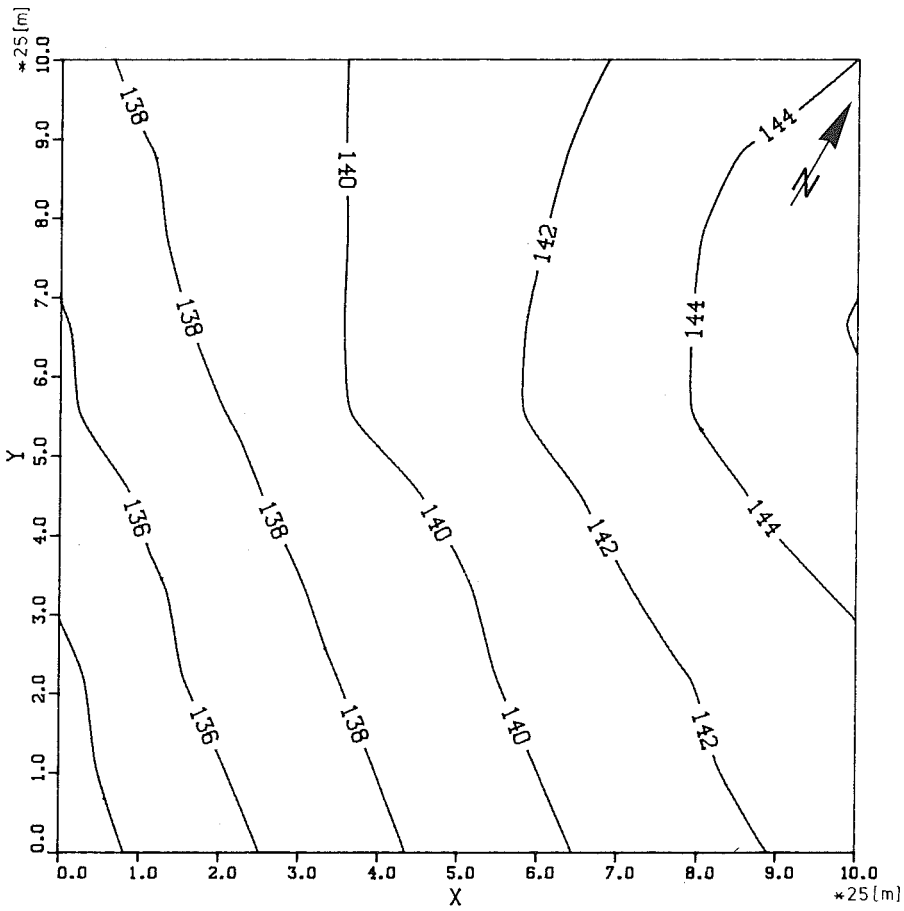

FIGURE 9. Panel: kriging of roadway data: Zollverein 8 seam

interpolated and contoured by means of kriging gave the impression that the entire area (100%) exceeded that threshold consistently. On the other hand and starting from the same variogram, we carried out conditional simulation to a 25 m x 25 m grid. Again we selected two simulation runs and represented them in the form of isoline maps (Figures 10a and 10b). It was found that the area proportions which during the first five simulation runs had been beyond cut-off, now showed wide oscillations of 64%, 87%, 60%, 87% and 80%. This would be due mainly to the large distances between roadway developments or to their small number within the test area, so that one could possibly have done without conditioning. In summing up one may say that, here again, the simulation results are clearly below the level obtained by kriging (100% beyond cut-off).

Comparative studies of face data using both kriging and conditional simulation are continuing, with no definitive results on hand so far.

Conditional simulation-assisted mine planning for seam M

Subsequently the attempt was made to translate the experience from the above pilot study to an actual planning task. Thirty-four thickness measurements for geostatistical purposes were available from seam M. The majority of the measurements stemmed from base roads extending at a relative distance of about 250 m (Figure 11). In spite of the scarce

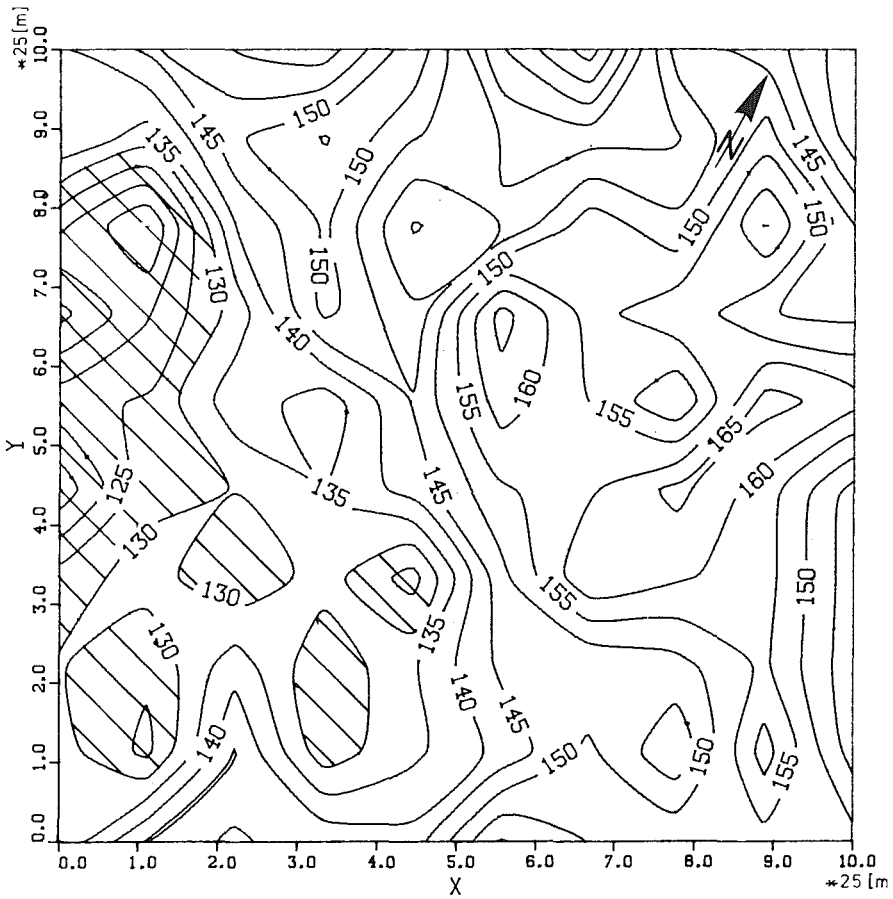

FIGURE 10a. Panel: conditional simulation on a roadway data base, run no. 1: Zollverein 8 seam

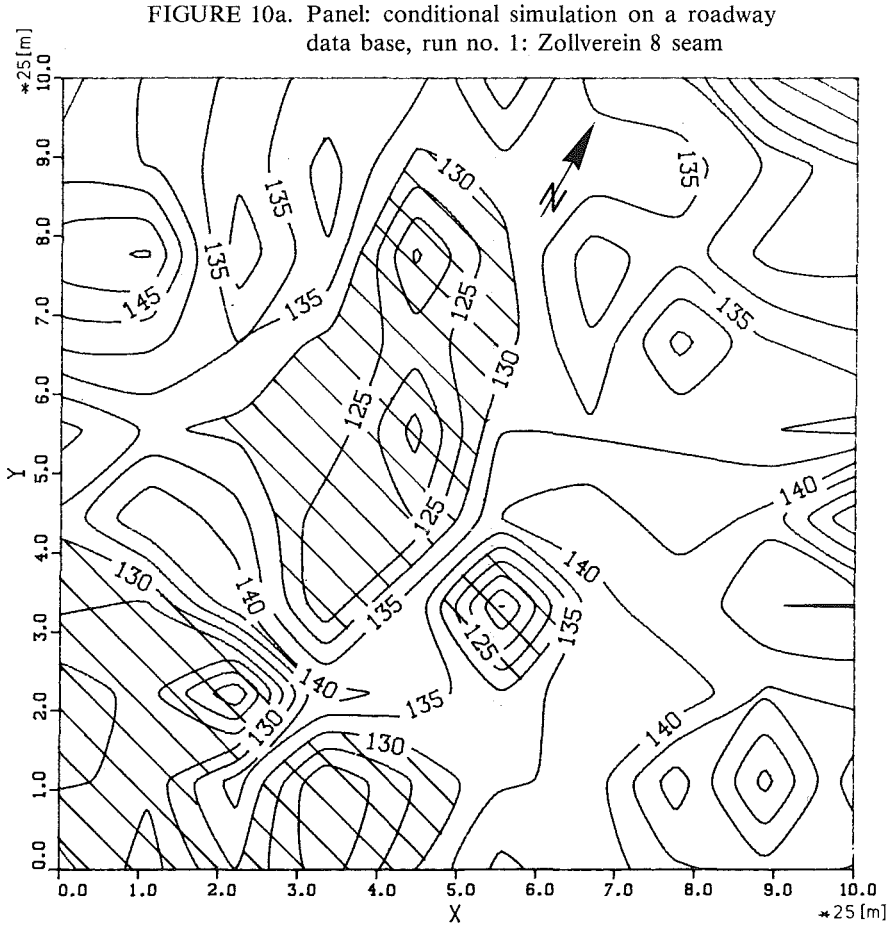

FIGURE 10b. Panel: conditional simulation on a roadway data base, run no. 2: Zollverein 8 seam

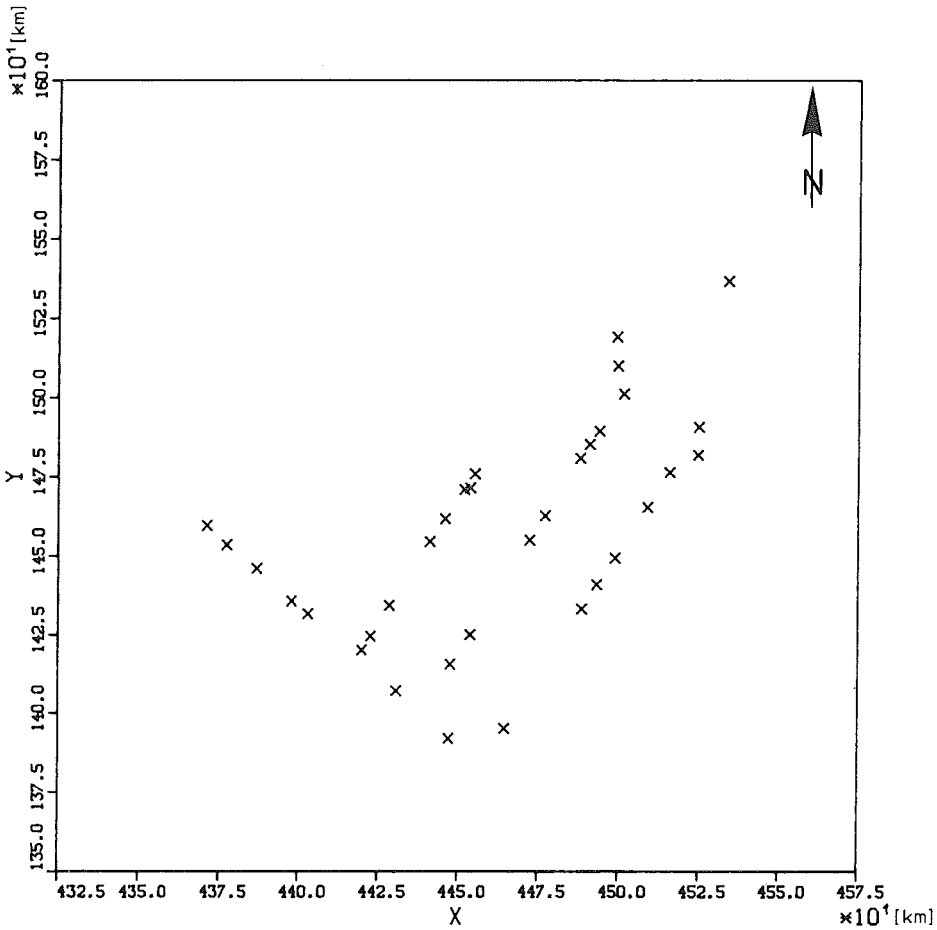

FIGURE 11. Grid of borehole data: Seam M

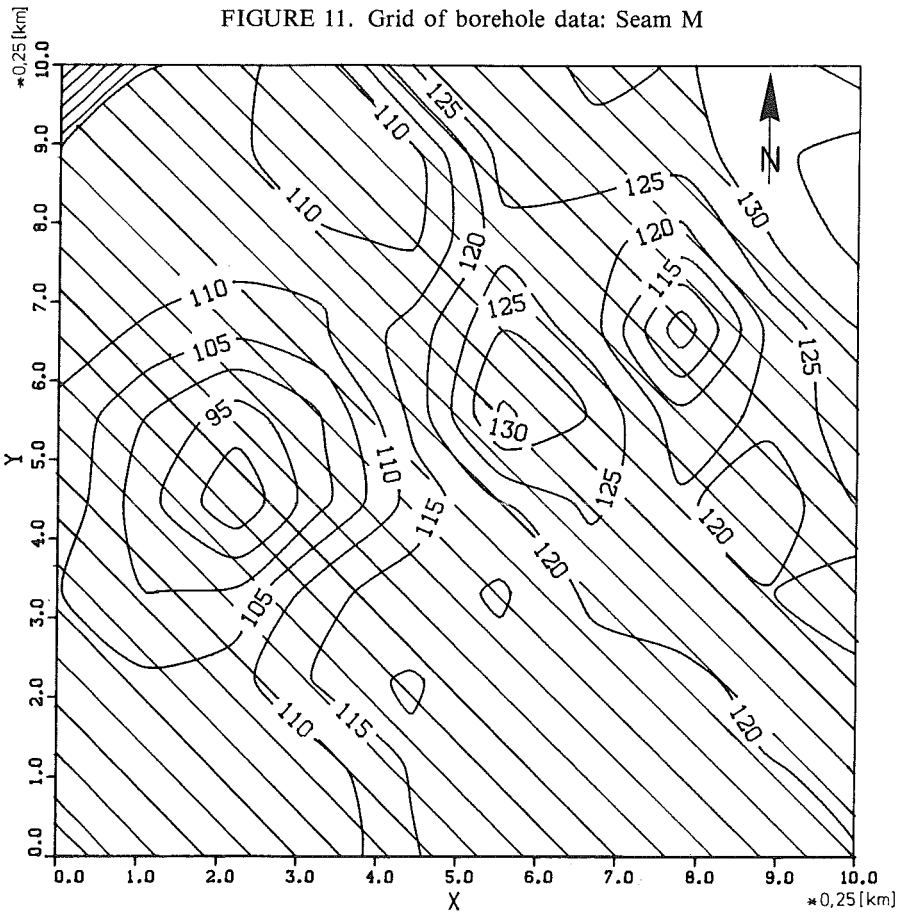

FIGURE 12. Kriging of borehole data: Seam M

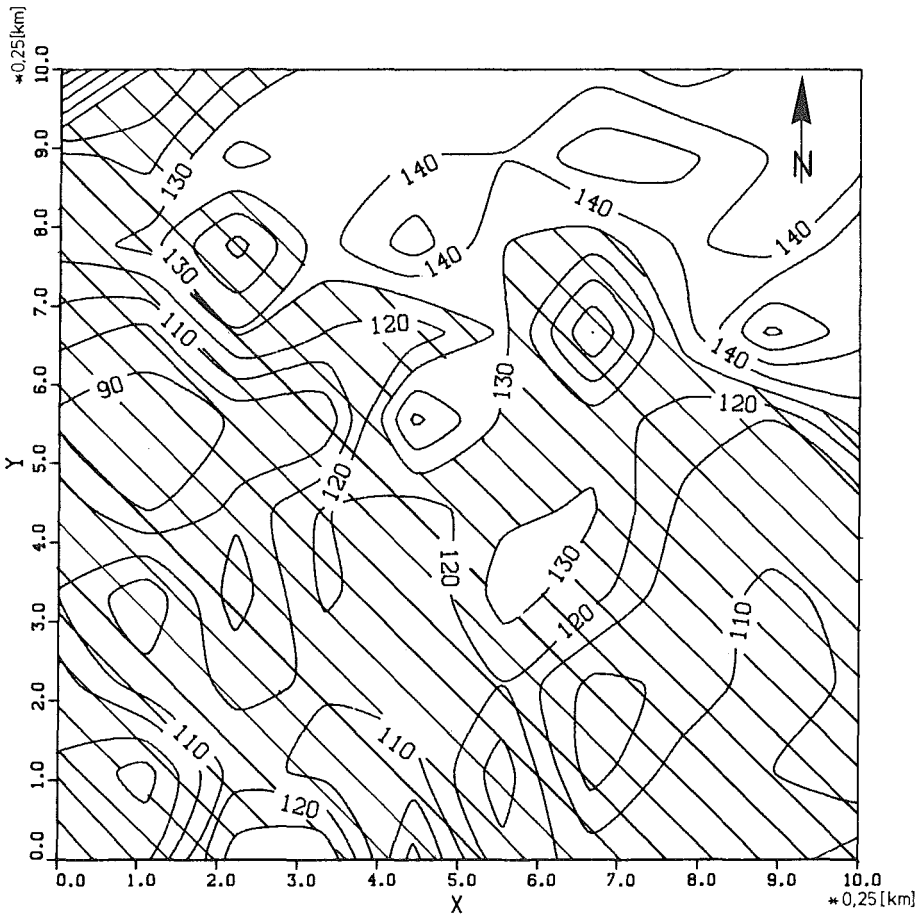

FIGURE 13a. Conditional simulation based on borehole data, run no. 1: Seam M

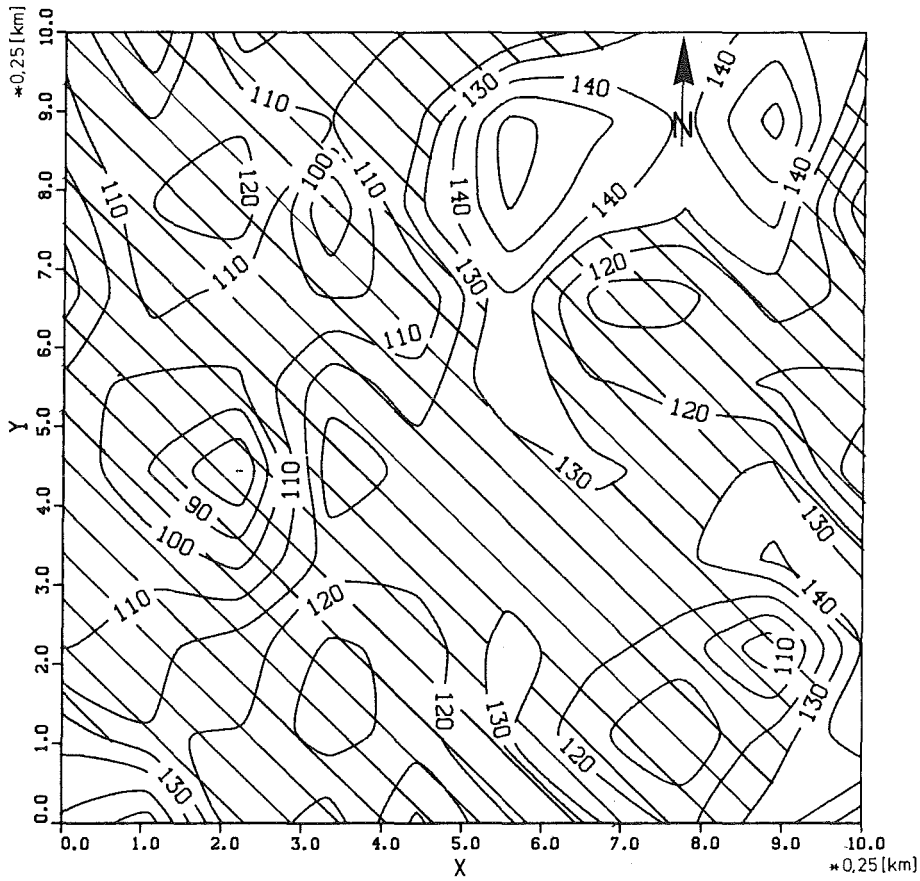

FIGURE 13b. Conditional simulation based on borehole data, run no. 2: Seam M

measuring data we were able to establish relatively reliable spherical variograms. As in the case of Zollverein seam, here again, the cut-off thickness was 130 cm, with as little as 18% of the initial data exceeding that cut-off. The studies for geostatistical comparison between kriging and conditional simulation were again made for a 250 m x 250 m grid.

A comparison between kriging and simulation yielded the following conclusion: By the frequency distributions of kriging values, viz. of the appertaining map of isolines (Figure 12), it appears that, except for a smaller central area, just one portion of 9% in the north-east exceeds the 130 cm cut-off. The area proportions subjected to simulation runs, however, are indicative of bigger seam proportions beyond 130 cm (33%, 26%, 21%, 31% and 26% for the first five runs). Two simulation runs are illustrated in Figures 13a and 13b.

Superposition of these five simulation runs, in Figure 14, shows once again the probabilities at which certain parts of the area under review exceed the 130 cm cut-off. As was expected by the kriging results, the north-east portion of that seam offers the best relevant potential.

Conclusions

In conclusion, it may be said that the conditional simulation method would lend itself very well to solving specific problems of mine

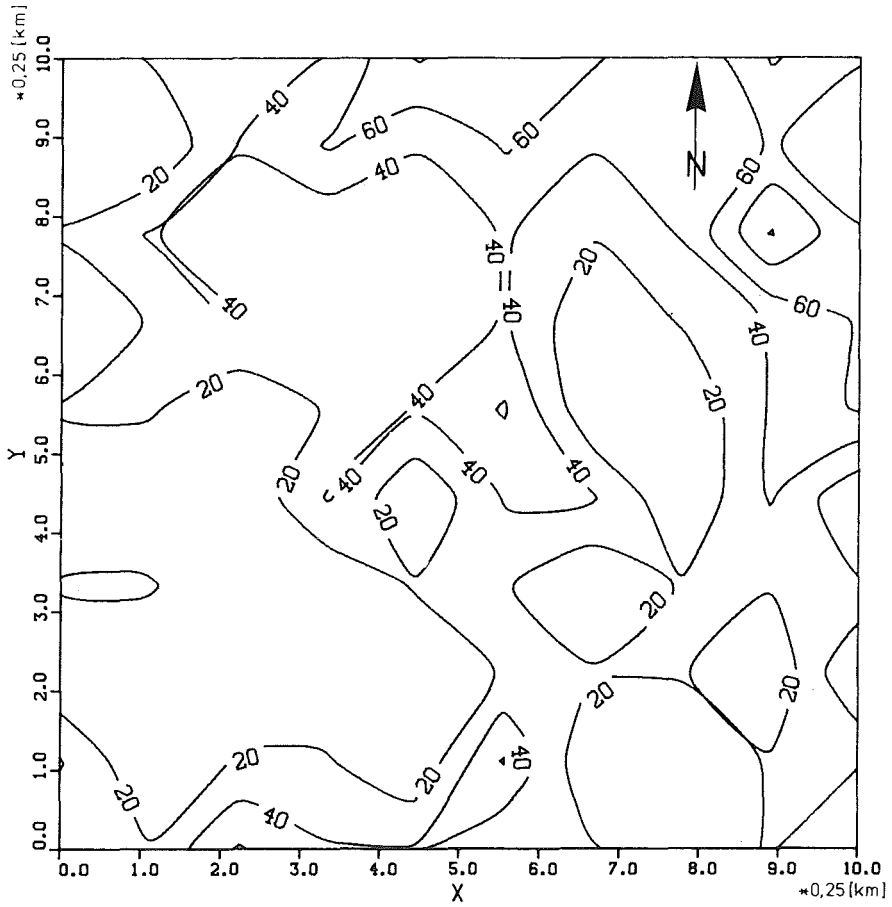

FIGURE 14. Representation of beyond cut-off (130 cm) probabilities by superposition of 5 simulation runs: Seam M

planning in hardcoal. This applies first of all if the more global evaluations, where cut-off contents or cut-off thicknesses are of critical importance, can be carried out rather early. Unlike the marked smoothing effect of kriging, the conditional simulation method yields results which comply better with the said objectives and are more realistic so that it is possibly to take appropriate action in due time. Due to its smoothing effect kriging tends to underestimate the proportion beyond cut-off of the areas examined whenever the cut-off line is situated in the upper half of the initial distribution pattern. This became obvious from the check on the roadway data for seam M where as little as 18% of the initial data were beyond cut-off. Whereas in this case kriging apportioned a poor 9% to the beyond cut-off reserves, simulation runs computed area proportions between 21 and 33% to be beyond cut-off (Figure 15a).

If, on the other hand (as this was the case with the exploration boreholes of Zollverein 8 seam), more than 50% of the initial data are beyond cut-off, i.e. if the cut-off

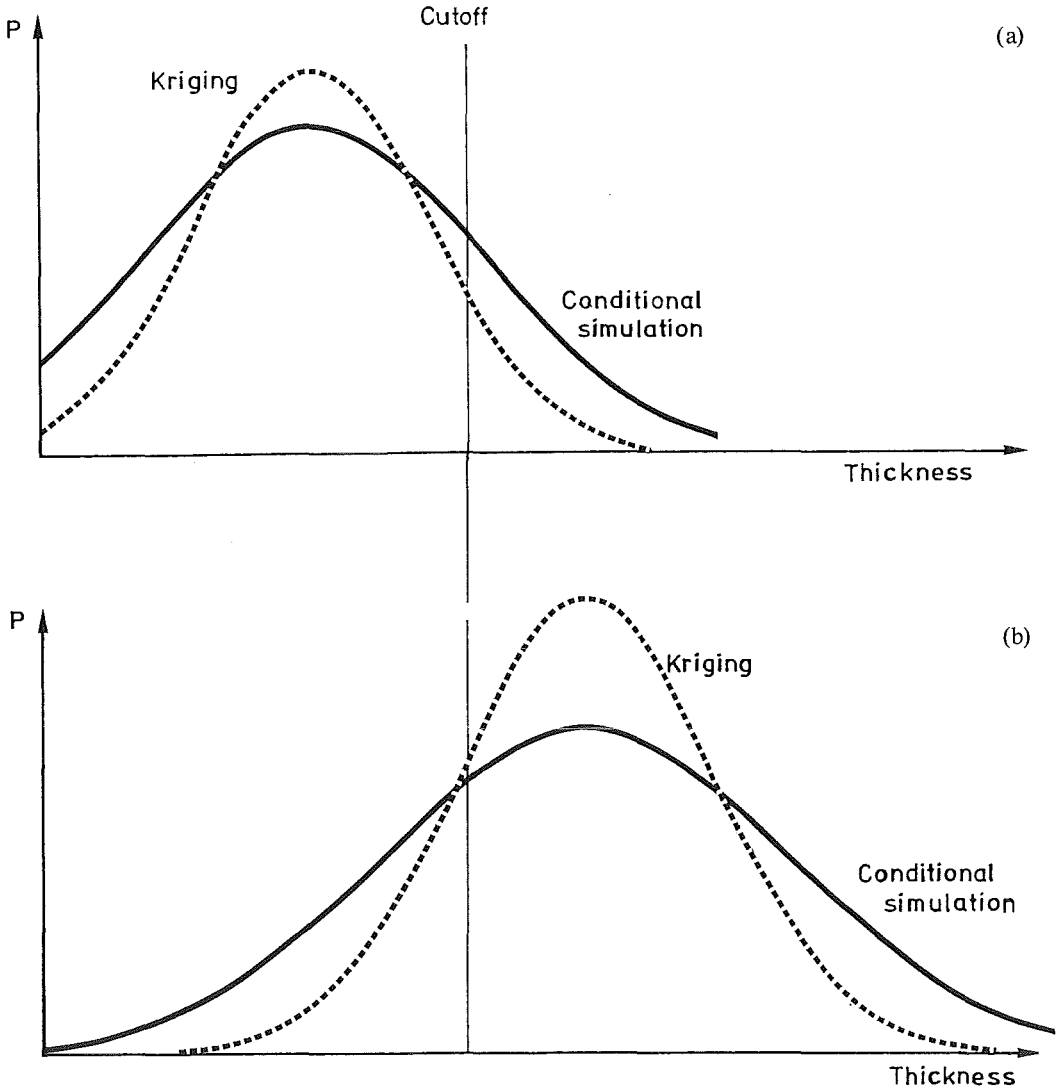

FIGURE 15. Over- versus under-estimation of seam thicknesses; kriging versus conditional simulation for Zollverein 8 and M seams

is situated on the left side of the initial distribution pattern, the kriging method tends to overestimation. In that example kriging calculations classified 91% of existing thicknesses as being beyond cut-off, whereas the simulations yielded area proportions between 68 and 75% (Figure 15b).

The above results which are, inter alia, supported by the theoretical deliberations of Journal & Huijbregts,[5] Journal,[4] and other authors, were in a similar way reconfirmed by the case histories dealt with by Burger,[3] and Dagberg,[6] as well as by Akin.[7]

Among the various advanced geostatistical methods, conditional simulation is one of highly practical relevance and able to solve specific problems. It should therefore be used more frequently also for solving issues of mine planning in deep hardcoal mines. One major benefit of conditional simulation is that it allows early prediction of thickness-related reserve losses. The conventional estimation methods, on the other hand, and even simple kriging, are susceptible of thickness-dependent over- and under-estimations as a function of the distribution of initial data.

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