Bulletin de la Société belge de Géologie, T. 101 (3-4), 1992, pp. 209-254.
Bulletin van de Belgische Vereniging voor Geologie. Ed. 1993

SEAM THICKNESS AND GEOLOGICAL HAZARDS FORECASTING IN DEEP COAL MINING : A FEASIBILITY STUDY FROM THE CAMPINE COLLIERIES (N-BELGIUM)

by

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KEY WORDS

Colliery archives, data processing, computer-generated graphics, depositional environments, geological hazards, coal geology, management tools, Westphalian, Campine Coal Basin.

ABSTRACT

Heterogenous geological data (sensu lato) have been selected from colliery archives at Beringen and Zolder (Western area of the N.V. Kempense Steenkolenmijnen) and subsequently digitized or processed into computer-generated contour maps, logs, cross sections and fence diagrams. Consequently, lateral trends in seam composition are visualized so that variation of coal seam quality (coal/dirt ratio) and incipient splitting is predictible. Furthermore, detailed analysis of core descriptions, the interpretation of sedimentological logs and that of lithostratigraphic fence diagrams, enables a reconstruction of the depositional environment and a geologic modelling of the deposit. This in turn can lead to the prediction of roof and floor rock quality, the identification of hazardous sandstone bodies (crevasse splays and distributary channels) and the forecasting of potential splits and washouts.
The reliability of the predictions depends on the quality and on the density of the available geological data. Unfortunately the quality of the latter is not uniform and varies even between collieries. The geologically most valuable information has been derived from surface and underground cored boreholes. However, their density is too low, their spreading uneven and their spacing often too wide for optimum mine production planning. The bulk of the data comes from geologically less valuable handmade mine maps and handwritten mine surveyors notebooks. Although the quality of the latter decreased over the years and considerable information has been lost, these data can still be processed into contour maps and hence be used as a management tool.

1. INTRODUCTION

The aim of this paper is to demonstrate that better use of geological data (*sensu lato*) retrieved from the colliery archives and their automatic processing, will provide additional management tools which can help decrease production losses and increase safety underground. Geological problems in underground mines do not have to be mysterious or surprising: by applying basic mapping techniques - using simple computing tools - important relationships between geological parameters and mining conditions will become obvious so that geological "hazards" can be forecast.

The actual management tool of the colliery staff consists of hundreds of handmade mine maps and of several thousands of handwritten mine surveyors' records of seam thicknesses. However, the lack of appropriate geological data bases and automatic

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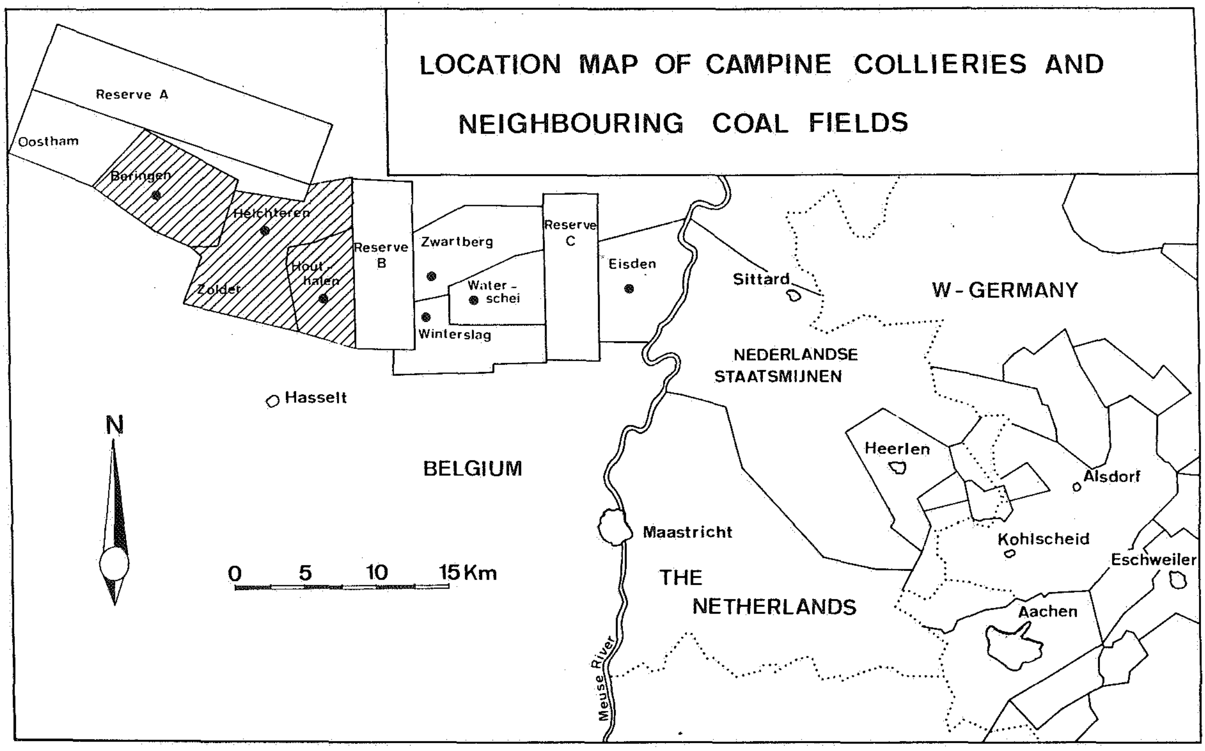


Figure 1. Locality map of the study area within the Campine coalfield.

graphical tools renders decision making in production management rather tedious.

Mine production planning is a very complex problem due to the broad spectrum of parameters to be taken into account. Before any technological or economical thought, a good geological appraisal of the deposit has to be considered as a priority.

Over the years the encounter of so-called "unforeseen " geological hazards in longwall coal mining of the Campine Coal Basin accounted for considerable production losses. Geological hazards such as roof falls, seam splits and washouts were usually dealt with as they were encountered : they were not related to any local or regional trend of the deposit. This apparently resulted from a lack of geological knowledge of the colliery staff and especially from their unawareness of the importance of geological phenomena of sedimentary origin. As a result numerous important geological data were irretrievably lost . For a long time geological hazards in the Campine collieries were synonymous with (post-sedimentary) faulting. Since the major faults affecting the coal basin were relatively well known (through underground workings and survey of stonedrifts) the role of the colliery geologist was restricted to the identification of coal seams and to the assessment of coal reserves. Cored surface boreholes were drilled to explore reserves away from the actual workings whereas underground cored boreholes were drilled to confirm the presence of the worked coal seam beyond a fault.

2. THE COLLIERY ARCHIVES - A GEOLOGICAL ASSESSMENT

A wealth of graphical and handwritten data is available from the mine surveyors' departments at the collieries of the "N.V.Kempense Steenkolenmijnen". For the purpose of this study information has been selected from the collieries of Beringen and Zolder, which are located in the Western area of the Campine Coal Field (fig. 1). Much project time has been spent at the collieries to critically evaluate the available geological data. Although laborious and painstaking, this phase was of great importance to the next step of the project: the input and processing of the selected data. Indeed, due to the great heterogeneity and the highly variable value of the (mostly handwritten) data and handmade graphical documents (dating from the beginning of this century up to the present), a rigorous selection of the collected data was necessary. The results of a comparative study of the different documents as data sources and the amount of available information per document are summarized in figure 2.

SOURCES OF DATA / AVAILABLE INFORMATION	mine maps 1:1000 - 1:2500 - 1:10000	monthly reports of surveyors (worked seam opening)	vertical sections along stonedrifts (1:2500 scale)	sections along blindshafts (1:100 scale)	horizontal sections along stonedrifts (1:100 scale)	sections along shafts (1:100 scale)	non-cored boreholes (variable scales)	reconnaissances (variable scales)	observations by the colliery geologist	reports of the coal face engineer	cored boreholes (1:100 scale) (colliery geological survey)	seismic campaigns (variable scales)	publications by the Belgian Geological Survey
Longwall + isolated outcrop coordinates	●	●							●	●			
Stonedrift + blindshaft coordinates	●	o	●		●					●			
Borehole coordinates	●		●		●		●	●			●		●
Coal seam identification	●	●	●	●	●	●	●	●	●	●	●		●
Coal seam composition (coal/dirt)	o	●	●	●	●	●	o	●	●	●	●		●
Description of associated lithologies				o	●	●		o	●	o	●		●
Faults: direction + throw + (dip)	●		●	o	●	●		o			●	●	●
Coal seam composition log			o		●			o			●		
Lithostratigraphical data				o	o				o		●		●
Sedimentological data				o	o				o		●		●
Paleontological data				o	o				o		●		●
Physico-chemical data			o								●		●

o = occasionnally available or according to colliery

Figure 2. Comparative table of data sources and available geological information.

2.1. Cored boreholes

The great value of the detailed borehole descriptions, carried out by the geological survey of the K.S. collieries (Aardkundige Dienst) and by the Belgian Geological Survey is undeniable: no other type of document in the archives provides the same wealth of lithological, paleontological, sedimentological and structural information (fig. 3 and 4). Besides information on the nature and the thickness of the strata (colour, lithology, structures,etc.) details are given of their paleontological content and on their preservation, as well as on post-sedimentary deformation (dip, fracturing, faults, slickensides, washouts,etc.). Each coal seam is recorded and identified (including incipient paleosols or eroded seams) whereas a macroscopic description ("composition") is given (thickness of individual coal leafs and degree of contamination by dirt) and some physicochemical parameters (volatile matter, ash and sulfur content) are listed. These descriptions refer to both surface and underground boreholes. Each of the surface exploration boreholes penetrates over 600 m of overburden (Tertiary and Cretaceous formations) before entering the productive Upper Carboniferous strata. Coring has been restricted to formations below the Mesozoic-Paleozoic unconformity. The main objective was to provide an inventory of economically important coal seams beyond the currently mined areas and to calculate their reserves. On the other hand, underground operational boreholes never exceeded a few tens of meters. Generally they are drilled out of stone drifts, gates or actual working areas. They are planned to account for fault-location and for confirming the mineable character and the stratigraphic position of coal seams beyond disturbances which cause a temporary stillstand of the coal face.

The original location of the subsurface boreholes was guided by the structural framework of the deposit (at least one borehole per tectonic unit, or block). Underground drillings were episodically planned during production: therefore their location is random. As a result they are unevenly spread for optimum exploration of the coal deposit. A further objective of the exploration boreholes was to improve, or to refine, the stratigraphic correlation of coal-bearing sequences between collieries: this was essential since each of the collieries uses its own terminology for identifying the same coal seam. Therefore one of the first tasks of the geological survey of K.S. was to detail stratigraphical correlation of all known coal seams from the 7 collieries of the Campine Coal Basin. This resulted in the introduction of a standard numbering system a total of 83 numbered seams have been identified within the Upper Westphalian A through to Lower Westphalian C strata (= Genk through Meeuwen "Zones" or Members of the Belgian Coal Measures Formation) (fig. 5).

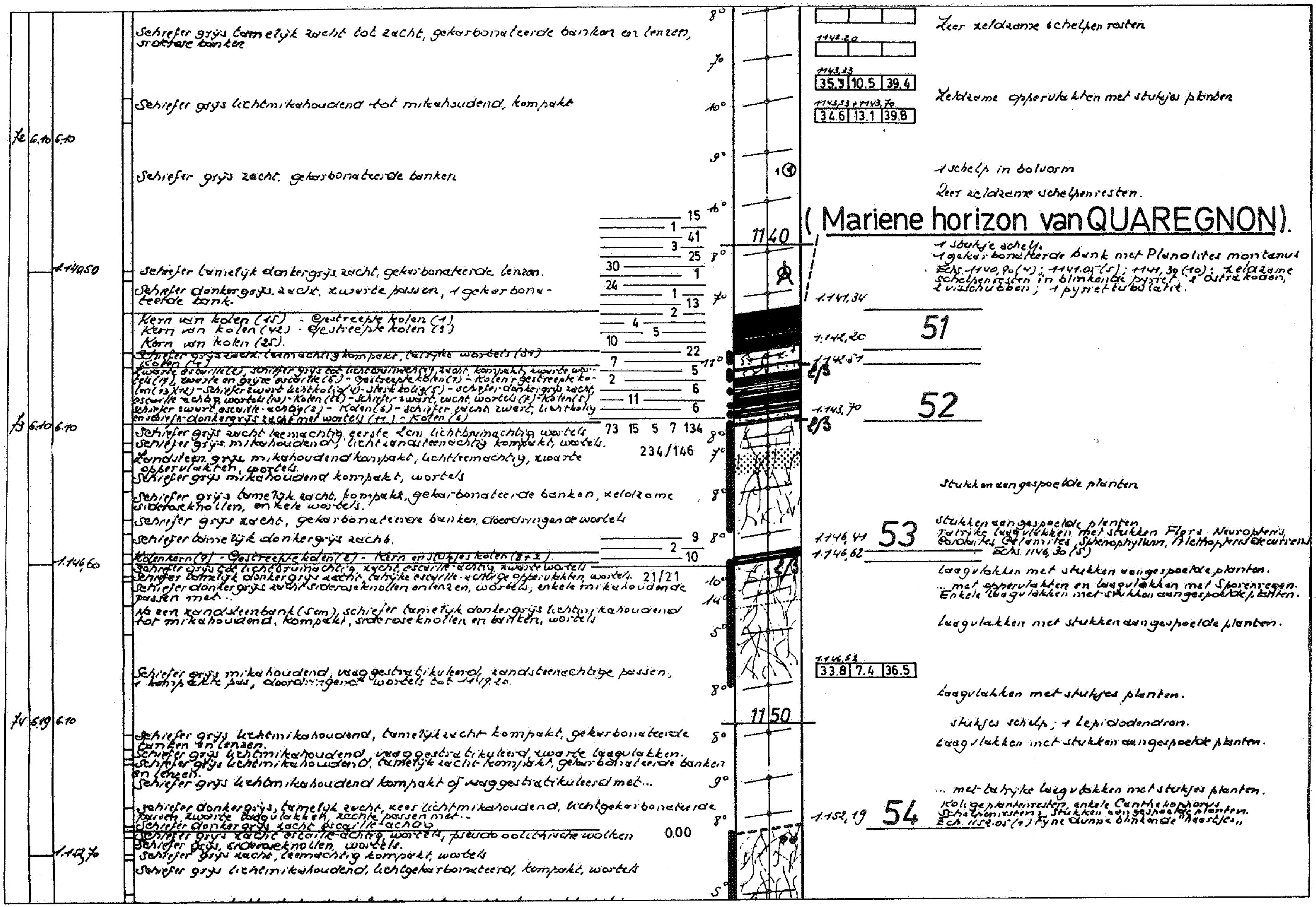


Figure 3. Extract from a hand drawn cored borehole description (courtesy of the "Aardkundige Dienst", N.V. Kempense Steenkolenmijnen).

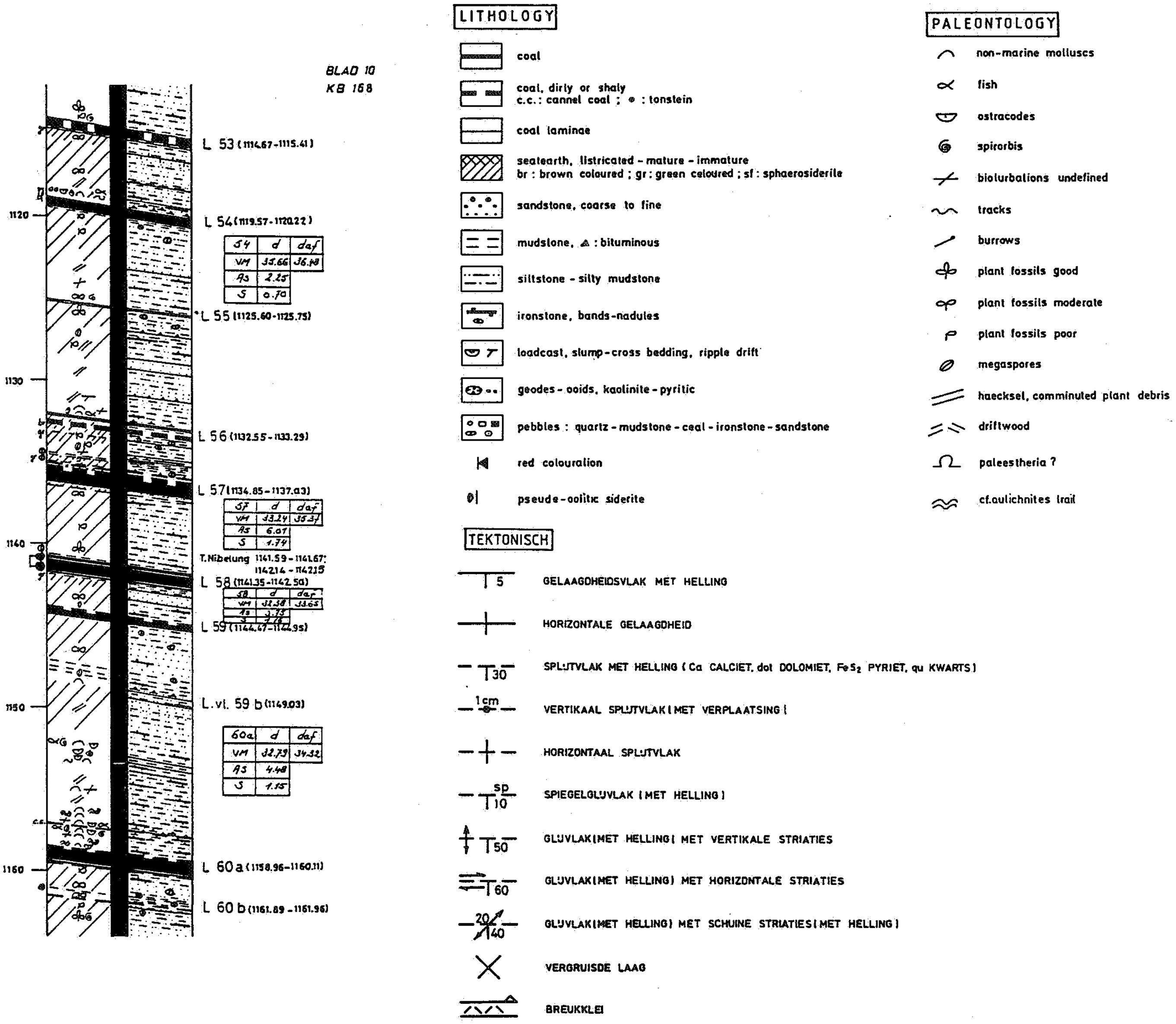


Figure 4. Extract from a published cored borehole description and legend (Belgian Geological Survey, Dusar *et al.*, 1985).

Particular lithological and paleontological data represent features of different correlation value. First-, second- and third-order marker beds have been differentiated (P.Verkaeren, 1989, pers. c-omm.). The stratigraphic correlations should be carried out before production planning commences: they are the basis of any geological modelling of a coal deposit (fig. 6).

The most valuable stratigraphical marker beds are without doubt the so-called "marine bands". These beds represent first-order stratigraphical horizons which can be traced over tens of kilometers within an individual coal basin. Moreover their faunal content allows further extrabasinal correlation with time-equivalent marine bands from other west-european coal-bearing strata. However, the marine nature of some of these marker beds in the Campine coal basin is questionable as a brackish origin is more likely, based on the occurrence of *Lingula*, "brackish" ostracodes and fish scales. Coal tonstein horizons (Kohlentonsteine) represent a second group of first-order marker beds for stratigraphic correlation of Westphalian coal-bearing strata. These horizons, due to their origin (weathered volcanic ashfalls), constitute excellent chrono-stratigraphic markers. They can be traced over several tens and even several hundreds of kilometers throughout west-european coal fields. At least 12 coal tonstein horizons have been recognized in the Westphalian strata of the Campine Basin (Tricot, *in* : Paproth *et al.*, 1983).

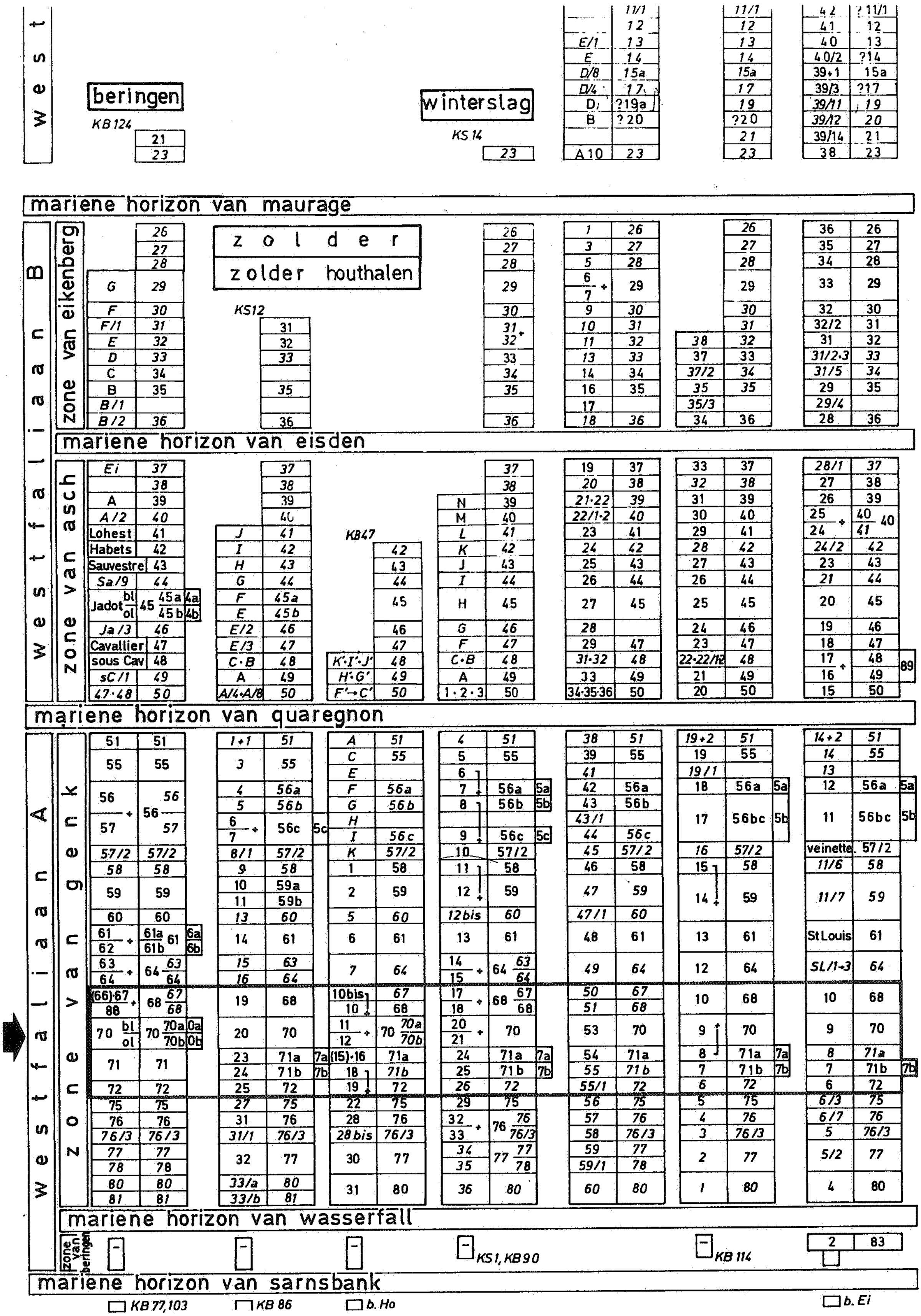


Figure 5. Stratigraphic scheme and correlation chart of coal seams in the K.S. Collieries (the so-called "Overeenkomst der steenkoollagen" ; courtesy of the "Aardkundige Dienst" of K.S.).

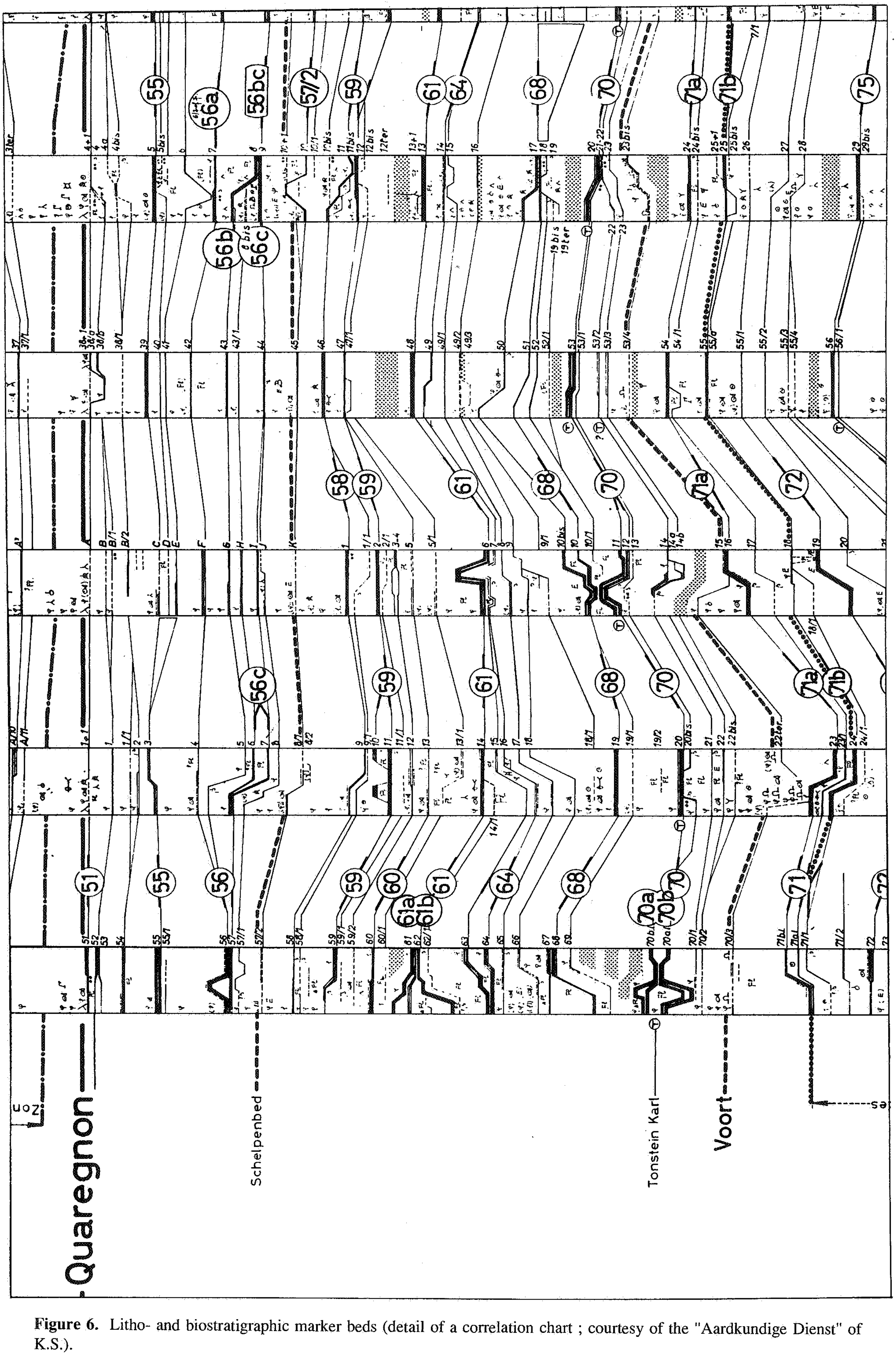


Figure 6. Litho- and biostratigraphic marker beds (detail of a correlation chart ; courtesy of the "Aardkundige Dienst" of K.S.).

Second-order paleontological features of variable value for correlation include "*Estheria* " bands, concentrations of lacustrine to brackish bivalves (e.g. *Carbonicola, Anthraconauta, Naiadites*), lacustrine to brackish ostracodes (e.g. *Carbonita, Geisina* or *Jonesina*) and particular ichnofossil (trace fossil) assemblages (e.g. *Planolites* group). Bed-by-bed stratigraphic correlation is not always possible because of their inherent and relatively poor zonal value (often long-ranging taxa) and because specialist identification is required. These organisms often are facies-dependent rather than zonal indicators. They are characteristic inhabitants of particular environments such as freshwater lakes, or brackish interdistributary bays. However, rich faunal and floral associations, especially monospecific assemblages, locally produce excellent marker beds. In the megascopic descriptions of the cores on site (the so-called "carnets de débitage" of the Aardkundige Dienst of K.S.) important concentrations of pteridosperms, lycopods and especially ferns are highlighted by the use of a green coloured pencil. The presence of conspicuous faunal concentrations (e.g. non-marine pelecypods, ostracodes, ichnofossils,etc.) is emphasized by the use of a red colour.

As a rule, the record of a single second-order paleontological feature (e.g. a thin shell layer) restricted to one horizon, or bed, is not of great value for correlation. However, the concentration of the same faunal, or floral, element over a certain stratigraphic thickness, or interval, has limited potential for correlation. Certain roof rocks with characteristic fauna (e.g. black mudstones or carbonaceous shales deposited in poorly aerated to anoxic lake bottoms with fish scales, ostracodes and non-marine or brackish bivalves) can be easily traced over relatively great distances and thus represent good local marker horizons. Relatively thin interseam intervals locally enriched in plant material point to the presence of a split or a multiple coal seam layer. The presence of non-organic structures, such as raindrop marks, is also frequently used as a local (second-order ?) feature of correlation value.

Third-order lithological features for correlation are of local importance and not always reliable. These include characteristic horizons, such as light-coloured (brown and green) palaeosols, kaolinite ooids, sphaerosiderite and ironstone beds (nodules and clay-bands). The later should be used with great care as they are of diagenetic origin. The areal extent of some light-coloured ("bistre" or tan) seatearths, often combined with the presence of kaolinite ooids, is related to particular depositional environments, such as the levees of distributary channels, hence they have restricted correlation potential.

Geophysical data (wireline logs) are used in the Campine coal district when core recovery is incomplete to confirm and pinpoint the presence of particular marker beds (e.g. thin tonsteins and marine or brackish carbonaceous shales). Wireline, or geophysical, logs in boreholes may be used to infer bed thicknesses, especially seam details (caliper and nuclear logs), to assist correlation (nuclear logs), and to derive processed logs such as those providing synthetic lithologies. Coal seams are identified on Gamma Ray and Long Spaced Density Logs at a 1:100 scale. Bed Resolution Density logs at 1:20 scale indicate seam thicknesses to within 5 cm under optimum conditions. Therefore, for seam thickness determinations only the best quality records are reliable (Elliott et al, NCB Procedures in Coal Mining, 1984).

The graphical documents, representing the columnar sections or logs, of the cored boreholes at a scale of 1:100, contain all the above-mentioned information. However these unique documents are all hand drafted and result from meticulous and tedious work. In order to preserve and to fully utilize the important information these invaluable documents contain, the information should be digitized and entered into a geological data base. However, this input requires also that the original handwritten documents ("cahiers de débitage") are reexamined in order to obtain first-hand lithological, paleontological, sedimentological and structural data.

Although the original borehole descriptions represent a major source of geological information, they highlight a lack of detailed information on sedimentary structures and on the nature of the contacts between succeeding lithologies. The latter information is important in sequence analysis (see later). Furthermore, the lithological terminology used by the Aardkundige Dienst does not conform to the international code and requires translation (see later).

The Belgian Geological Survey regularly publishes Professional Papers with descriptions of surface cored exploration boreholes in the Campine Coal Basin. Generally these boreholes are located well outside the actual mining area and far beyond the concessionary limits of the Campine collieries. The value of these descriptions is similar to those of the Aardkundige Dienst of K.S. Stratigraphical correlations are based on analogies of time-equivalent lithological sequences, on the presence of particular marker beds (e.g. roofs of bituminous shales with freshwater molluscs, thick homogenous coal seams, sandstone bodies, etc.) as well as on analogies of the geophysical logs (Dusar *et al.*, 1986). The graphical representation of the columnar sections and the symbols for lithologies, paleontological content and structural parameters are identical to those used by German coal geologists.

2.2. Non-cored boreholes and reconnaissances

Voluminous geometrical data (including approximate thicknesses of coal and associated "sterile" rocks) are derived from small non-cored drillings, so-called water-drillings which range from a few to several tens of meters in length. The reliability of the inferred thicknesses of coal seams and of sterile rocks is relatively poor because lithological changes are based on changes in colour of the drilling water (fig. 7).

2.3 Sections along shafts, stonedrifts and blindshafts

The hand-drafted graphic sections along shafts, stonedrifts and blindshafts contain information on the composition of each coal seam (coal/dirt) and on the lithological characteristics of the associated interseam siliciclastics (fig. 8 and 9). Depending on the colliery, the sections also contain information on structural parameters such as the location, dip and throw of major and minor faults. However, it is regrettable that the precision of these documents and the quality of lithological data differs for each colliery. Moreover, the quality of the drawings and the lithological descriptions of the "sterile" siliciclastic rocks have changed over the years. The multicolour drawings and sketches made by the mine surveyors between 1930-1960 are more precise and more reliable than similar documents from the last three decades. Because the outcrops in stonedrifts and blindshafts are no longer accessible, since they are lined with concrete, this has resulted in considerable information loss to the coal mining geologist.

2.4. In-situ underground observations

The quality of these observations depends on the degree of collaboration between the geologist and the coal face engineer. The latter normally informs the former of any important changes in the "behaviour" of a particular coal seam in a particular working area. The engineer will have to focus attention more especially on geometrical and lithological changes in the worked seam opening for example: abrupt thickness variations, erosional phenomena, mining behaviour of roof and floor strata, occurrence of splits and appearances of cannel coal bands. One of the main problems is the relative high extraction rate in longwall coal mining and the fact that several faces are operational simultaneously. Thus soon after the engineer has informed the geologist of any important geological event, any reported anomalies might have already dissapeared.

Because exposures along faces are temporary, the colliery geologist will have to plan regular visits to the different working areas (faces and their immediate surroundings) in order to corroborate the engineer's observations and to record all available geological information. Underground visits should be programmed in relation to the geological rate of change, the extraction rate and method of working, the long-term importance of each seam and the degree of priority of each reported anomaly. Gen erally one geological visit for every 200 m advance is adequate. Closer observations are required when workings are traversing zones with much geological variation, whilst minimal coverage may be given to areas in a predictable reserve zone.

2.5. Mine maps and surveyors' records

The bulk of the "geological" data used in the current study has been extracted from hand-drafted 1:1000 mine maps and from handwritten surveyors' records. As the coal faces prograde, the surveyors periodically measure (generally twice a month) the worked seam opening at regular intervals (20 to 30 m) along the coal face which is approximatively 200 m long. Over the years these measurements have provided tens of thousands of handwritten data with respect to the thickness of the worked coal seams, including data on individual coal leaves and dirt bands. However, it is striking that the quality of those observations has decreased over the years. Before 1960 the surveyors not only measured the seam opening but also identified the nature of the coal (e.g. bright, or dull, clean, or dirty, or cannel coal) and that of the dirt beds (e.g. grey mudstone) (fig. 10). Incipient roof and floor splits can be located later thanks to the detailed observations (such as: "false" roof or "false" floor) of the surveyors. Unfortunately, in the last two or three

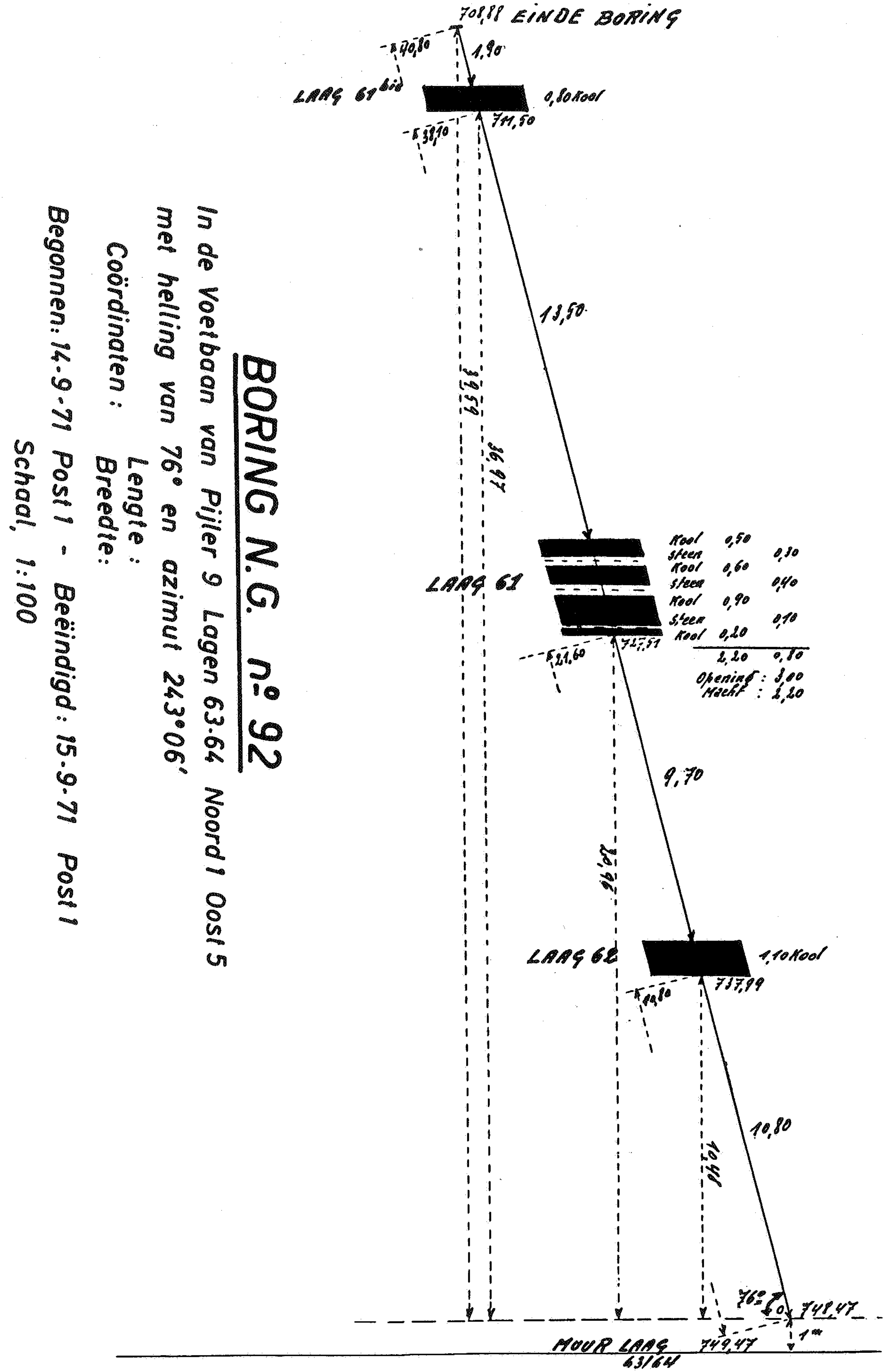


Figure 7. Example of a non-cored drilling (so-called "water boring"). Beringen colliery archives (courtesy of K.S.).

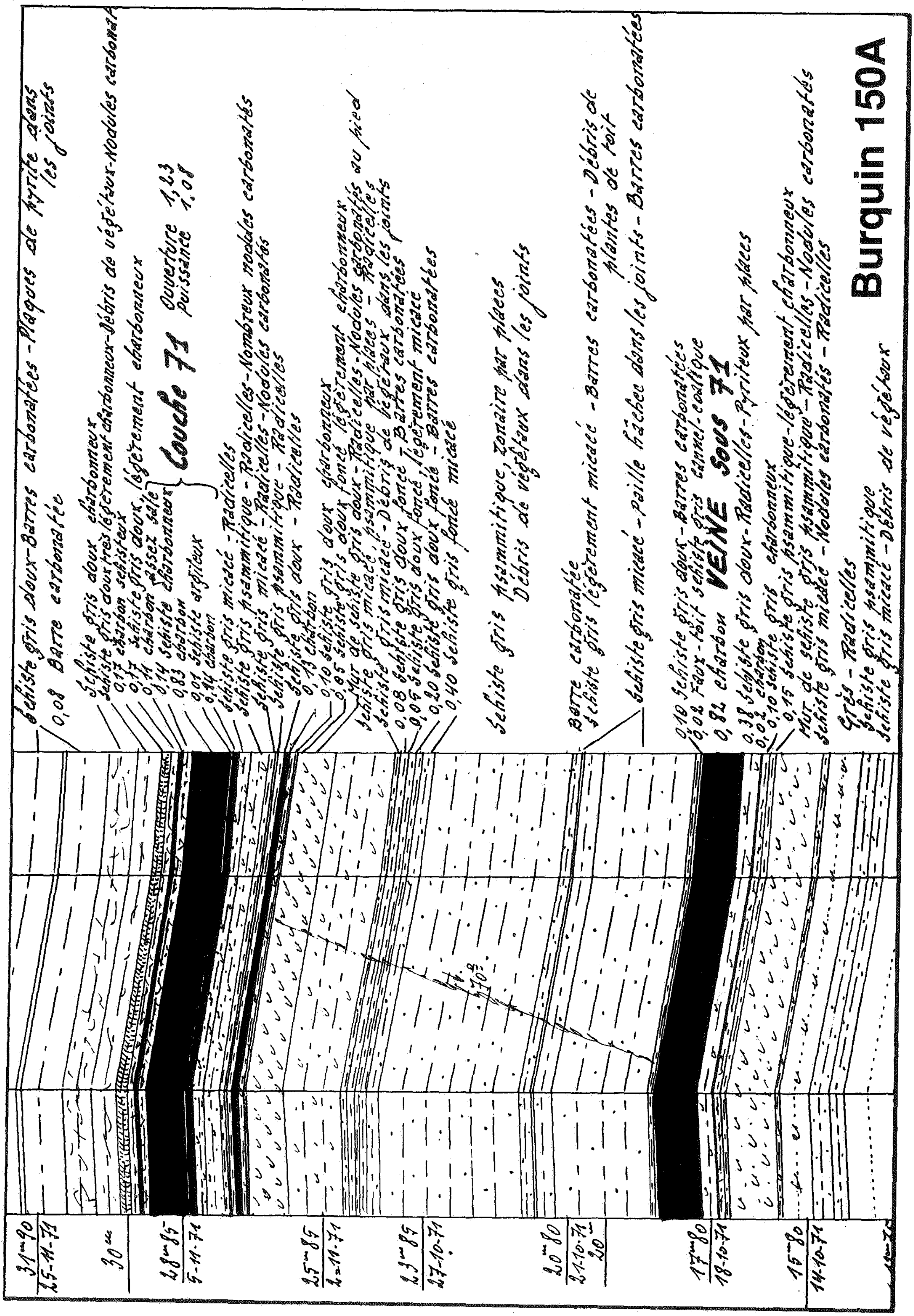


Figure 8. Detail of a hand drawn columnar section of a blindshaft. Beringen colliery archives (courtesy of K.S.).

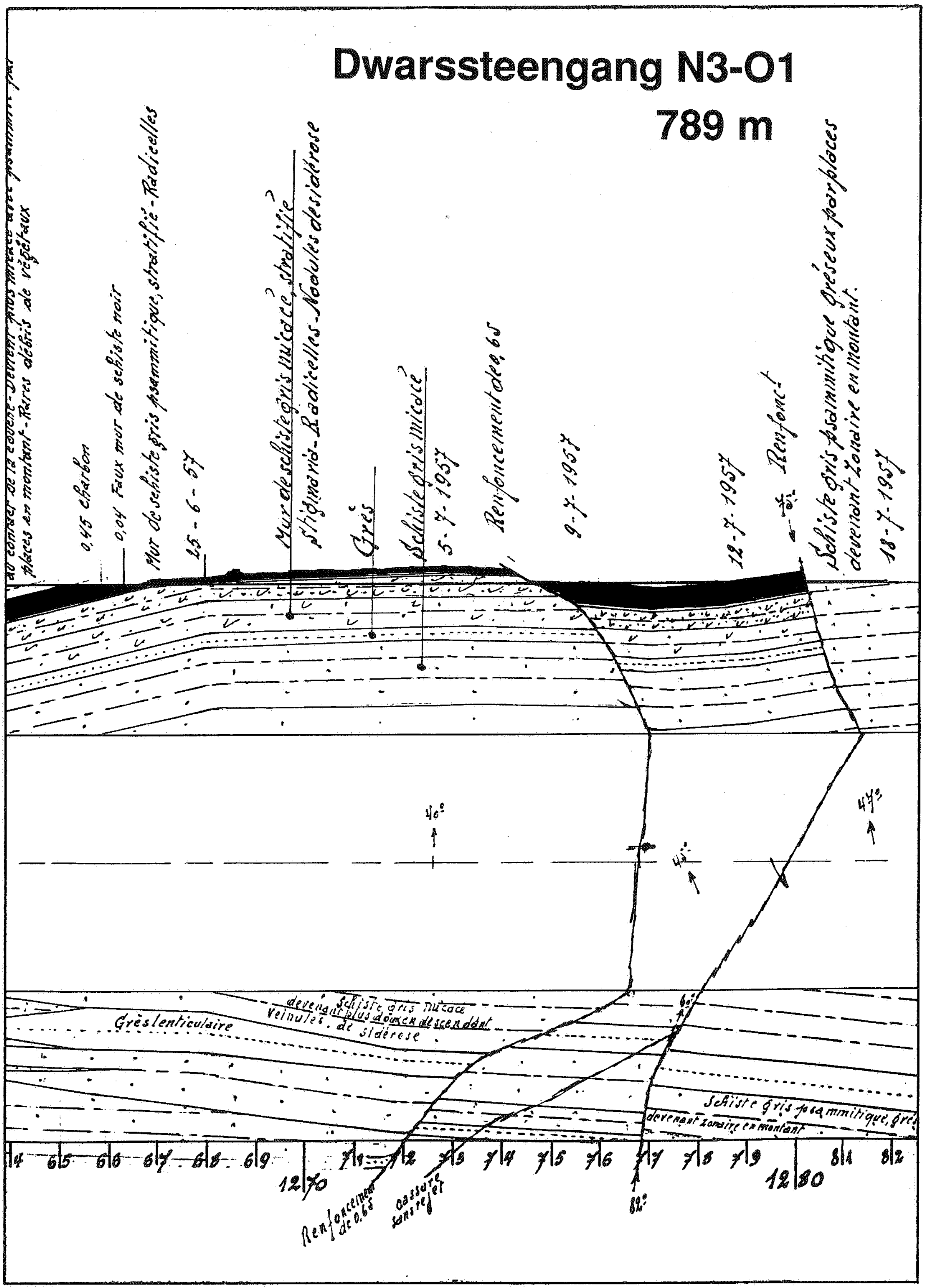
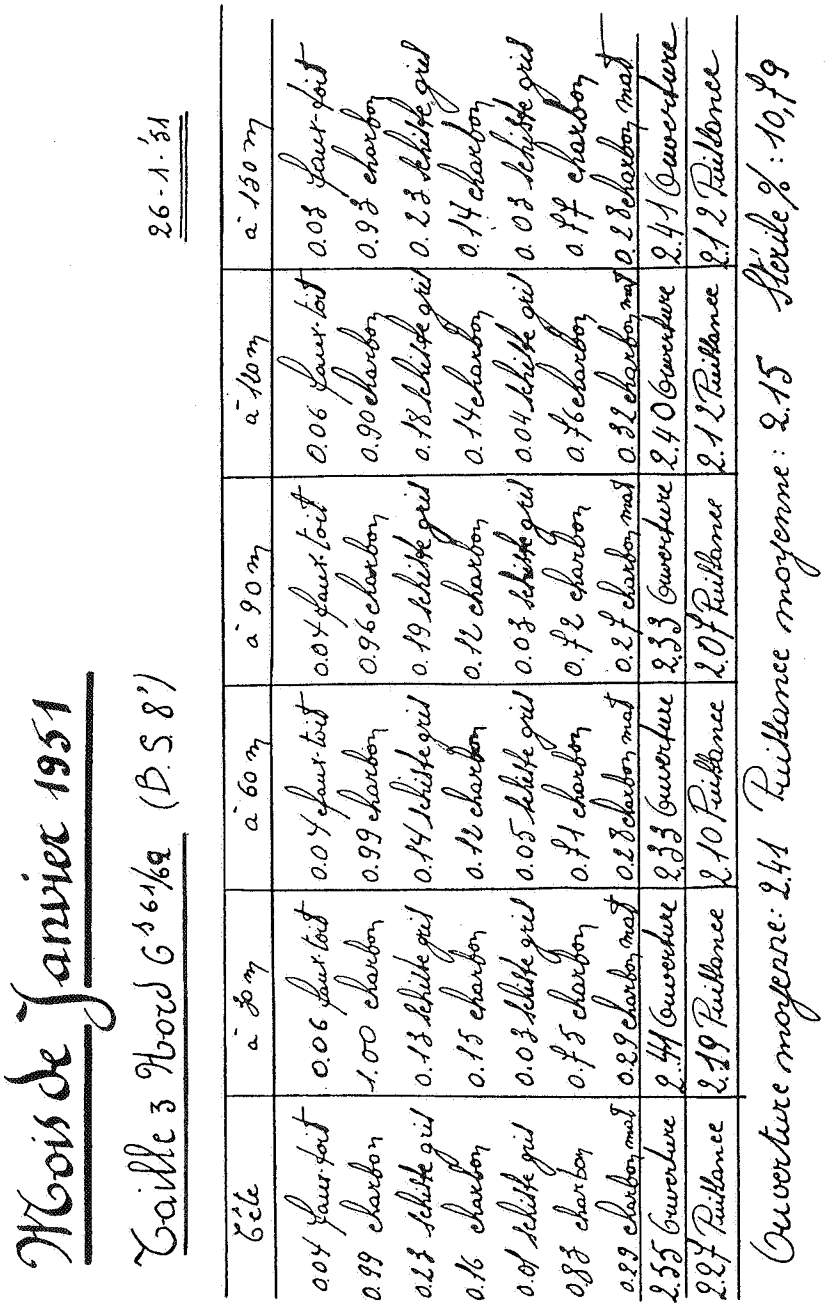


Figure 9. Detail of a mine surveyor's drawing and description of the walls and the floor of a stonedrift (Beringen colliery archives, courtesy of K.S.).



Mois de Janvier 1951

Taille 3 Nord G 3 61/62 (B.S 8')

26-1-'51

Côte	à 30 m	à 60 m	à 90 m	à 120 m	à 150 m
0.04 faux-toit	0.06 faux-toit	0.04 faux-toit	0.04 faux-toit	0.06 faux-toit	0.03 faux-toit
0.99 charbon	1.00 charbon	0.99 charbon	0.96 charbon	0.90 charbon	0.93 charbon
0.23 schiste gris	0.13 schiste gris	0.14 schiste gris	0.19 schiste gris	0.18 schiste gris	0.23 schiste gris
0.16 charbon	0.15 charbon	0.12 charbon	0.12 charbon	0.14 charbon	0.14 charbon
0.01 schiste gris	0.03 schiste gris	0.05 schiste gris	0.03 schiste gris	0.04 schiste gris	0.03 schiste gris
0.83 charbon	0.75 charbon	0.71 charbon	0.72 charbon	0.76 charbon	0.77 charbon
0.29 charbon mat	0.29 charbon mat	0.28 charbon mat	0.27 charbon mat	0.32 charbon mat	0.28 charbon mat
2.55 Ouverture	2.44 Ouverture	2.33 Ouverture	2.33 Ouverture	2.40 Ouverture	2.41 Ouverture
2.27 Puissance	2.19 Puissance	2.10 Puissance	2.07 Puissance	2.12 Puissance	2.12 Puissance

Ouverture moyenne: 2.41 Puissance moyenne: 2.15 Stérile %: 10,79

Figure 10. Extract from a mine surveyor's notebook (1951) : thickness of coal and dirt beds along longwall coal faces (Beringen colliery archives ; courtesy of K.S.).

2572 Laag 72 Pijler 5 $Z_3 O_2$:- September 1983

	Kop	30m.	60m.	90m.	120m.	150m.	180m.	Voet
C.C.	0,05	0,03	0,02	0,07	0,04	0,08	0,07	0,05
Kool	0,28	0,30	0,27	0,18	0,26	0,25	0,28	0,20
Steen	0,50	0,17	0,20	0,14	0,12	0,11	0,16	0,20
Kool	0,62	0,69	0,67	0,68	0,72	0,72	0,63	0,63
Macht	0,95	1,02	0,96	0,93	1,02	1,05	0,98	0,88
Opening	1,45	1,19	1,16	1,07	1,14	1,16	1,14	1,08

Gem. Op. = 1,174 m.
Gem. M. = 0,974 m.
% steen = 17,04

Figure 11. Extract from a mine surveyor's notebook (1983) : thickness of coal and dirt beds along longwall coal faces ("kool" = coal ; "steen" = dirt ; "C.C." = cannel coal) (Beringne colliery archives ; courtesy of K.S.).

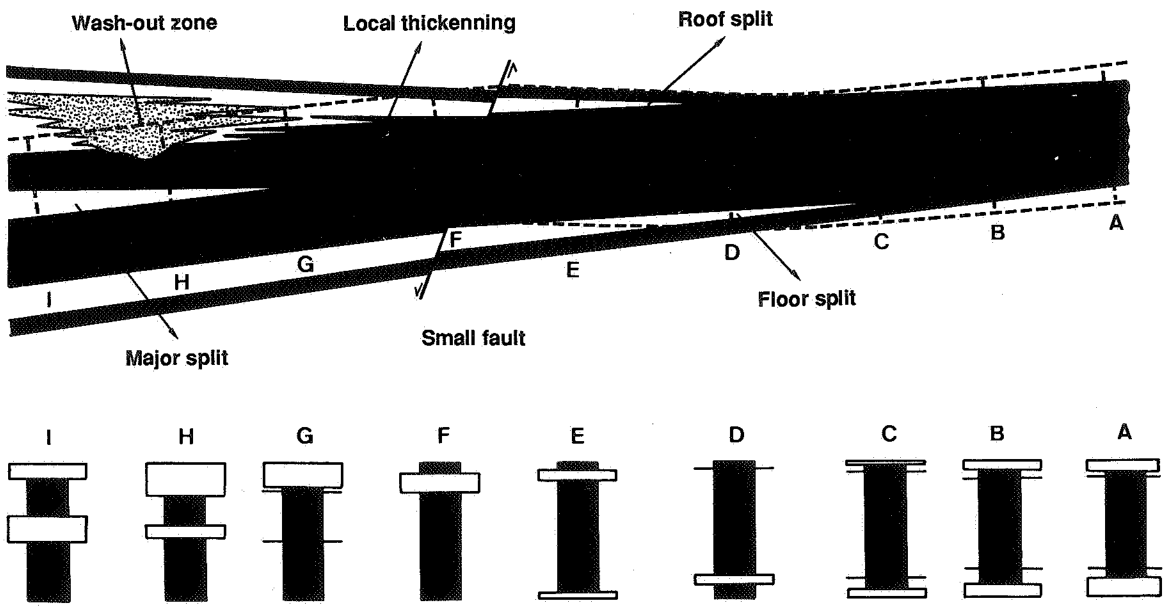


Figure 12. Hypothetical cross-section through a mined coal seam (top) and interpretation based on successive mine surveyor's observations at different moments in time A to I (bottom). Coal face progrades from the right to the left. Horizontal dashed lines correspond to the upper and lower limits of the coal face opening.

decades, the information found in the surveyor's notebooks has been restricted to the thicknesses of coal and dirt only ("steen") (fig. 11). Obviously this has resulted in important information loss to the colliery geologist. The hypothetical example given in figure 12 illustrates well the dangers of interpreting raw data retrieved from more recent notebooks. In the lower half of the figure, columnar sections are depicted which could have been based on actual (=less-detailed) monthly observations of the surveyors and which represent successive measurements of the worked opening in the progradation direction of a longwall. The dashed lines represent the upper and lower limits of the worked opening. It is clear from this figure that most of the geological phenomena affecting the coal seam cannot be properly identified without additional information. Thus interpretation of the data is rather tentative and subjective.

Mine maps represent one of the most important management tools for the colliery staff. For each worked coal seam there is a series of separate sheets on different (1:1000, 1:2500, 1:5000 and

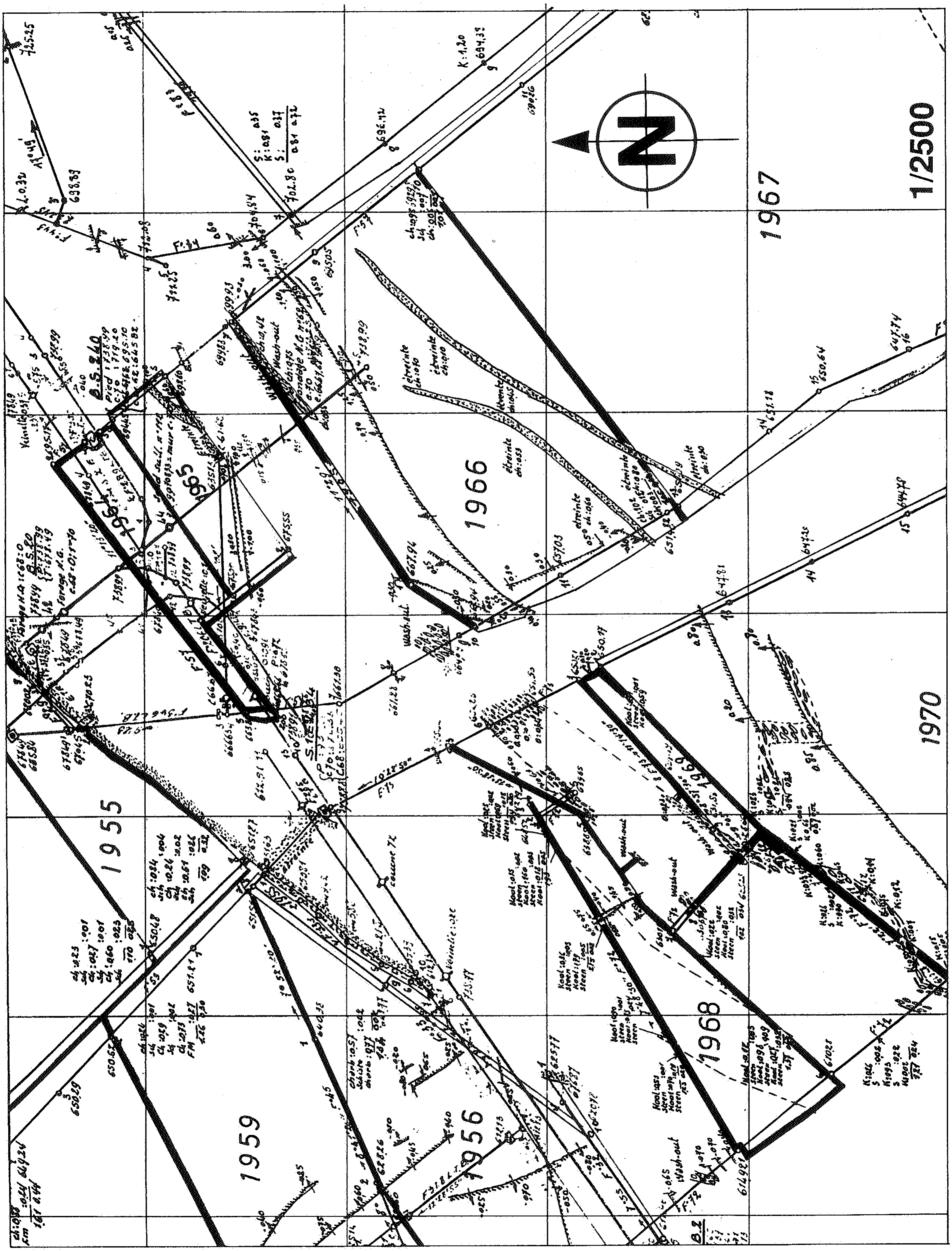


Figure 13. Detail of a hand drawn mine map (Beringen colliery archives ; courtesy of K.S.).

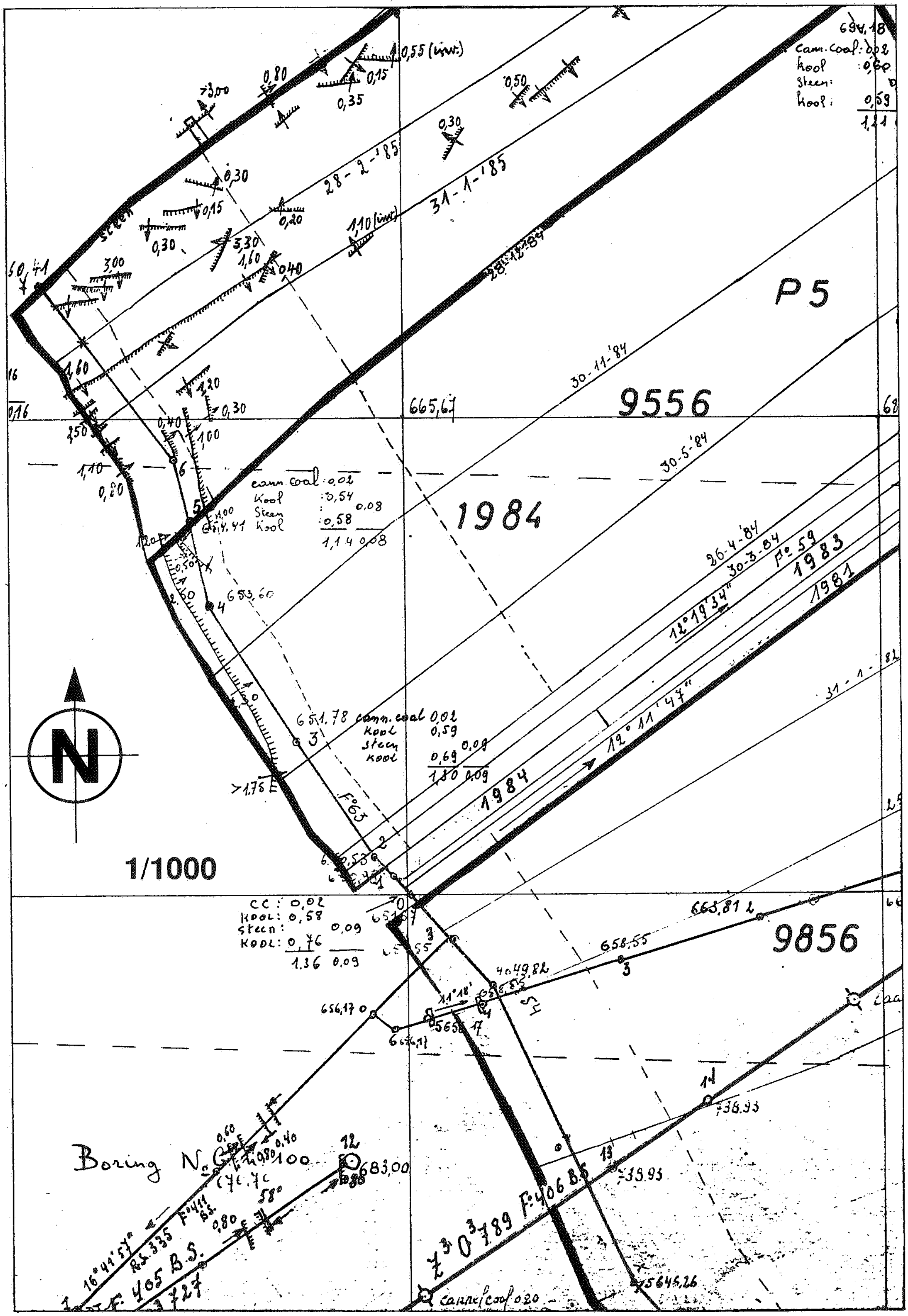


Figure 14. Detail of a hand drawn mine map (so-called "minuut plan". Beringen colliery archives ; courtesy of K.S.).

1:10000) scales. These unique handmade planimetric maps (especially the so-called 1:1000 scale "minute" map) are continuously updated as soon as new information from underground operations becomes available. The maps display not only the location of important faults, of old and actual workings within the seam, and of galleries, road works, gates, blindshafts, cored boreholes and reconnaissances, but show also spot information on seam thickness (coal/dirt ratio) and on tectonic events affecting the worked seam (dip and throw of small faults) (fig. 13). The succeeding positions of the prograding coal face are indicated so that all mine surveyors' records of seam thicknesses can be located exactly. Besides topographical and geometrical data, the mine maps occasionally display probable split lines of a coal seam and the known extent of wash-out zones within a seam (fig. 14).

Before any processing of data commences stringent selection of surveyors' records is needed, because only comparable data (the same parts of a coal seam) should be compared. Due to the frequent roof and floor splitting the worked opening at each measuring point does not necessarily correspond to the complete coal seam. Lateral variation of thickness of a coal seam is gradual, hence abrupt thickenning and thinning of a particular seam has to be checked carefully since sudden thinning might result from the loss of a thin coal leaf due to a minor roof or floor split whilst a sudden increase in thickness could point to the merging of coal leaves). Incompatible (=incomparable) coal seam profiles may result from another cause, such as changes in thickness of particular coal leaves due to observations made by different surveyors. Indeed, very thin dirt bands (1 cm and less) might not be identified and might even be included in a coal leaf in order to artificially "increase" the monthly production of a particular working panel.

2.6. Seismics

In-seam seismic exploration has been episodically tested by the "Aardkundige Dienst" in a few collieries and for a few selected seams only. The major objective of such seismic techniques was to predict tectonic disturbances within individual coal seams. The results were unsatisfactory due to the reduced thickness of the investigated coal seams. Major surface seismic (vibroseismic) investigations have been carried out jointly by the Belgian Geological Survey and by N.V. Kempense Steenkolenmijnen. The aim of the investigations was to provide an inventory of the reserves which were non-accessible to the actual underground workings. In the present study only a few seismic profiles crosscutting or extending some of the major stonedrifts have been selected. Comparison of the seismic profiles with nearby cored boreholes permits the identification (corroboration) of the Westphalian megasequences. Unfortunately the resolution (at the time of the survey) was not sufficient to identify individual coal seams, or individual sandstone bodies, or to locate faults with throws not exceeding 20 m. However, 3D seismics might well enhance this resolution.

3. THE GEOLOGICAL DATA-BASE PROCESSING SCHEME AND APPLICATIONS

Computer techniques are being developed worldwide to improve the basis upon which geological assessments are made for planning purposes. Most application programs are designed to present a series of menues showing step-by-step options. Images created on a graphic screen can be interactively manipulated and alternatives can be rapidly evaluated by the geologist, or the operator, prior to plotting. Computer technology is advancing rapidly. In the present study, rather than developing new computer programs, existing software packages have been adapted. Several geological databases exist, the structures of which are especially adapted to mining problems.

Software packages for coal mining such as DIGMAP or GEOSTAT (developed by the Bergbauforschung Essen, FRG), STARMAP, GEOTREND and GEOLOG (used by Britisch Coal, Doncaster, UK) were found to be either incompatible with our hardware, too expensive, or not commercially available (1987). For the purpose of this study, most procedures of the computer program STAR TOPOGRAPHIC (from STAR Informatic, Liège, Belgium) have been adapted, whereas some procedures of the GDM (Geological Data Management) software package (from the BRGM, Orléans, France) have been used in a later stage. Hardware facilities used in this study include two 330 Hewlett-Packard and one 386 Compaq PC work stations, two HP plotters (sizes A4-A3 and A0) and one Calcomp digitizing table (size A0).

The storage, organisation and retrieval of geological data are handled by a database constructed on a hierarchical pinciple. Header files contain the

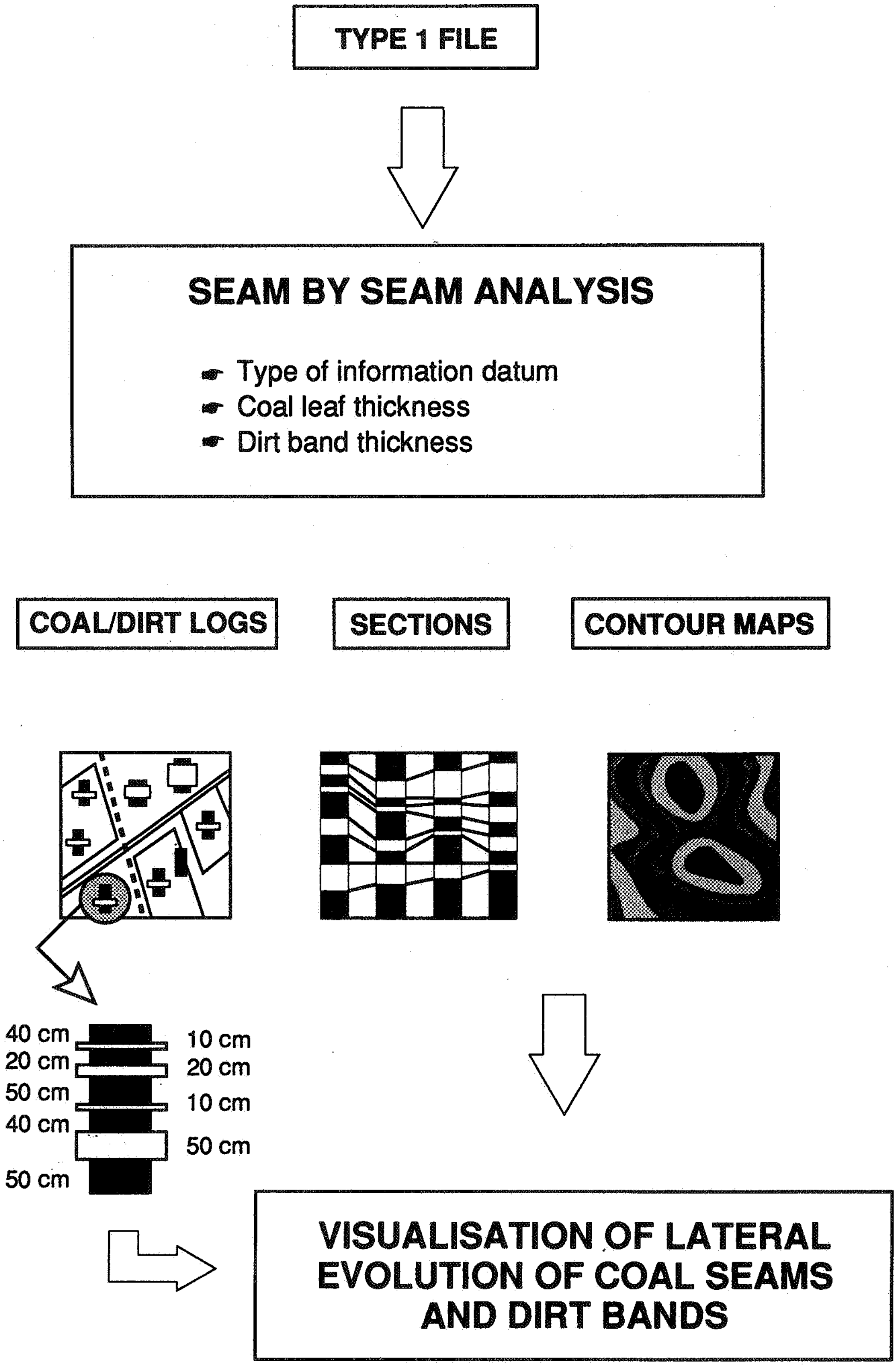


Figure 15. Seam-by-seam analysis processing diagram.

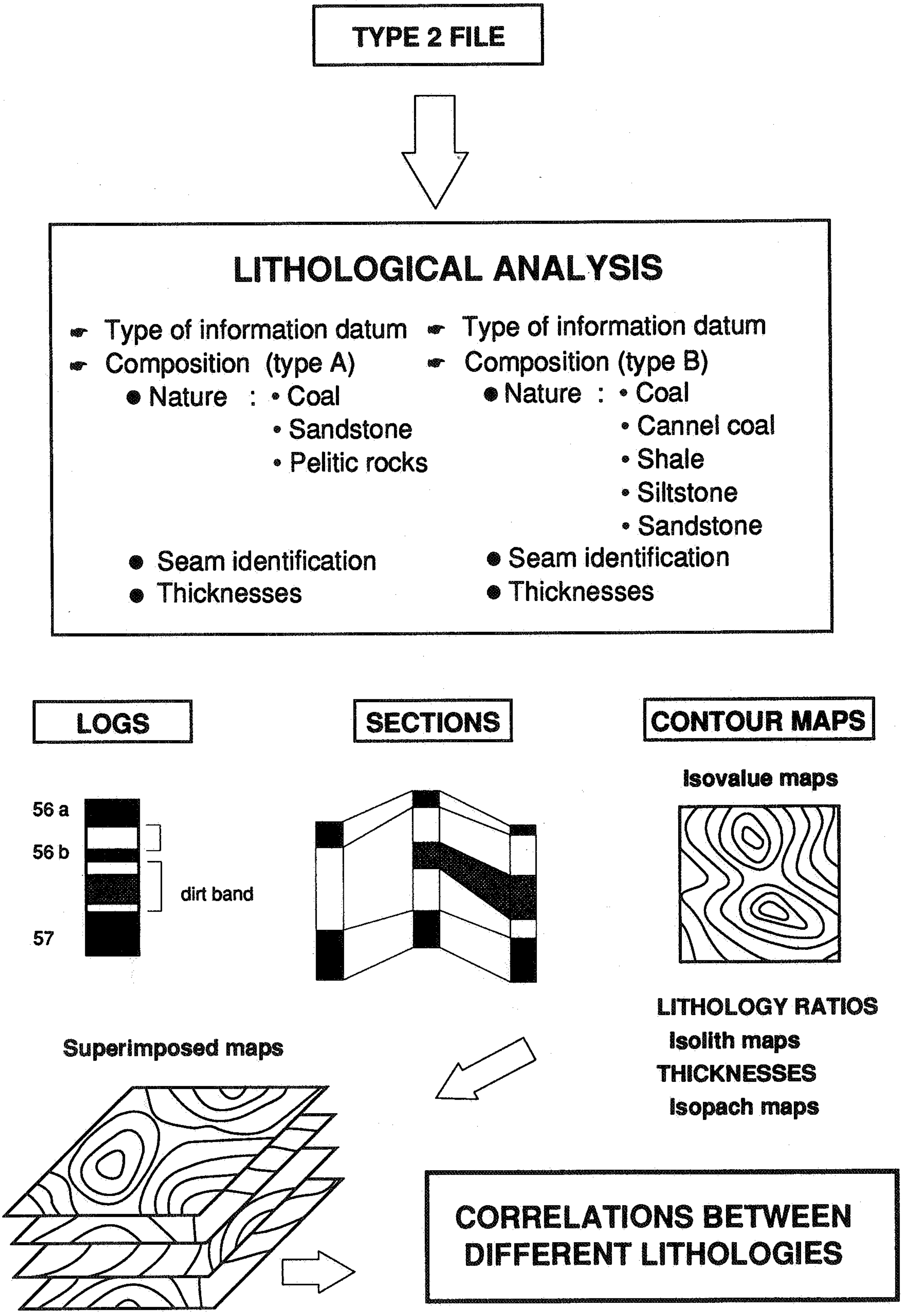


Figure 16. Lithological analysis processing diagram

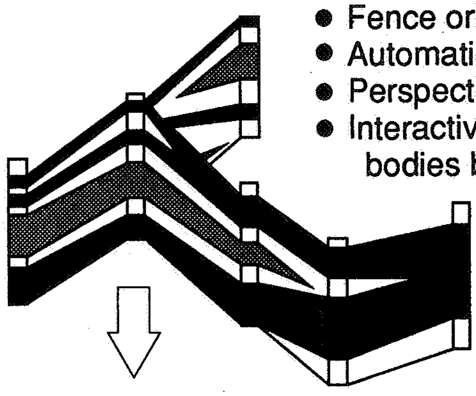
TYPE 2 FILE

LITHOSTRATIGRAPHICAL ANALYSIS

- Type of information datum
- Lithologies
  - Nature : • Coal
    • Cannel coal
    • Shale/mudstone
    • Siltstone
    • Sandstone
  - Seam number (identification)
  - Thicknesses

FENCE DIAGRAM

- Fence orientation (direction)
- Automatic correlation of seams
- Perspective view
- Interactive correlation of interseam sandstone bodies based on interpretation of geologist



- **LOCATION OF PALEOCHANNELS (distributary channels, crevasse splays,...)**
- **EVOLUTION IN TIME AND SPACE OF SEVERAL COAL SEAMS AND ASSOCIATED SILICICLASTIC ROCKS**

Figure 17. Lithostratigraphical analysis processing diagram.

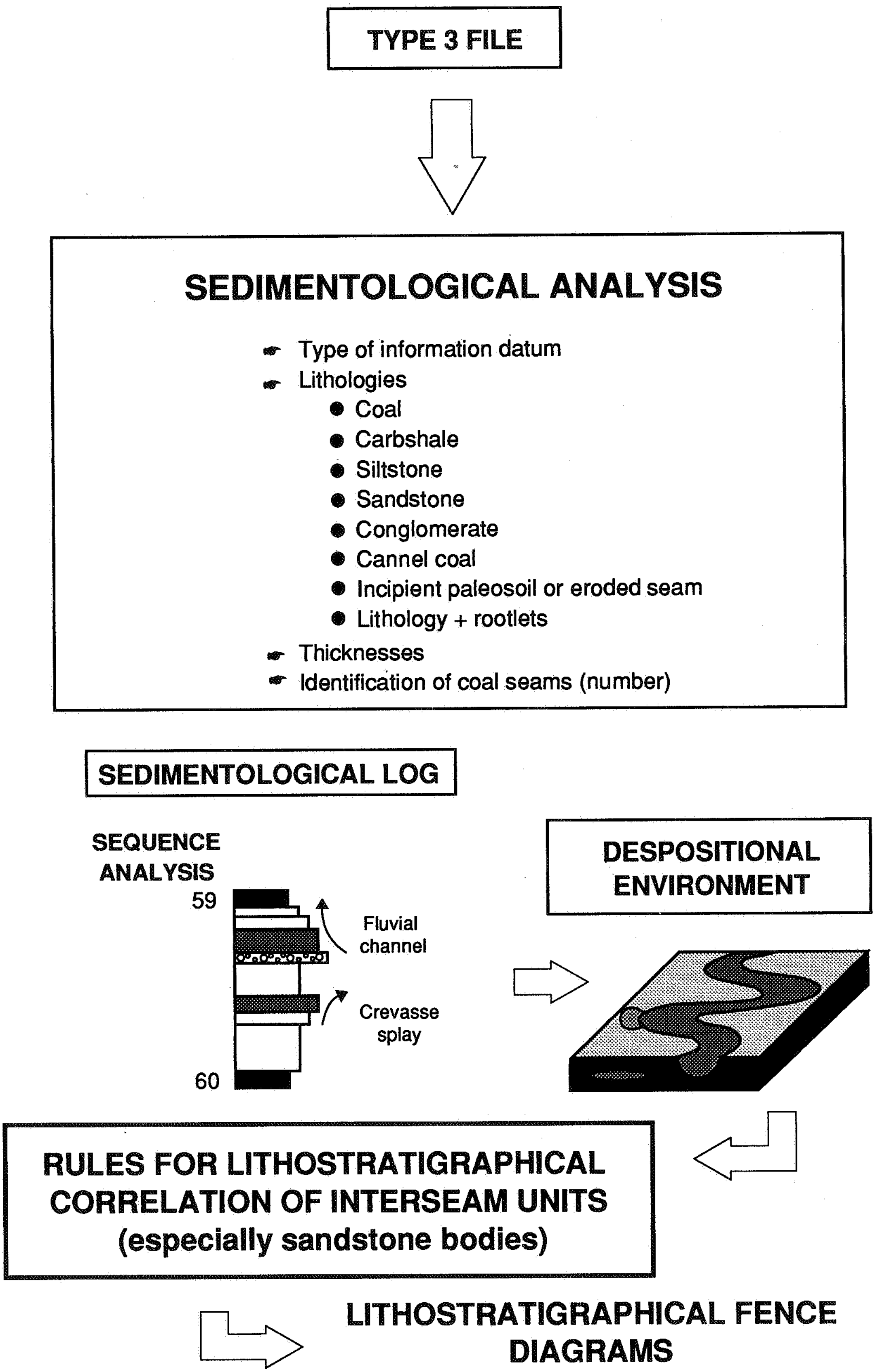


Figure 18. Sedimentological analysis processing diagram.

location, category and ancillary details relating to all selected source data. Under the header files are others containing data corresponding to coal seams and intervening strata.
Figures 15 to 18 illustrate the processing scheme for the selected geological data. According to the available type of information and the required graphical output, different procedures have been employed. Subsequently the computer-generated graphical documents have been used as working tools for the geologist in order to aid colliery planning.

Three types of files have been used which are directly related to the quality (detail) of the source data (Dreesen, R., 1990).

3.1. Seam-by-seam analysis and seam mapping

The type 1 files contain rudimentary data such as those retrieved from the surveyor's records. The source data correspond to thicknesses (in cm) of coal leaves and dirt bands of a given coal seam. These can be graphically processed into three categories: simplified logs, sections and contour maps which visualize the lateral evolution of the "quality" (in terms of coal/dirt ratio) of the seam. The combination of coal/dirt logs and location maps (digitized plan areas) visualizes well the "behaviour" (coal/dirt evolution) of a particular mineable seam, especially for working panels with little or no variation of the whole seam thickness. The sections category correspond to graphical correlations of individual coal/dirt logs: these have proved to be of little importance except for homogenous coal seams. Indeed, reliable correlation of all section points is only possible if each log contains the same number of coal leaves and dirt bands. The accuracy of the latter cannot be guaranteed for the reasons expressed above. Contouring routines are available for drawing isopach lines of whole seam, individual leaf and intervening dirt band thicknesses. Before contouring the operator has to be absolutely sure that equivalent data will be processed in order to preclude artefacts on the resulting isoline maps.
The user has to select an appropriate algorithm which is suited to the particular data population. The program procedure then constructs a surface and calculates the grid values on it for contouring. The degree of "smoothing" (averaging method) is controlled by the selection of constants embodied in the formulas (e.g. the influence radius).

3.1.1. Case study : predicting seam thickness and cleanness

The evolution of the seam thickness and the degree of contamination by dirt has been studied in the easternmost district of the Beringen Colliery for seam no 56/57 in two working panels A and B and in their surroundings, (fig. 19). From the (smoothed) isopach maps of the studied areas (fig. 20 and 21) and from the map with coal/dirt logs (fig. 22), corresponding to the uppermost zone of fig. 20), it is clear that the zone adjacent to panel A is a high risk zone for production: although panel A is located in a zone for which the isopach lines predict a mean total coal thickness of 130 cm and a mean thickness of 10 cm for the main (middle) dirt band, the amount of dirt bands increases to the east and a potential splitting of the seam is to be expected in the same direction. The latter will eventually lead to the forced abandonment of the coal face. The forecast for the zones adjacent to panel B is more optimistic: here the total dirt will not exceed 10 cm and the total coal thickness will vary between 120 and 140 cm (although a minor roof split accounts for the loss of a thin coal leaf).

In order to check these forecasts manual processing has been carried out successive monthly surveyors' measurements of the seam thicknesses along the coal faces in panel A and B (between May and October 1986) (Dreesen, R. & Liegeois, R., 1987). The evolution in time and space of the mean thickness of the upper and lower coal leaves and of the middle dirt band in the prograding coal faces is illustrated (fig. 23 and 24) and corroborates the prognoses: a general increase of dirt and a mean value of 130 cm for the total seam thickness in panel A; 10 cm of dirt and a mean total value of 134 cm for the worked seam opening in panel B. Moreover, in 1987 a reconnaissance gallery dug directly east of panel A confirmed the forecast split : indeed, underground observations recorded a relatively abrupt thickening of the middle dirt band generating a major split (from a few cm up to 180 cm over a distance of 40 m). Furthermore the presence of siltstones grading into thin sandstones pointed to the proximity of a fluvial sandstone body contemporaneous with the coal deposit (crevasse splay deposit ?). The presence of a sandstone complex between coal leaves 56 and 57 has been corroborated in nearby underground boreholes (fig. 22). Hence all workings planned in this zone were suspended in 1987.

Furthermore, after digitizing the strikes of all recorded small faults (with throws equal to or less

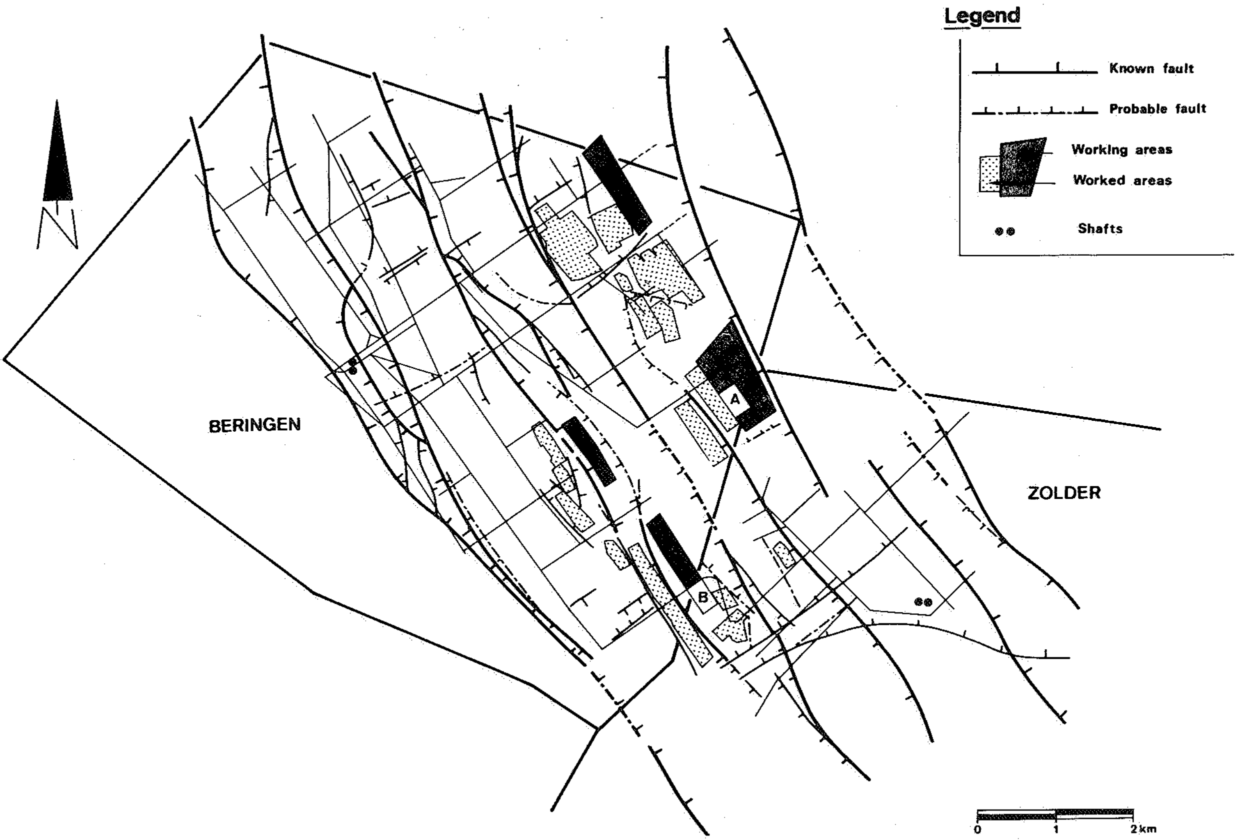


Figure 19. Simplified planimetric map of the Beringen and Zolder collieries with location of main galleries, stonedrifts and major faults. Panel orientation and location of studied panels (A and B) within coal seam 56/57. Polygon corresponds to the extent of the Beringen colliery (after colliery archives ; courtesy of K.S).

than the worked opening) which had affected the different worked panels of seam 56/57 in the eastern district of the Beringen colliery, and after their processing into frequency rose diagrams, a positive correlation between the frequency of some faults and the amount of dirt in the seam became obvious (fig. 25). The frequency of transversal faults (SW-NE) increased to the east and to the NE, which related to a regional trend inferred for the dirt/coal ratio: the amount and thickness of dirt increases in the same direction due to an imminent splitting caused by the proximity of a fluvial sandstone complex. These small transverse faults have an important impact on the productivity (extraction rate) of the panels, as they are oriented parallel to the coal face. Their origin is not related to any regional structural trend but rather is due to the mechanical effects of differential compaction (dirt versus coal).

3.1.2. Case study : predicting roof support equipment

In this example the colliery management needed to know whether or not they could use the same mechanical roof support in a planned panel in the SE-district of the Beringen colliery. They had to consider the fact that, on one hand the coal seam to be worked (seam no 70) showed a splitting tendency, whilst on the other hand a maximum worked opening of 280 cm for the seam was allowed for according to the available mechanical roof support equipment.

The contouring of values from 100 sources of data with information on the thickness of the main dirt band produced an isopach map (fig. 26), which indicated that in the planned area the thickness of the dirt band would rapidly increase from a few tens of centimeters to a few meters, so that it would be impossible to work the two coal leaves simultaneously. As a result of this information the colliery management decided to work the coal leaves one at the time, hence avoiding the problem of encountering a split which would have exceeded the maxi mum opening allowance of the roof-support equipment.

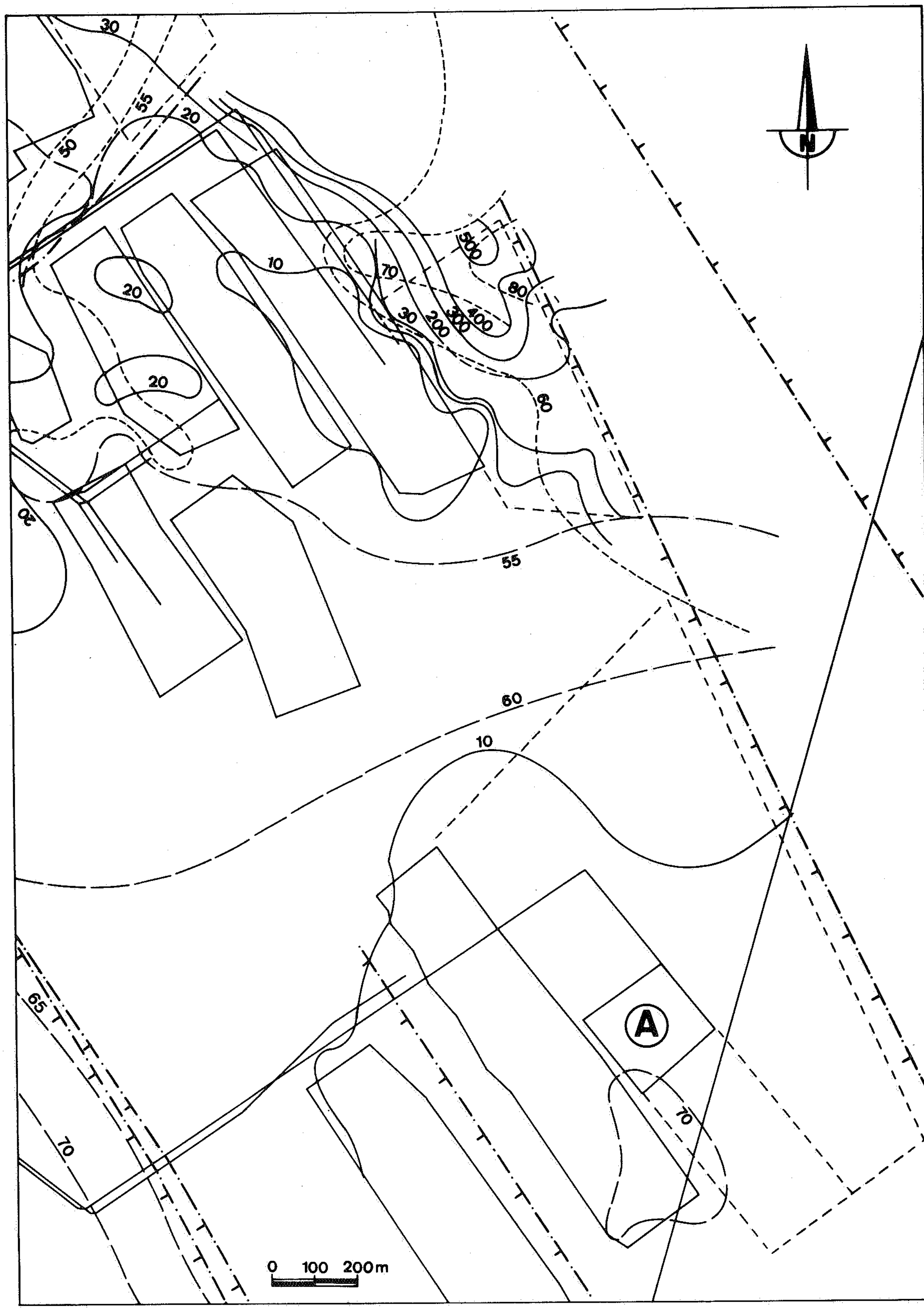


Figure 20. Detail of a computer-generated isopach map (seam mapping) : total seam thickness of coal seam 57/57. A refers to studied panel A of figure 19.

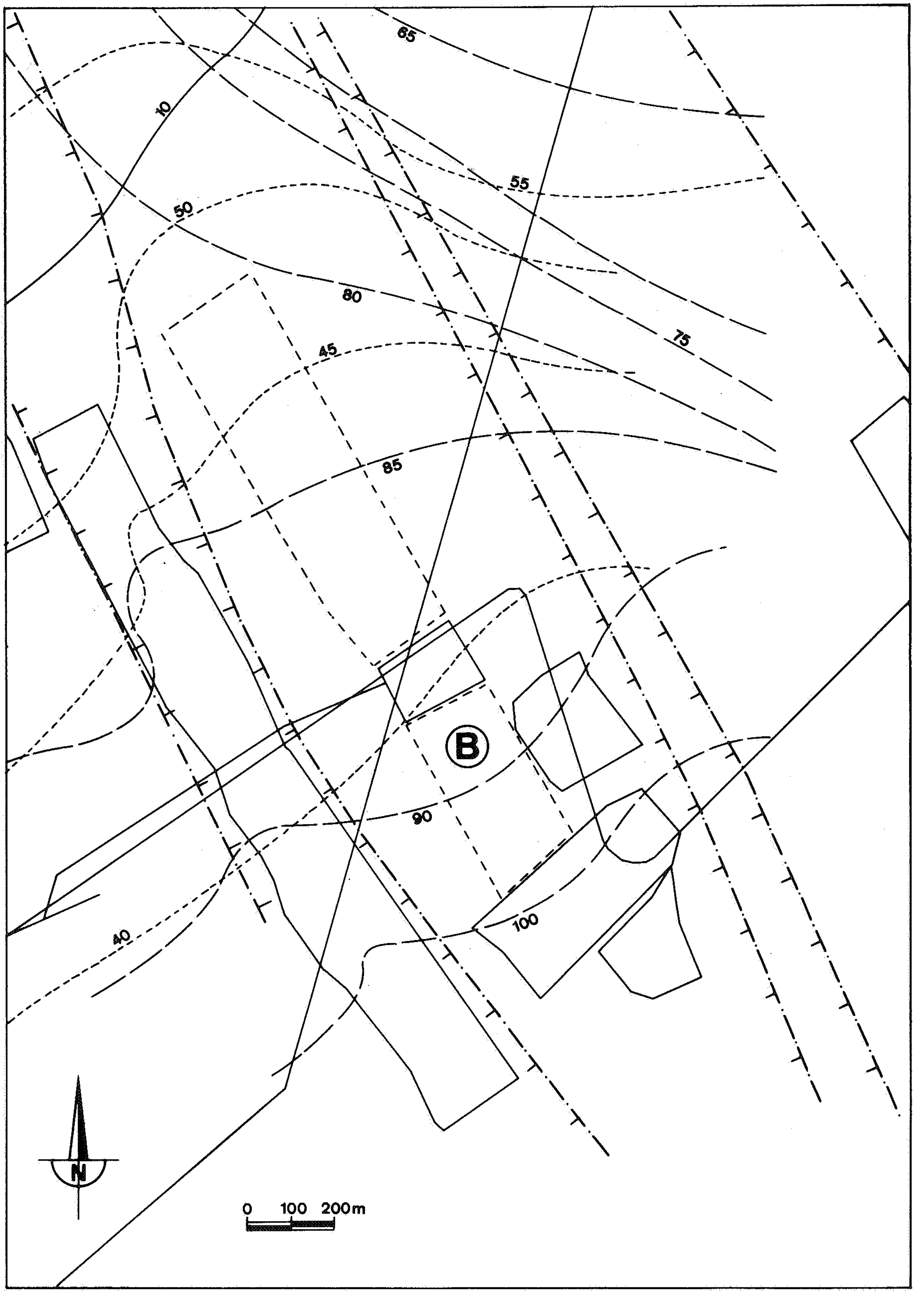


Figure 21 Detail of a computer-generated isopach map : total seam thickness of coal seam 56/57. B refers to studied panel B of figure 19.

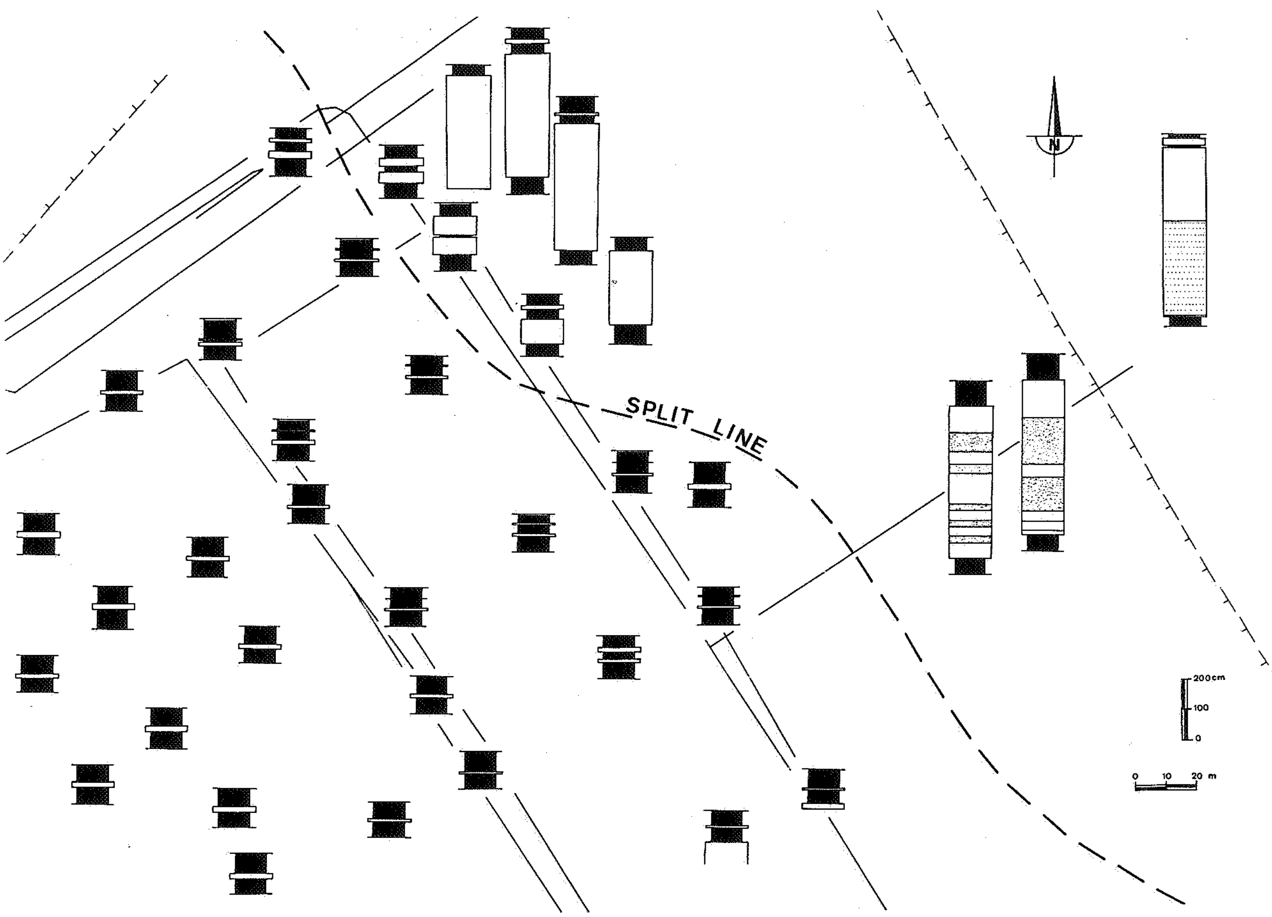


Figure 22. Detail of a computer-generated coal/dirt logs (seam-by-seam analysis) and split line for coal seam 56/57.

3.1.3. Case study : extrapolating wash-out zones and associated phenomena

In this example the thickness variation of a complex seam (seam no 66-67-68), which had been affected by an important wash-out in several old workings in the SE-district of the Beringen colliery, was studied. Over 600 values related to seam thickness data(total amount of coal) were selected and processed into isopach maps.

Coloured screen copies of the isovalue maps (so-called "aplats couleurs") showed interesting trends and provided a preliminary working document for the colliery staff, which visualized positive, or maximum (red), and negative, or minimum (blue), anomalies (fig. 27). On the isopach map inferred axes point to the junction of different arms of a fluvial channel complex and thinnings parallel to the main wash-out axis (fig. 28). These trends could then be extrapolated to new working panels about 1 km to the E within the same coal seam, located in the prolongation of the main wash-out axis (fig. 29). Moreover, the lithostratigraphic information gathered from nearby cored underground boreholes has led to the proposal of a geological model (fig. 30 and 31) predicting thickness and lithological facies variation parallel to the wash-out axis. Furthermore, it could be demonstrated that the thickness variation of the mined coal seam, in the operational coal face from the NW to the SE, was identical to that observed in the former wash-out zone, and hence had been neglected as a prediction tool. The subsequent thinning and thickening phenomena parallel to the wash-out axis were predictable as they were related to minor roof splits and to small erosional events. The latter in turn were genetically related to the approach of the distributary channel complex. The sudden thickening of the coal closest to the wash-out resulted from differential compaction of peat and sand : the less compressed sandstone wedge producing at its borders a local thickening of the enclosing coal (fig. 31).

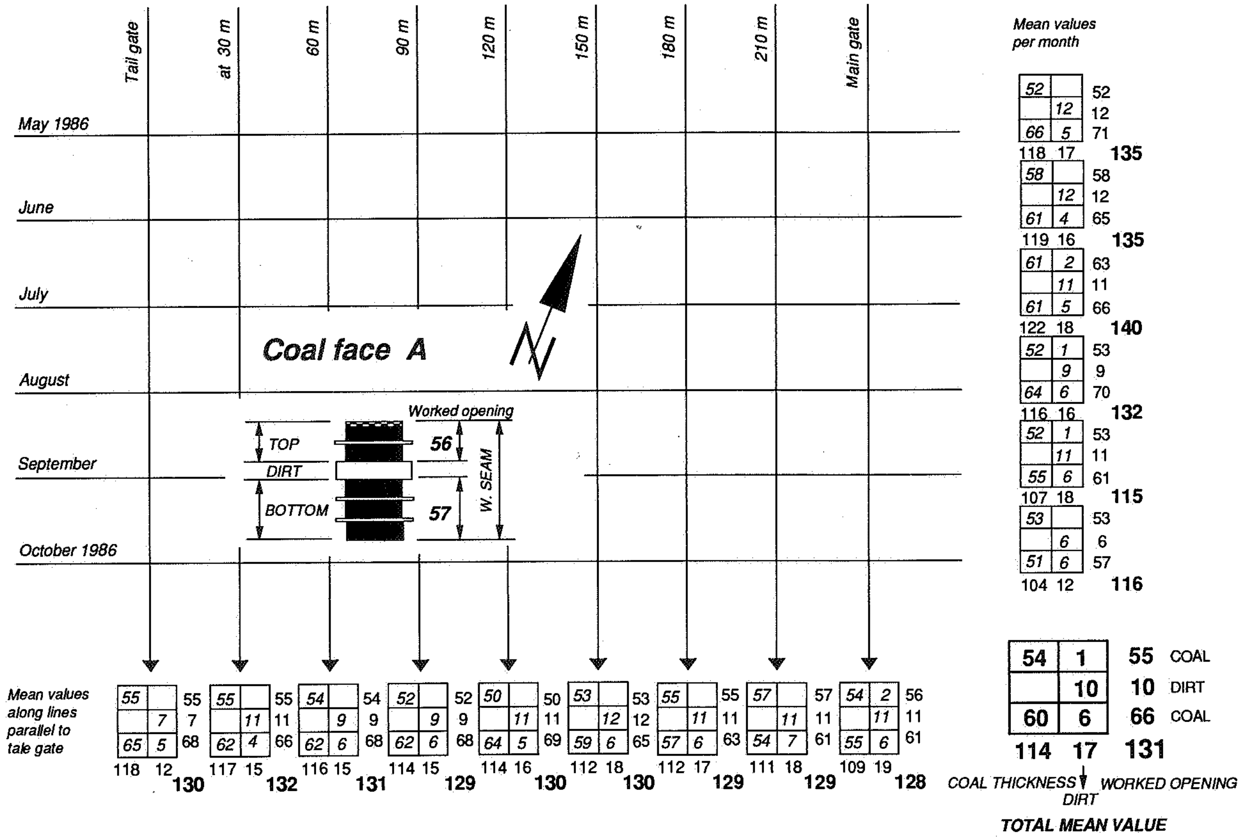


Figure 23. Evolution in time of the mean thickness of coal seam 56/57 along coal face in panel A (see figure 19).

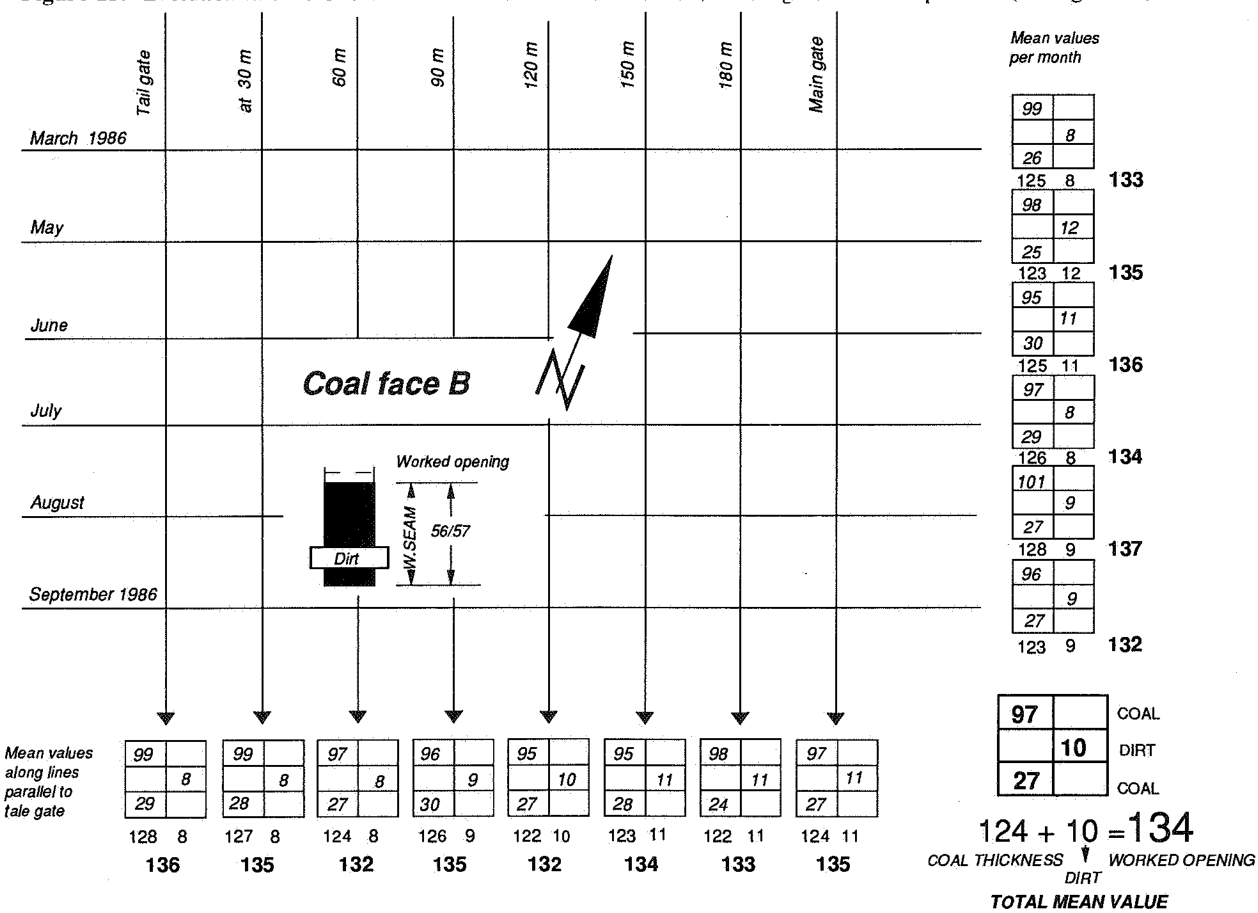


Figure 24. Evolution in time of the mean thickness of coal seam 56/57 along coal face in panel B (see figure 19).

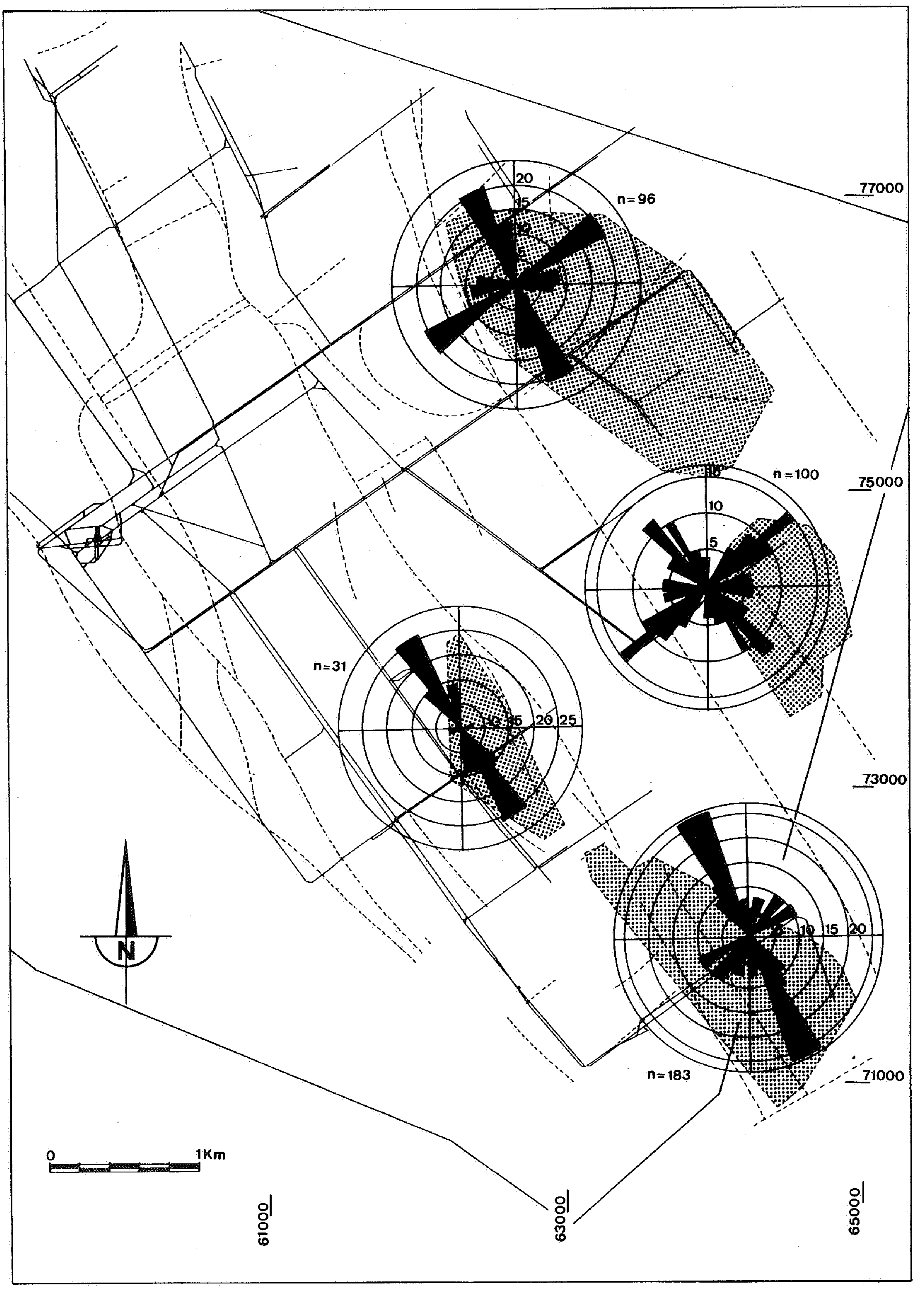


Figure 25. Frequency rose diagrams of the strikes of small faults affecting coal sema 56/57 in the eastern district of the Beringen colliery (after Dreesen & Liégeois, 1987).

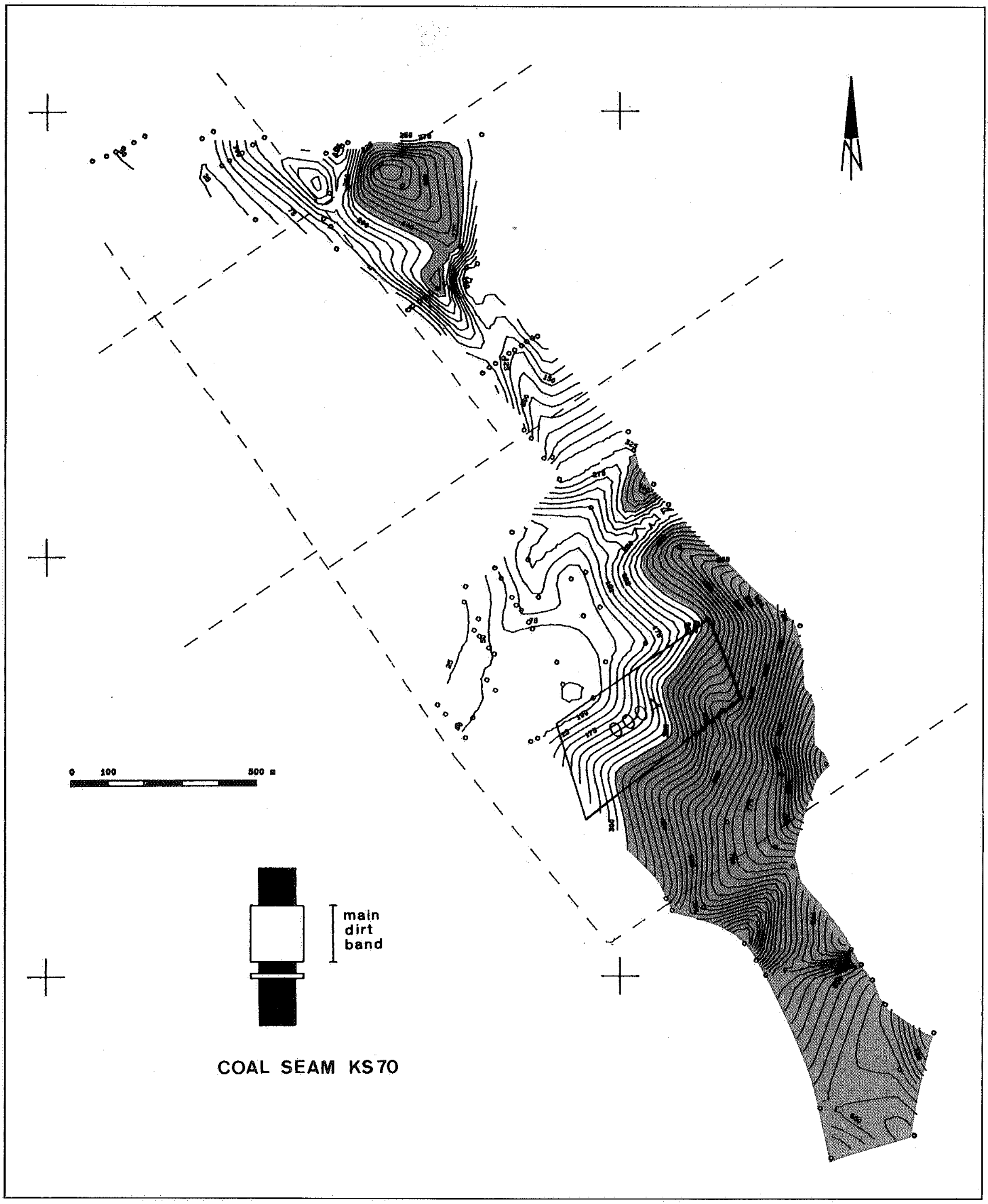


Figure 26. Computer-generated contour map of the main dirt thickenss within coal seam 71 (Beringen colliery).

3.2. Lithological and lithostratigraphical analysis

Type 2 and Type 3 files contain data on the thickness and stratigraphic position of coal seams (KS numbering system) as well as on the thickness and the lithological nature of the associated "sterile" rocks. However, the latter are grouped into 2 to 3 different rock types for Type 2 files (fig. 16 and 17), whereas a broader spectrum of lithological classes is available in Type 3 files (fig. 18). The lithological composition of the associated detrital rocks in Type 3 files is essentially based on a reinterpretation of the original on-site descriptionsof surface and underground drilling cores. The "pelites" include all of the finer-grained siliciclastic rocks, such as: mudstones, siltstones and all transitional lithologies.

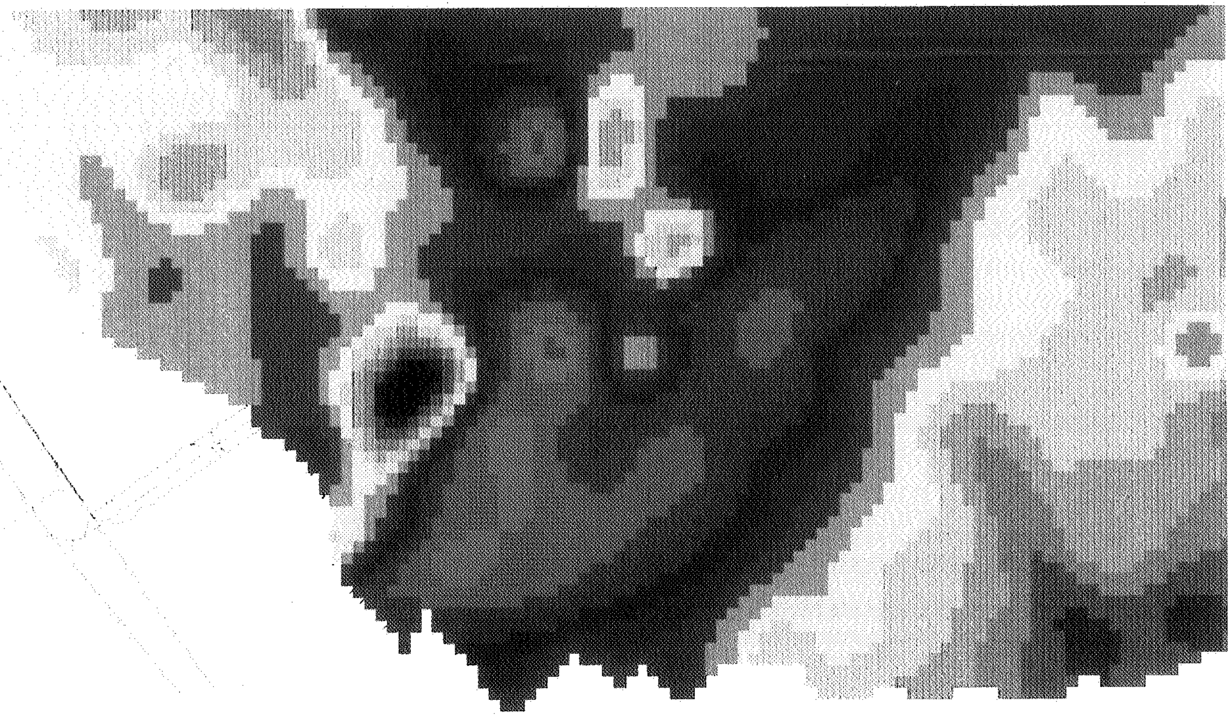


Figure 27. Colourd screen copy an isopach map (so-called "aplats couleurs") : thickness evolution of a complex seam (66-67-68) affected by a wash-out complex (Beringen complex).

Before input of lithological data a "translation" of the local, vernacular lithological terms into more standardized terms is often necessary. It is striking for instance that the terms "silt" or "siltstone" have never been used in the lithological descriptions of the Campine colliery archives. Instead, confusing lithological terms such as: slightly to strongly micaceous, sandy, psammitic, straticulated, zoned shales, ...; weakly to medium "soft" shales, ...; shales with "sandy clouds",..., are currently used for describing the fine-grained siliciclastic rocks.

From a practical colliery management's point of view a detailed lithological terminology is not required. However mudstones, siltstones and sandstones are important and easily identifiable rock types. Differentiation between for example mudstones, silty mudstones, compact siltstones, sand--streaked siltstones and so forth, is only relevant for sedimentological analysis and environmental recon structions, although some simplification is also recommended (see later) because of the common gradual transitions. Alternating lithologies are worth mentioning, as also are the presence of gravelous lags within the sandstones (see later).

Processing of Type 2 file data produces relatively simple columnar sections (logs), cross sections and contour maps. The graphical correlation of coal seams is automatic, provided that time-equivalent seams, coal leaves and dirt interbeds are numbered identically. On the other hand, correlation of sandstone beds is interactive and depends on the experience of the colliery geologist (e.g. wedging out of lenticular sandstone beds).

Contour maps of coal seams and intervening lithologies may be superimposed in order to determine positive or negative correlations or relationships between them. Furthermore, the variation of lithological ratios (e.g. mudstone / sandstone or sandstone / total rock) within a determined stratigraphical interval, can be processed into "isopercentage"or "isolith" maps. So-called roof and floor quality maps are particular applications of the latter isolithmaps. The critical thickness, or interval, of a roof for which such lithological information is needed, is generally up to 2 to 3 m above the roof. Roof and floor maps represent important tools for the colliery geologist in order to forecast strata behaviour and competence, essential for mine construction and safety planning. However, it was impossible to generate such maps in the Campine col lieries. Indeed, as pointed out previously, detail on the lithological nature of the roof rocks is often lacking from mine surveyors' records and only a limited number of (unevenly spread) underground borehole, or blindshaft, descriptions is available.

3.2.1. Case study : split coal and interseam sandstone thickness prediction

Comparison of a series of three (superimposable) isopach maps, covering the area of two neighbour

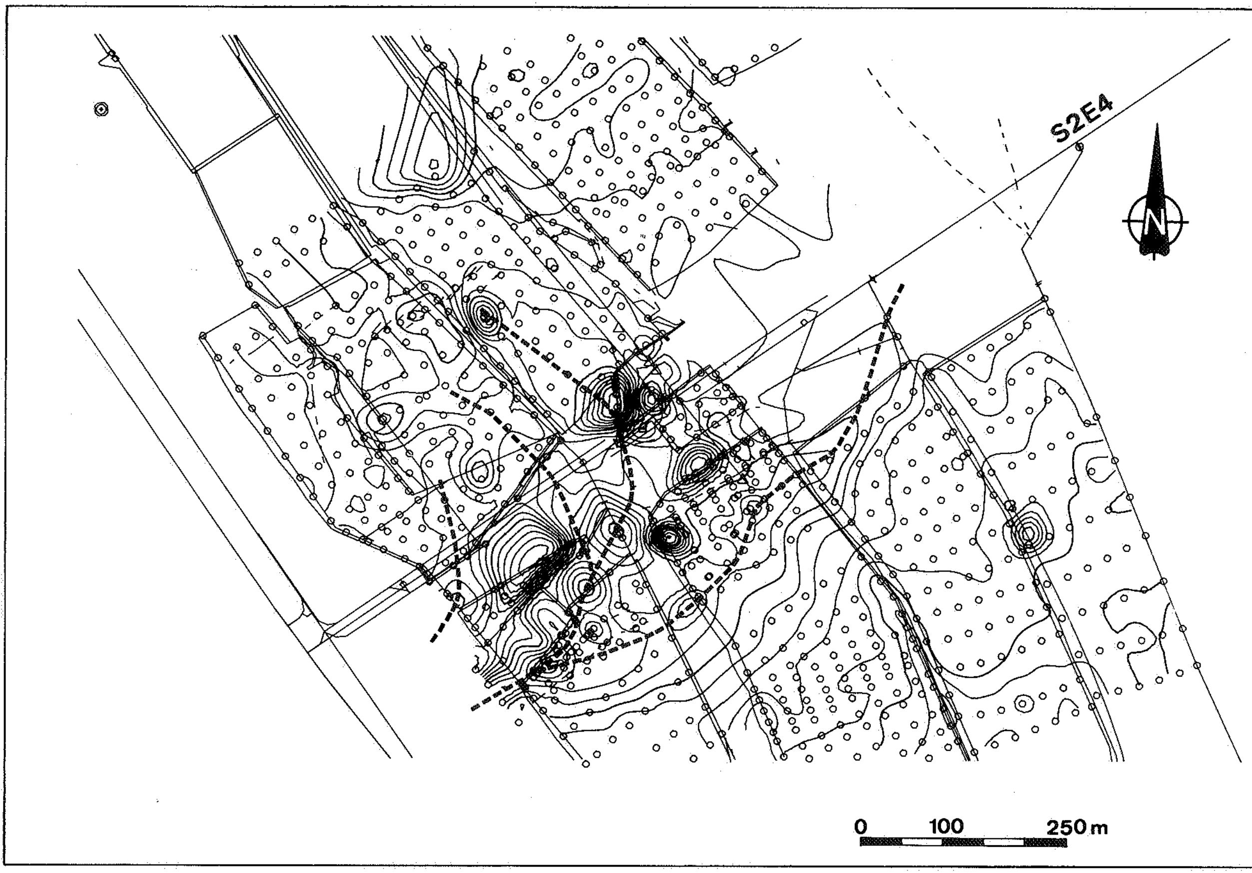


Figure 28. Computer-generated isopach map corresponding to figure 27. Dashed lines correspond to supposed fluvial channel axis (want areas - minimum thickness of coal seam).

ing collieries (fig. 32), which correspond to the spatial evolution of the total thicknesses of an upper coal leaf (no71 A), a lower coal leaf (no71 B) and that of intervening sandstone beds, point to an inverse relationship between the coal leaf and the sandstone maxima: areas with minimum coal thickness are to be expected above and below areas with a maximum sandstone content. This phenomenon has also been observed for other split coal seams with intervening sandstone beds.

Furthermore, source data from Type 2 files can be processed into lithostratigraphical fence diagrams (fig. 17). These diagrams give a perspective view of the evolution in time and in space of a series of coal seams and interseam strata. According to the available software facilities the orientation of the fence diagram will be either random (free choice of the panel orientation) or preselected (grid with panels at 90°). The graphic correlation of time-equivalent coal seams (including that of individual leaves and dirt bands) is automatic; the correlation of interseam strata, particularly sandstone bodies, is interactive. The lithostratigraphic correlation of the latter depends on their origin (depositional environment). Therefore before any correlation can be attempted, the sandstone units should be genetically identified as either ribbon-like lenticular distributary channel sandstone bodies, or lobe-like crevasse splay sandstone sheets. This identification is only possible after a sedimentological analysis of the sequences (see later).

3.2.2. Case study : location of potential wash-out zone

One of the applications of fence diagrams in coal geology is the determination of the geometry of the fluvial system. After sedimentological analysis of the lithological sequences on logs and the genetic identification of the interseam sandstone bodies, correlation of time-equivalent and identical sandstone units will reveal the probable orientation of the paleochannels. The areas where these channel sandstones are close to the roof of a coal seam thus represent potential wash-out zones for that particular seam. Moreover, recognition of the generalpattern of the paleochannel system within a particular stratigraphic interval will improve recognition of the location of future panels for that seam. In this study several fence diagrams which correspond to the different succeeding stratigraphical intervals

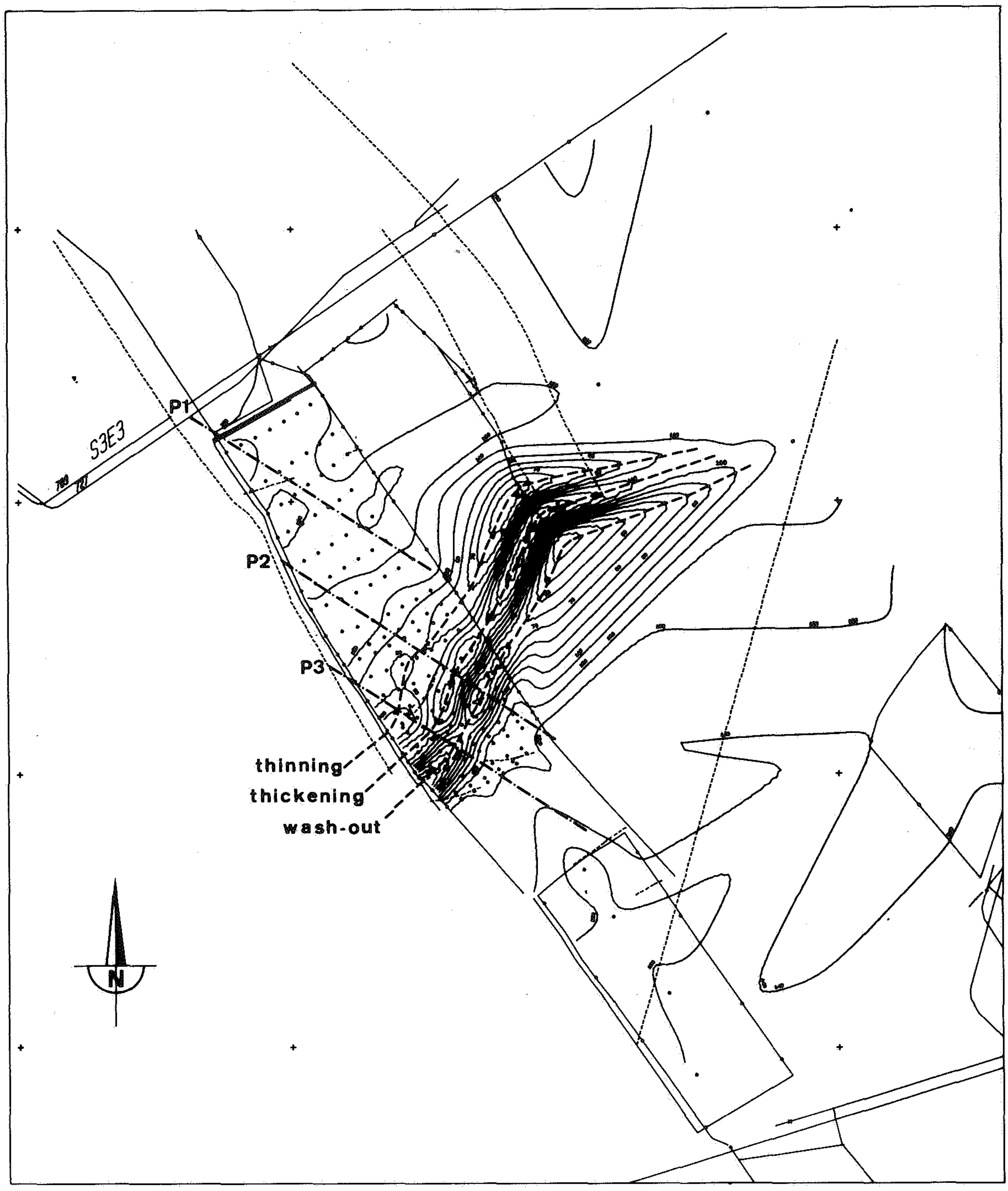


Figure 29. Computer-generated isopach map of coal seam 66-67-68 affected by a wash-out, in a new panel located about 1 km to the east of the former studied area (figures 27, 28). Lines P1 to P3 correspond to cross-sections of figure 30.

have been constructed : for each of these fence diagrams, channel sandstone bodies have been identified and possible channel axes have been inferred (fig. 33). After digitizing all the channel axes it became obvious that the paleochannel system had remained unchanged throughout the studied stratigraphic interval (coal seam no KS 72 through coal seam no KS 65): NNE-SSW (fig. 34). Conversely, the structural framework of the investigated area is characterized by NNW-SSE-directed major faults, which are perpendicular to the general orientation of the paleochannels (fig. 19).

The strategy of the colliery management for locating new panels is essentially based on the structural framework: all new panels are located parallel to and in between the major faults.

Although the staff was unaware of the orientation of the fluvial system, their strategy seemed to be

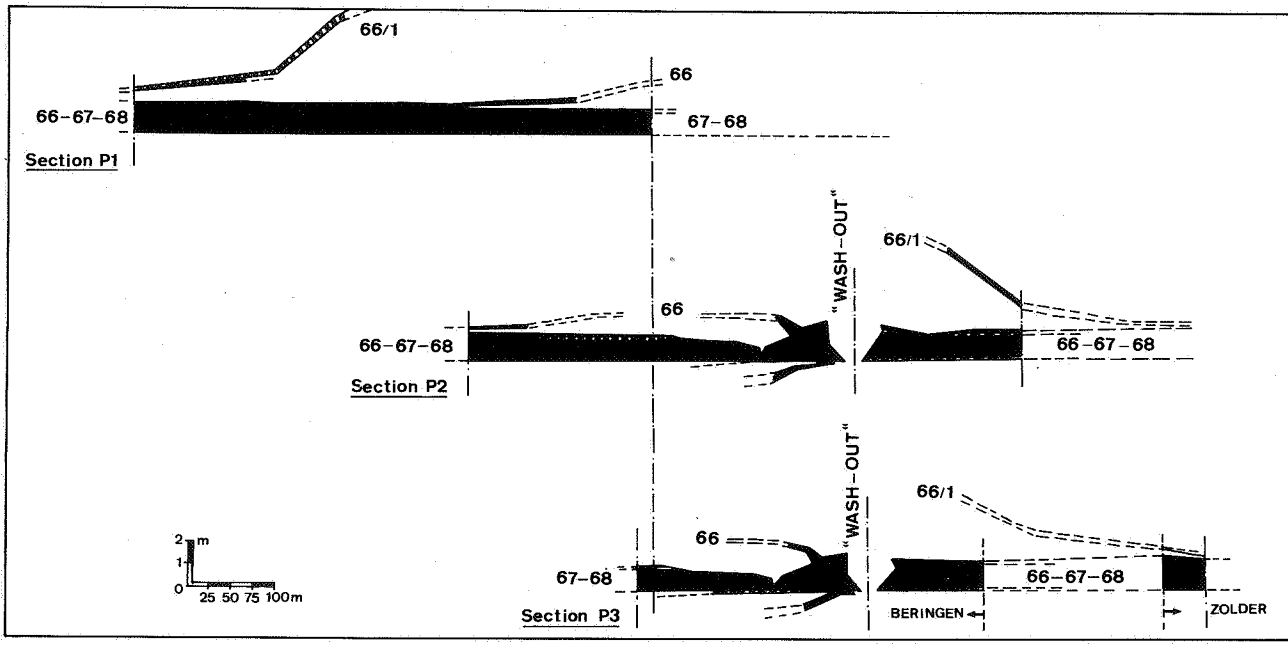


Figure 30. Successive cross-sections of complex coal seam 66-67-68 affected by a wash-out (see figure 29).

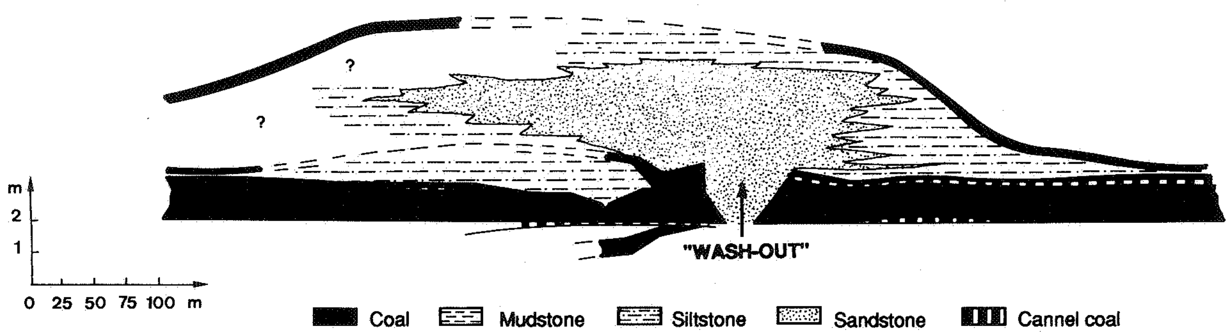


Figure 31. Ideal geological model of the wash-out affecting coal seam 66-67-68 in the SE-district of Beringen colliery (based on sections P1 to P3 of figure 30).

correct, since the panels are located perpendicular to the paleochannel system. Thus when a wash-out zone was to be expected, the longwall mining operations would have to face a drop of coal production (channel sandstone) during 250 to 350 m at most (average width of a distributary channel in the Westphalian coal- bearing strata of the Campine Basin). Moreover, the actual orientation of the panels implies a risk in encountering coal seam splits related to crevasse splay sandstones: indeed the latter are generally oriented perpendicular, or oblique, to the main channel axis and they are more extensive than the distributary channels (up to several square km). This fact in turn, would imply an increase of the frequency of small faults parallel to the coal face: the latter are related to differential compaction of the silty or sandy dirt bands (distal to proximal crevasse splay facies) .

3.3. Sedimentological analysis and environmental reconstructions

Processing of Type 3 files (fig. 18) produces sedimentological columnar sections : logs withdifferent widths related to the lithological nature of the unit. This kind of columnar sections enables a quick visual evaluation of the lithological nature of the interseam sequences and the relative amounts of sandstone, mudstone, siltstone or alternating lithologies to be determined. The width of the column (fig. 35) corresponds to the relative "alterability" of the sedimentary rock (in descending order: coal, carbonaceous shale, mudstone, siltstone, sandstone and conglomerate). However its greatest advantage is in the fact that it allows sequential analysis of the siliciclastic interseam strata and a reconstruction of the depositional environments. The resulting data in turn provide "rules" for the lithostratigraphical correlation of sandstone bodies as well as information on the potential extent of some particular

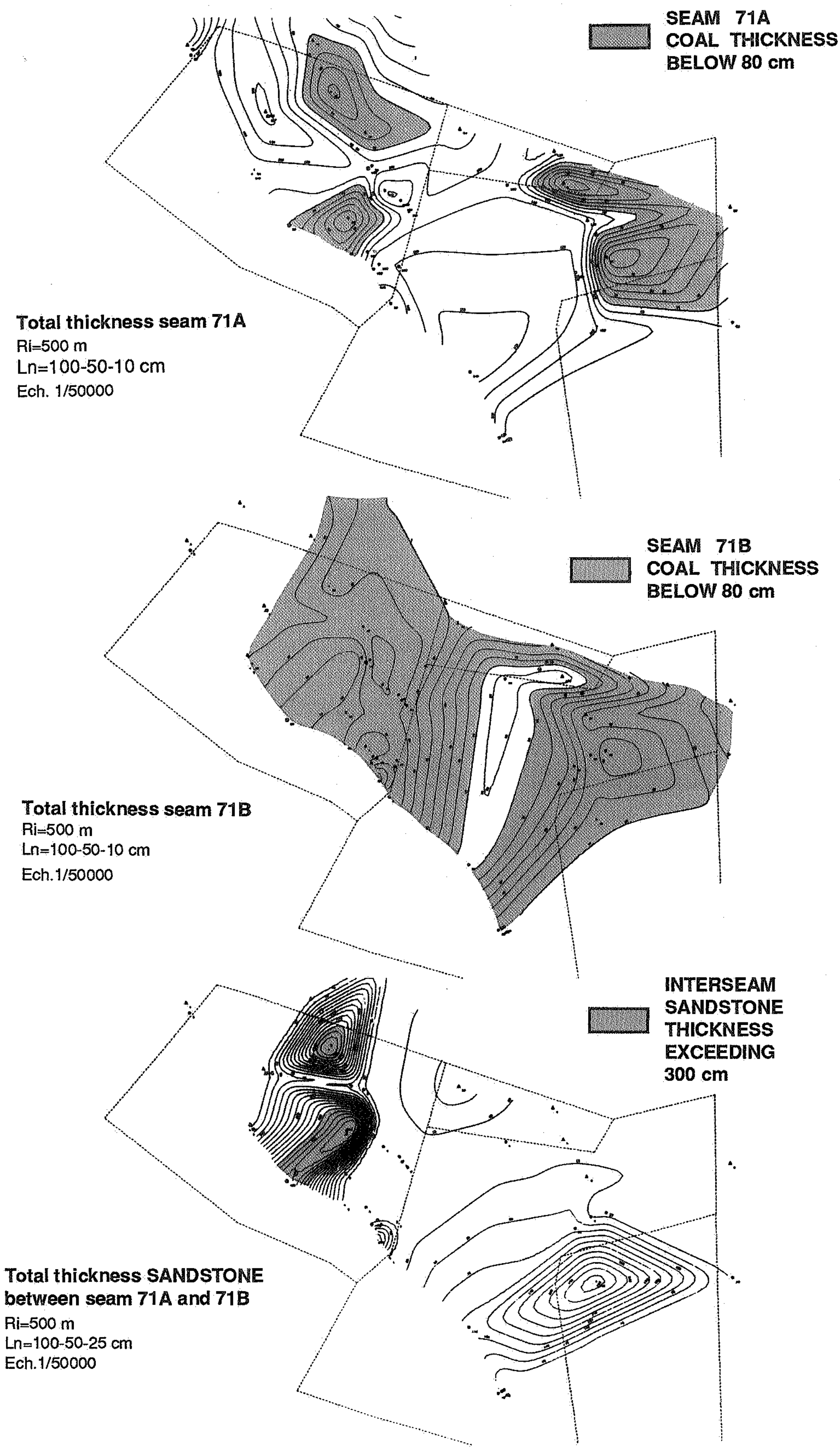


Figure 32. Series of computer-generated isopach maps illustrating the influence of an interseam sandstone body on the thickness evolution of the overlying and underlying coal seams Beringen and Zolder collieries.

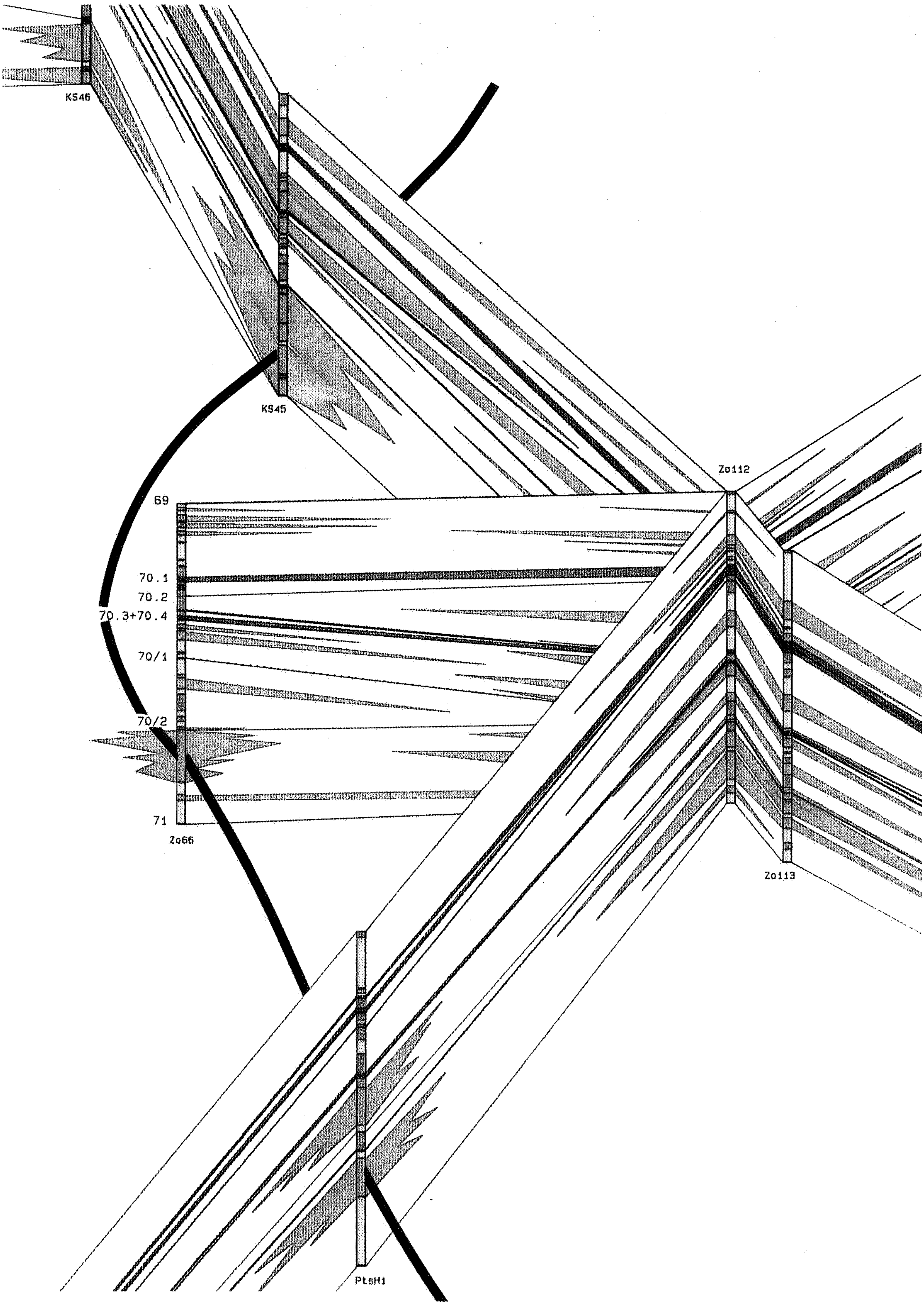


Figure 33. Detail of a computer-generated lithostratigraphic fence or panel diagram. Selected interval : seam 69 through seam 71 (Zolder colliery). Heavy black line corresponds to a probable fluvial distributary channel. Legend of colours (orange : sandstone ; yellow : siltstone ; green : mudstone ; black : coal).

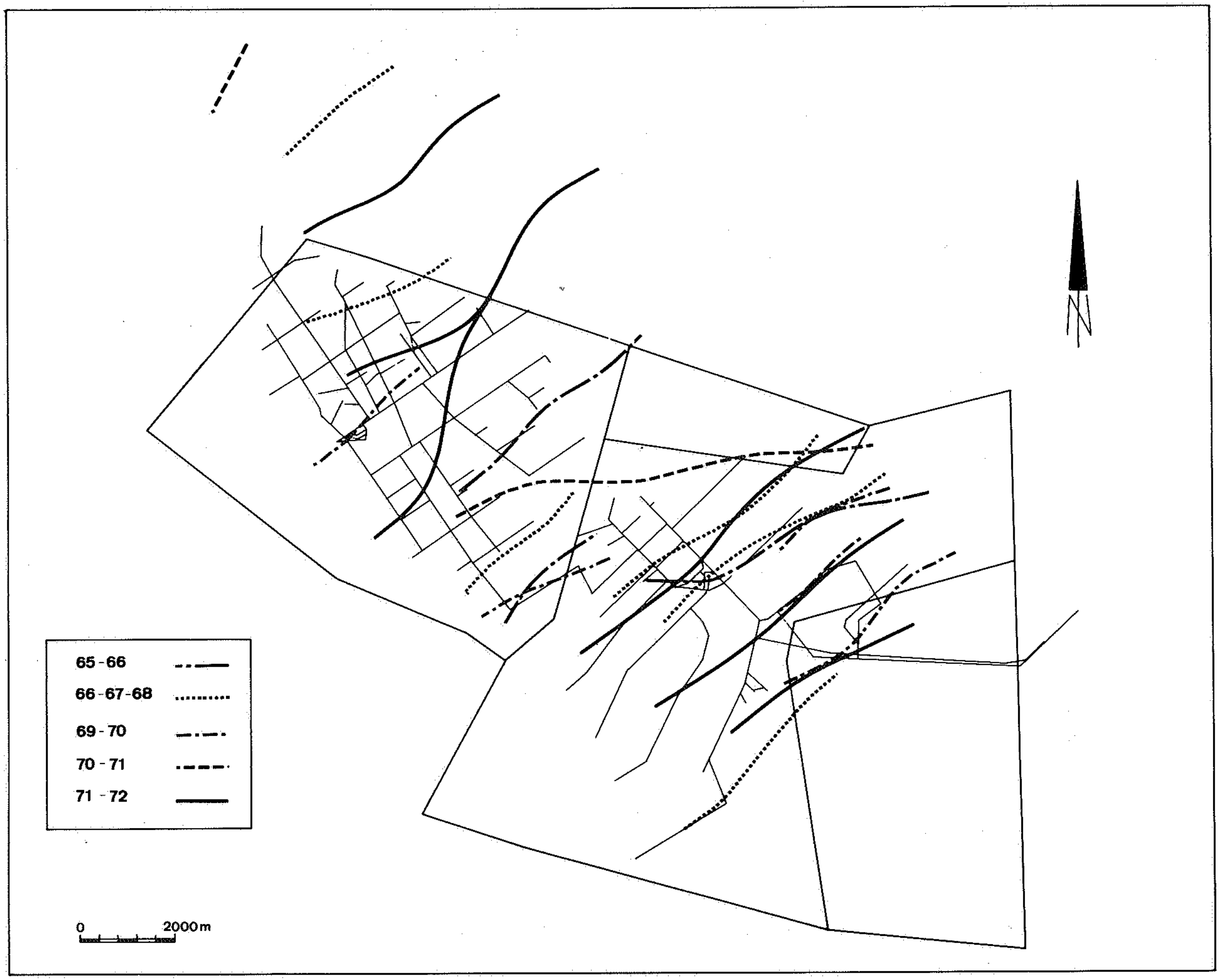


Figure 34. Location and orientation of palaeofluvial channels at different stratigraphical intervals, based on the interpretation of successive fence diagrams (Beringen - Zolder - Houthalen collieries).

lithological units. As a rule, the colliery geologist starts with the identification of coarsening upward (CU), or fining upward (FU) sequences, on the computer-generated logs. This information coupled-with the thickness of the individual sequences, will result in an environmental interpretation of the sandstone bodies (e.g. fig. 36). Only then can reliable lithostratigraphic correlations be achieved and fence diagrams constructed. However, some restrictions exist in the detailed environmental interpretation of the sequences, due to the general lack of information on sedimentary structures and on the nature of the lithological contacts in the data retrieved from the archives. The fence diagrams in turn, permit the determination of the location of distributary channels (potential wash-outs) and the extension of overbank areas with crevasse splay sandstones. The following "rules" have been applied to the data, rules which are mainly based on data from the literature and on field experience (R.-FLORES, 1988 and 1989, pers. comm) :

(I) a sandstone-dominated FU-sequence often displaying an abrupt, or an erosional base, and with a thickness of generally 10 m or more, corresponds to a distributary channel. These sandstone complexes have a width of a few hundred meters and a length of several km. Thin siltstone-mudstone "drapes" within the sandstone body correspond to lateral accretion phenomena related to the meandering of the channel, whereas recurring thin gravely beds indicate a multistorey channel complex. A thick mudstone on top of the sequence followed by a paleosol, most probably represents a "mud plug" related to channel abandonment. The presence of these phenomena have to be taken into consideration when forecasting potential wash-out zones in a given production zone.

(II) a sandstone-dominated FU-sequence with a maximum thickness of about 5 m corresponds to a crevasse channel. These crevasse

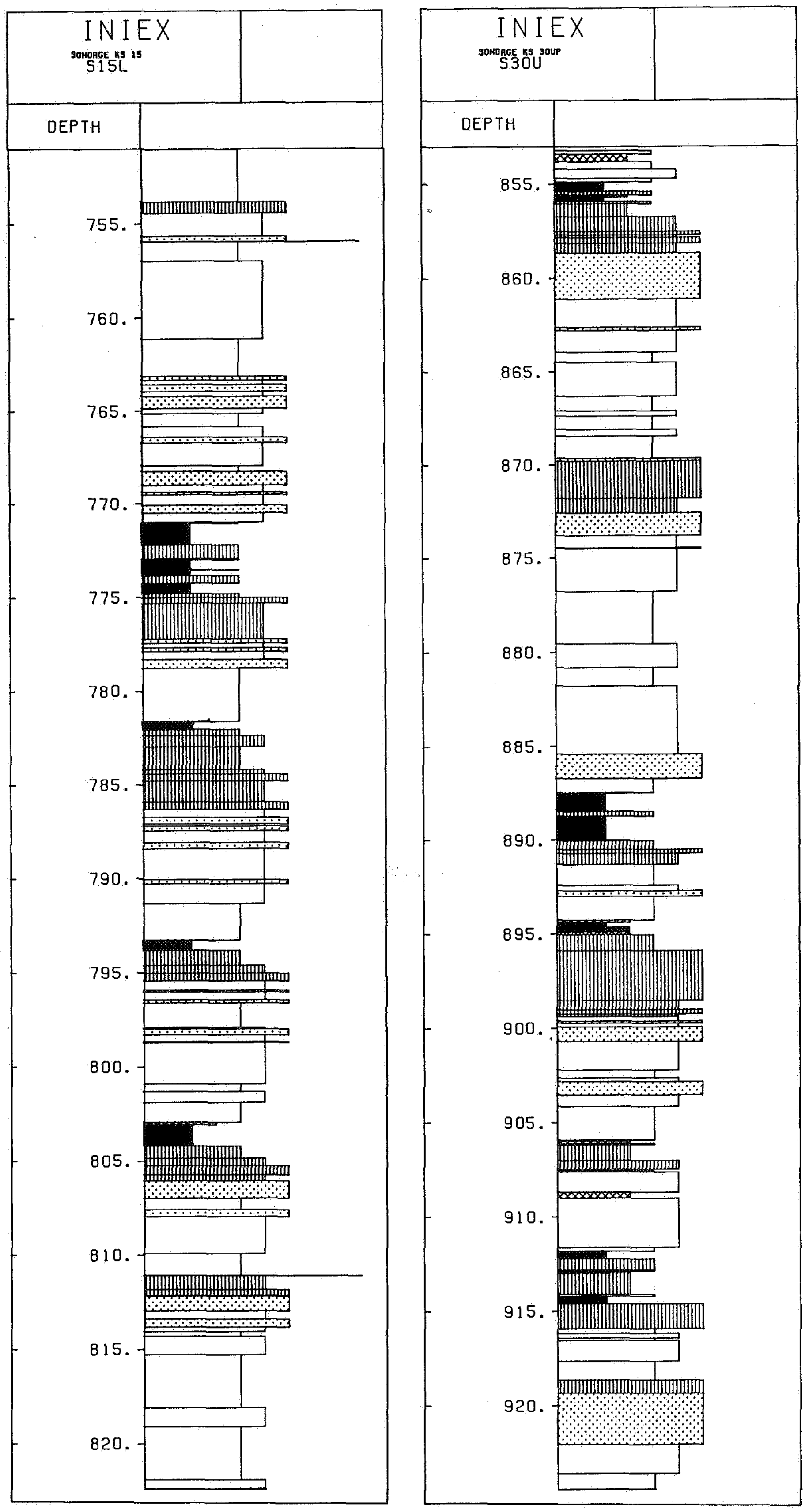


Figure 35. Detail of computer-generated "sedimentological" columnar sections of logs of cored exploration boreholes. Differences in width correspond to different lithologies ; vertical hatching represents rooting.

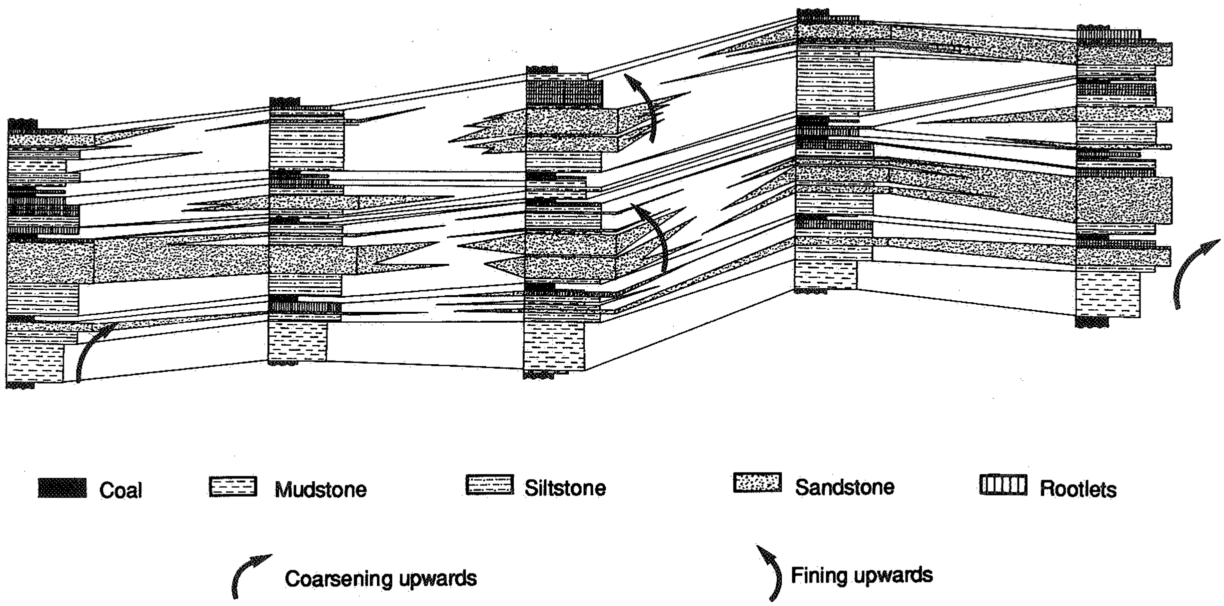


Figure 36. Example of lithostratigraphical correlation between selected cored borehole columnar sections. Correlation of sandstone bodies is based on facies analysis (coarsening and fining upwards sequences).

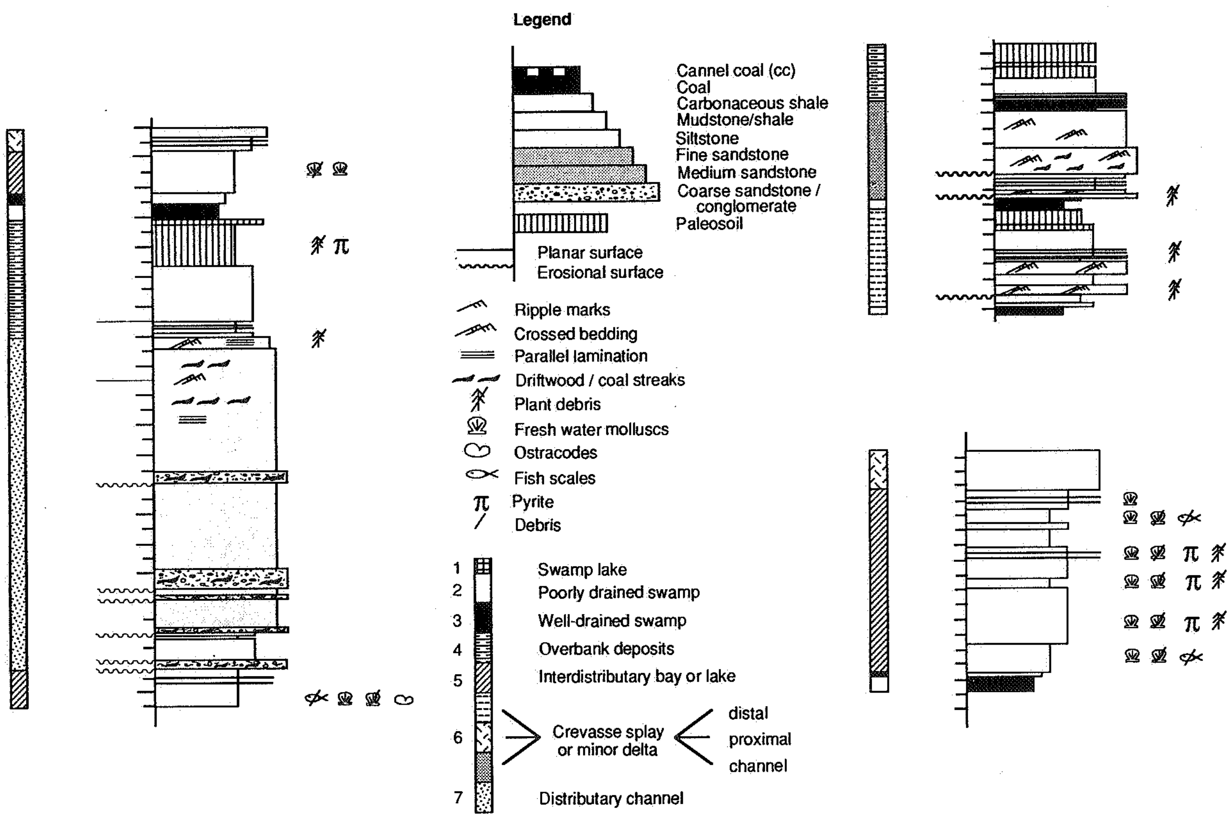


Figure 37. Selected columnar sections of exploration boreholes and interpretation of depositional environments, based on sedimentological and paleoecological data (retrieved from hand written in situ borehole descriptions).

3channels are generally perpendicular to the distributary channel levees. Their width is restricted to some 200 metres and their length does not exceed a few hundred metres.

(III) a CU sequence (mudstone-siltstone-sandstone) with a thickness less than 5 m generally represents a crevasse splay deposit. These splay deposits produce irregular, coalescent, lobelike sandstone bodies downstream of the crevasse channels, with a

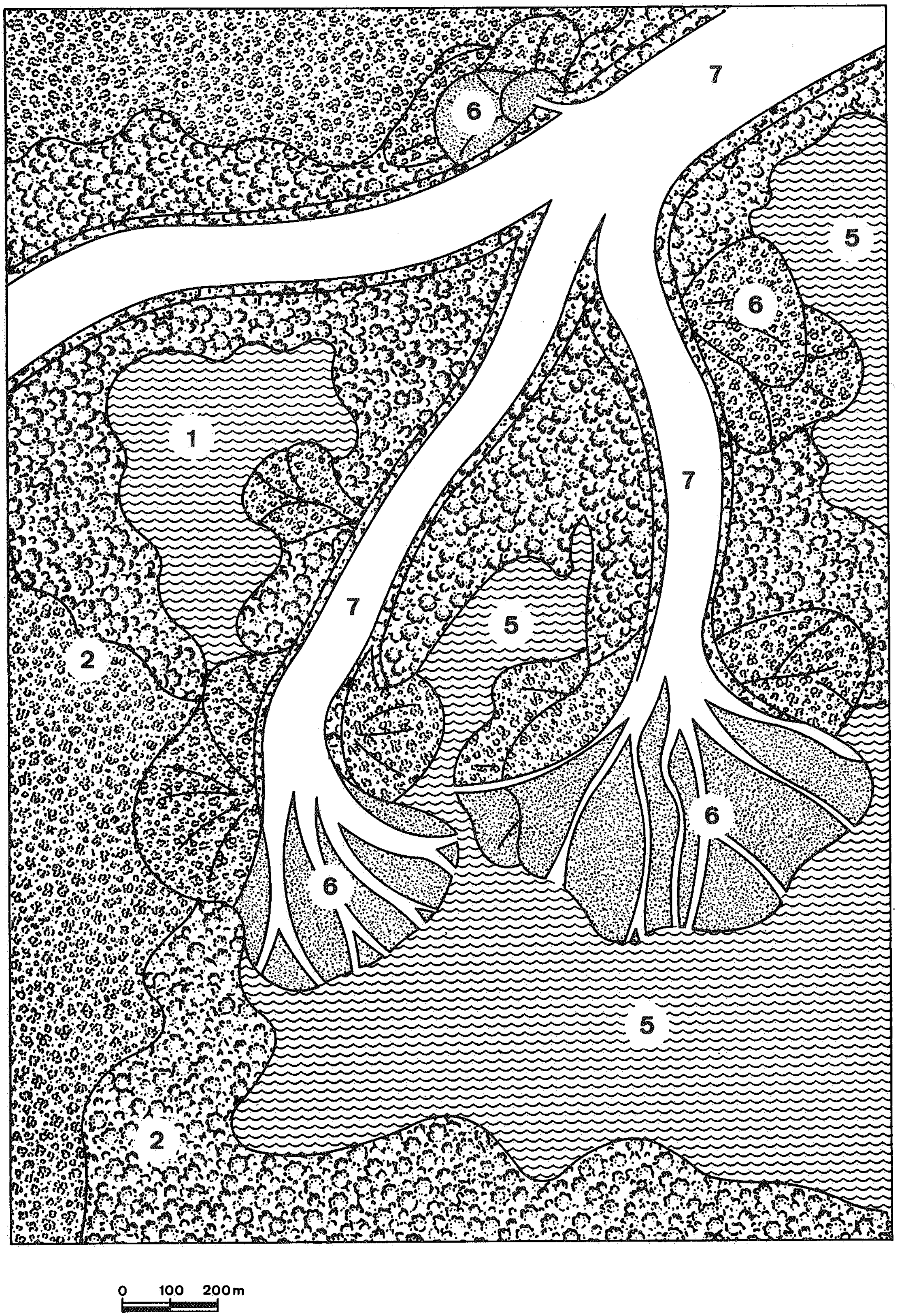


Figure 38. Idealized paleogeographical reconstruction of the depositional environments of the Westphalian A to B coal-bearing strata, from the western part of the Campine coalfied (after Dreesen *et al.*, 1991).

highly variable extension (up to several km). According to their relative thickness and to the coarseness of the sediment, proximal and distal crevasse splay deposits may be recognized. Distal crevasse splay deposits are characterized by one or more thin (less than 3 m) FU sequences. They can attain a few km in extent.

4. DEPOSITIONAL ENVIRONMENTS AND RELATED GEOLOGICAL HAZARDS

4.1. Early Westphalian depositional environments

In order to assess the depositional environments which occur most commonly in the studied stratigraphical interval, the cores of surface exploration boreholes (KS no15, 30, 42, 27, 29 and 46) have been studied in great detail. Attention has been focussed more especially on the interval covering the Eisden through Wasserfall marine bands, across the Westphalian A-B boundary (Quaregnon Marine Band). This interval incorporates economically important coal seams. The overall paleogeographical picture is that of a fluvial- dominated delta plain, with a gradual shift from a lower to an upper delta plain setting. This shift apparently took place around the Westphalian A-B boundary. It is reflected by a greater proportion of siltstones and sandstones in Westphalian B strata, as compared to the mudstone-dominated Westphalian A strata (Dreesen, Lorenzi & Bossiroy, 1991).These environments closely resemble those described from Early Westphalian strata (Lower to Middle Coal Measures) in Britain (Elliott, 1974, 1975 ; Fielding, 1984 ; Guion & Fielding, 1989), from time-equivalent coal-bearing strata in the subcrop of East Gelderland, Netherlands (Pagnier *et al.,* 1988, internal report, Dutch Geological Survey), from Westphalian A2 strata in the Aachen-Erkelenz Coal District (Müller & Steingrobe, 1991) and from the corresponding Bochumer and Essener Schichten (Westphalian A2 and B1) in the Ruhr area, NW--Germany (Strehlau, 1990).Based on a combination of lithological, sedimentological and paleoecological criteria, several subenvironments, or micro-environments have been recognized in the studied stratigraphical interval in the subcrop of the Campine area (fig. 37 and 38).

4.1.1. Fluvial distributary channels

Fluvial channels are characterized by relative coarse grain sized sediments: fine to medium- grained sandstones (petrographically: lithic greywackes) with minor siltstones and/or mudstone interbeds ("drapes", or lateral accretion surfaces), as well as some thin gravely beds (microconglomerates) mostly at their base. This facies characteristically displays an overall upward fining trend resulting from lateral migration or from channel abandonment. Single and multi-storey channel fills can be recognized. Common sedimentary structures include, from base to top, scoured surfaces, through cross-bedding, ripple laminations and parallel plane laminations. The basal channel-floor lags commonly feature shale and ironstone clasts, as well as abundant carbonized plant debris, ranging from bits of twigs to large fossil logs (e.g. *Calamites*).

Excess discharge was diverted during flood periods from the distributary channels into the flood plain, or into the interdistributary bays. Morphological features which result from these processes include levees, various types of crevasse sands and crevasse channel or minor deltas (lake margin mouth bars).

4.1.2. Interdistributary areas of fluvial-dominated delta plain

This enclosed still, shallow or even stagnant water and episodically aerially exposed environment, groups several distinct subenvironments such as natural levee, flood plain, crevasse splay, flood basin (backswamp), and interdistributary bay, or lake and minor delta (lake margin). "Overbank deposits" generally include the coarser sediments of the levees, which are confined to the channel margins, as well as the more distal fine-grained flood basin deposits, which commonly enclose coarser crevasse splay deposits. The *levees* are composed of centimetric to decimetric repeated alternations between thin erosive-based fine-grained sandstones and siltstone-mudstone intervals. Sometimes the sand-siltstones may increase in thickness due to lateral encroachment of the levees associated with channel migration. The sandstone beds display distinctive sedimentary structures, such as small ripple cross- bedding, climbing ripple lamination and plane-parallel laminations. The more pelitic sediments generally lack structures, but they frequently include rootlets which indicate near emergence. Tan paleosoils with kaolinite ooids occur locally. Fine plant debris is common as well as large, upright fossilized tree trunks. The levee facies fines away from the channels. The *flood plain* s.s. is commonly characterized by uniform, apparently structureless, but finely laminated fine-grained sediments. The sediments (mudstones, silty mudstones and siltstones) result from deposition of suspended sediment dropping out of the inundating flood waters. Interbedded with these flood- plain deposits may be sheets of fine sand, which prograde away from the channels as crevasse splays, or natural levees. The original lamination of the flood-plain sediments may be obliterated by the effects of burrowing organisms and by the disturbing effects of plant roots. In this flood plain setting mud cracks and rain-drop impact craters occur sometimes on top of well-drained, subaerially exposed flats. Closed depressions within the flood plain, which are under water for long periods, become backswamps ("mires") in which peat may accumulate and eventually they may grade into coal.

4.1.3. Crevasse splays

Crevasse splays originate from a break or crevasse, cut in the levee crest during a major inundation. Incursions of sediment-laden waters deposit sediments over a limited area on the lower flanks of the levees, the flood plain and the flood basin (backswamps). Crevasse splay deposits are narrow to broad tongues of sediment somewhat coarser grained than the associated levee deposits, and tapering in one direction: the tongues or lobes become narrower and rare towards the flood plain. Small-scale cross-bedding, climbing-ripple lamination and some horizontal bedding are the main sedimentary structures. Drifted plant material may be concentrated into the crevasse splay deposits. The following subenvironments can be recognized

(I) crevasse channel, mainly composed of fine to medium grained sandstones, sometimes associated with siltstones and mudstones. The thickness of the sandstones never exceeds 3-4 m. Typically FU-sequences are often multiple. Sedimentary structures are analogous to those of the distributary channels (trough cross-bedding; ripple cross-bedding).

(II) proximal to medial crevasse splays with alternating, decimetric to metric beds of mudstone, siltstone and fine sandstone. These are characteristic simple, or multiple, CU - sequences. Morphological features include coalescing lobelike bodies a few metres thick with variable extension (up to several square km). Sedimentary structures include an erosive base, or sharp contact, ripple cross-bedding and planar bedding.

(III) distal crevasse splays. These alternating mudstones, siltstones, and fine sandstone occur in decimetric beds, showing CU-trends. They have finer grain sizes and less-thick units than the proximal crevasse splay facies. Their thickness does not exceed 3 m.

4.1.4. Interdistributary lakes and bays

These deposits consist of bioturbated, dark-grey to black (medium to poorly oxygenated) mudstones, which may exceptionally be laminated by silt, or sand, laminae. These mudstones are either fossiliferous or non fossiliferous, with low- diversity non-marine faunas including ostracodes (*Carbonita*), pelecypods (*Carbonicola*), arthropods, fish debris. The over-all absence of current ripples and the presence of characteristic ichnofossils (e.g. *Pelecypodichnus*) are indicative of quiet, non-turbulent conditions. Plant fossils are common and are generally well-preserved. Nodular and bedded siderite (ironstone) is common. Isolated siltstone or fine sandstone beds within the mudstone sequences point to episodic crevassing (distalmost facies): their frequency is related to the proximity to shore, or lake margin (minor deltas or mouth bars). Black mudstones, rich in pyrite and organic matter, correspond to anoxic lake floor sediments. Exceptionally, these mudstones contain brackish, or even marine fossils including pelecypods, brachiopods *(Lingula)*, ostracodes *(Geisina)*, conchostraceans *(Estheria)*, spirorbids and foraminifera. These marine-influenced mudstones are relatively thin (a few centimeters or tens of centimeters only) and commonly occur on top of coal seams. They are interpreted as the result of marine transgressions causing drowning of the swamp.

They can be correlated with the so-called "marine bands", which represent first-order marker beds for stratigraphic correlation. These marine beds point to remote connections with open marine settings. The thickness of these lake, or bay mudstones reaches several tens of meters whereas their spatial distribution generally exceeds several square kms.

4.1.5. Lake margin

Minor deltas develop at the margins of lakes and interdistributary bays due to prograding crevasse splay lobes and minor mouth bars. The facies characteristically exhibits coarsening-upwards alternations of laminated mudstones, and silt- and sandstones. Flaser bedding and convoluted bedding are common. Rooting is generally absent.

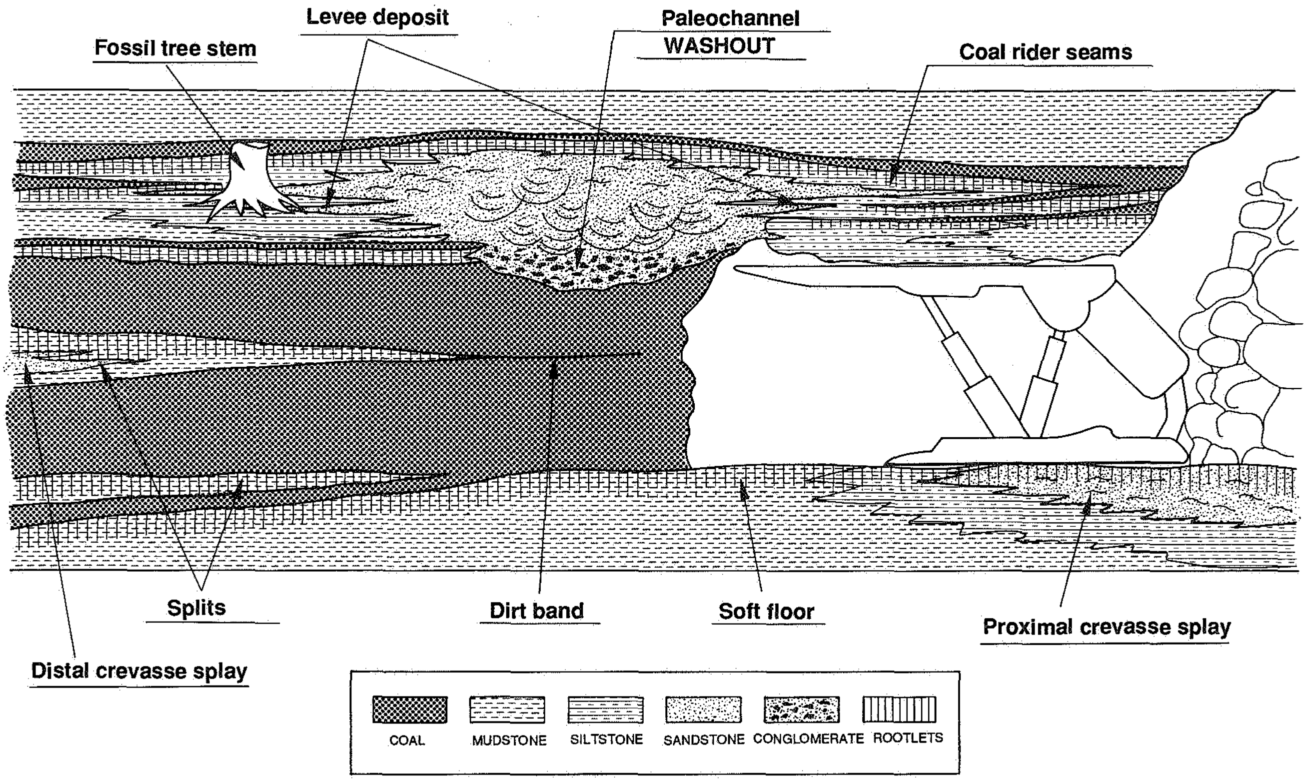


Figure 39. Cartoon showing geological hazards of sedimentary origin, affecting longwall coal mining in the Campine collieries (not to scale ; after Dreesen, 1990).

4.1.6. Swamps

These environments include paleosols (*Stigmaria*--mudstones, or rootlet beds) on well-drained temporarily subaerially exposed flats (gley, or pseudogley, and alluvial paleosoils), or laterally extensive peat blankets of open mires with a higher groundwater table (coal-streaked mudstones, coals) on different substrates in the backswamp areas of the flood plain. Open mires with herbaceous vegetation developed in the centre of extensive nutrient-poor swamps, whereas forest mires developed at the nutrient-rich borders of the floodplain, in the proximity of distributary channels. Carbonaceous mudstones ("shaly coal", or "carbshales") represent the most marginal part of the former swamp (Strehlau, 1990). Individual coal seams rarely exceed 180 cm in the Campine area and frequently enclose dirt bands. The latter result from flooding of the swamp (mudstones), or from prograding crevasse splays (siltstones and sandstones). The latter mechanism commonly leads to splitting of the coal seam. Cannel coal represents a particular deposit which forms from organic sediments deposited at the bottom of moor lakes (sapropelic-coal facies). It commonly occurs on top of coals. Gradual transitions to mudstone are common and form the so--called pseudo-cannel coals.

4.2. Geological hazards of sedimentary origin

Important geological hazards in coal mining, such as wash-outs and splits, can be directly related to fluvial environments. Other, less spectacular but equally important hazards, such as bad roof and floor conditions, tend to be related to particular facies within fluvial-dominated delta plain settings (fig. 39).

4.2.1. Roof instability

The competence, or degree of coherence of the roof strata, affects mine productivity. The thickness of roof strata, which affects conditions, varies depend-knowledge of the mineralogy of the floor rock (e.g. percentage of expansive clays) can assist in determining the ripping horizons and the effect that water can have on the floor rock.ing on coal thickness, mining of other seams, overburden depth and mining methods. Strata within 2 to 3 meters of the worked seam are usually critical. In order to understand and predict variation in the roof stability, reconstruction of the depositional environments is very useful (Truman & Horne, 1982 ; Vaninetti *et al,* 1982). The nature of the sediments deposited after peat development is a major factor controlling roof stability. Consequently a depositional model, identifying rock variability can be used as a predictive tool to determine potential minability and roof-support systems. Different types of roof maps, sequence maps and slice maps, can be generated to illustrate roof conditions above coal seams (Truman & Horne, 1982). Sequence maps define vertical and lateral variability of the entire sequence of rock types that occur up to about 3m above the coal. These rocks are examined and categorized into sequences that were deposited in different environmental settings and have varying stabilities as roof material (e.g. channel sandstone; coarsening-upward sequence; sandstone-mudstone interbedded sequence). Slice maps display lateral variability of rock types present at specific horizons above a coal seam (e.g. cross-bedded grey sandstone, dark-grey mudstone with sandstone streaks, or black mudstone).

- fluvial channel sandstones generally offer competent support for roof in an underground coal mine. However, some problems can occur. The sandstones are potential aquifers that can cause water inflow. Moreover, this water can contribute to the weathering of the finer-grained rock types, thus decreasing their competence. The basal portions of channel sandstones often contain coalified tree logs and pebble lags which represent zones of weakness. If the channel sandstone has not scoured into the top of the coal, intervening mudstones may show slickensides caused by differential compaction. Rolls are small-scale folds in the coal seam and enclosing strata, generally associated with paleochannel sandstones in the roof stratum; they result sometimes in decreased productivity.

- channel margin interbeds or levee deposits have been found to be particularly unstable due to differential compaction effects within interbedded siltstone, sandstone and mudstone. Moreover, these deposits are often penetrated by rootlets which disrupt the bedding and reduce rock strength. Occasionally, tree stumps "kettle bottoms" are preserved in place above the coal and may cause severe roof falls. Rider coal seams, or "wild coals", are thin coal seams in the roof strata. They provide planes of weakness for rock separations and are responsible for unstable roof conditions.

- crevasse-splay deposits: severe roof problems may occur when rider coals (thin coal seams in the roof strata) form on splay deposits that are deposited over minable seams (HORNE *et al*, 1978). Splay lobes often provide a platform for coal development. Not only are the coals weak horizons, but the underlying mudstones are usually root- penetrated and weak.

- overbank mudstones and siltstones: these rather massive-looking, homogenous rock types most commonly provide good roof conditions. They are generally competent but exposure of the mudstones to moisten air can contribute to their rapid weathering and swelling.

4.2.2. Bad floor conditions

The behaviour of the floor strata influences the mobility of miners and mining equipment throughout an underground coal mine. Floor conditions are influenced by the competence, the lithology and the moisture level of the strata which immediately underlies the mineable coal seam. Productivity losses due to floor conditions are usually associated with wet, muddy, or soft floors (Vaninetti *et al*, 1982). Overbank interbedded mudstones-siltstones and channel or crevasse sandstones generally provide optimum floor conditions. Mudstones have a tendency to decompose more readily than sandstones and siltstones, particularly when water is present. In the case of longwall mining, premature failure of the roof may be caused by the sinking of the roof-support equipment in the soft floor. Because the floor generally consists of clays,

4.2.3. Wash-outs

Wash-outs cause problems not only because the coal is thin, or even missing, but also because of roof problems (MESA, 1977). One of the first problems usually encountered when approaching a channel is water dripping from the roof. The roof rock tends to become more fractured when the wash-out zone is approached, and numerous slickensides are in evidence. When a sandstone channel, or wash-out, is approached the coal sometimes becomes abnormally thick and the number of partings, or minor splits, will increase. The roof splits can greatly affect the roof conditions due to differential compaction. The roof tends to be very prone to falls above the sandstone-mudstone contact. The wash-out represents a major problem for longwall units as a wash-out cutting through a panel can force the entire panel to be abandoned.

4.2.4. Seam splits

Crevasse splay deposits often cause splits in coal seams which reduces the coal thickness to below

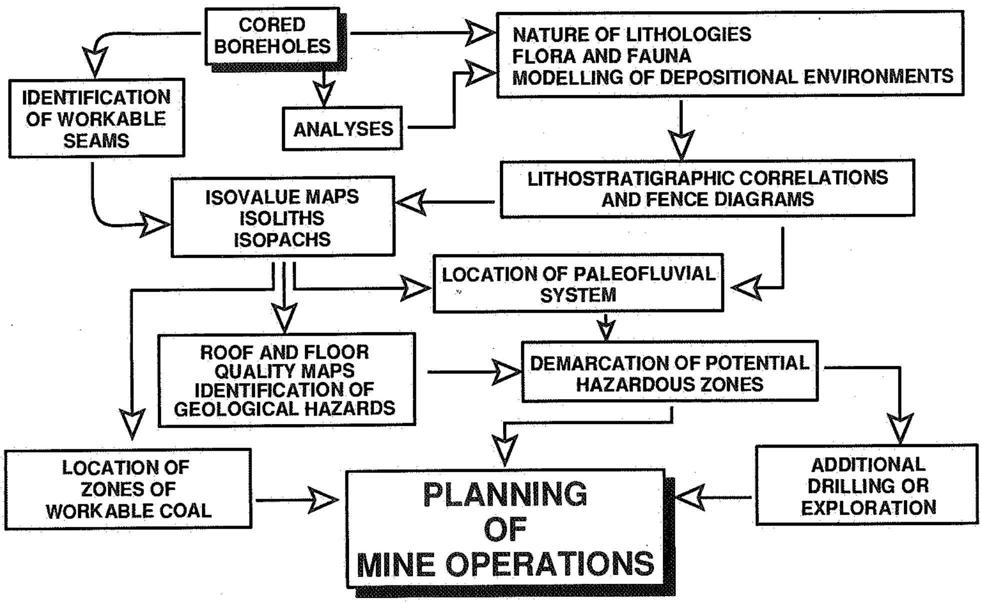


Figure 40. Flow sheet illustrating the importance of cored boreholes for the planning of coal mine operations.

mineable minimum levels and increases the percentage of reject material ("dirt") above tolerable limits. Rock splits, which range to about 50 centimeters in thickness, are commonly mined with the coal. Rock splits over 50 centimeters are normally avoided by mining the coal beneath or above. This practice is only possible in thick coal seams, which are rather exceptional in the Campine area, so that panels in coal seams affected by a major split must be abandoned.

5. CONCLUSIONS

From the case-studies outlined in detail above it is clear that prediction of seam thickness and forecasting of geological hazards, can easily be achieved through better use of the geological data, currently stored, or hidden, in the colliery archives. Unfortunately, geologically important information has been lost during the last decades and thus is no longer avilable to the colliery geologist, due to a general unawareness, at that time, of the importance of geological phenomena other than tectonics.

This unawareness apparently not only results from a lack of geological training of the colliery staff but also from a lack of communication between the geologist and the mining engineer.

The importance of geology in coal exploration and reserve evaluation is reasonably well-known and recognized. Mine planning and development on the other hand are almost entirely the domain of the mining engineer. Without doubt mining engineers are important to successfull mining operation, but so too are geologists !

Prior to the start of any mining operation, the geologist should identify the potential geological problems that could affect operations. During mining, the geologist should play an active role, mapping geological features and abnormalities, inaddition to "trouble-shooting" problems, that may have geologic solutions. By performing these tasks, the geologist can complement the input of the mining engineer, and together they can form a team capable of achieving optimum results from any given mining situation. In order to achieve these objectives, the geologist will need an optimum density, spacing and quality of geological data, which will eventually be computer- processed into graphical documents. Evidently, this involves systematic core borings, seam sampling, geophysical investigations, and the systematic detailed recording of geological mine data, something that has rarely been done in the Campine collieries during the past decades. The geological value of theselected data within the colliery archives was highly variable and essentially consisted of rather "primitive" information (surveyors' records). Better use of the data and especially its automatic processing to generate graphical documents has helped productivity planning. Furthermore, better geological interpretation of the data has proved to be helpful in locating potential geological hazards and hence in decreasing production losses. It also has been demonstrated that cored boreholes represent the most important information source for the colliery geologist (fig. 40). Unfortunately, the spreading and density of cored boreholes in the Campine coal basin is generally too low for adequate exploration. Moreover, storage of the detailed core descriptions into a database has never been done, so that the original handwritten on-site core descriptions had to be checked.

An additional handicap in this study was the almost total absence of sedimentological information necessary to interprete the depositional environments of the coal-bearing strata. Nevertheless, simplified sequence analysis, coupled to geometrical data, has allowed a rough genetic identification of the sandstone bodies and reconstruction of the paleofluvial system. This reconstruction in turn permits location of potential hazardous areas for the longwall mining activity in the studied area.

ACKNOWLEDGEMENTS

This research project has been conducted with the financial support of the European Commission for Steel and Coal (convention no 7220-AF/205 and 206). I am indebted to the staff of the N.V. Kempense Steenkolenmijnen for its generous hospitality and for allowing me to study and use their colliery archives. I thank MM. Y. Sleuwaegen, A. Van Parijs and R. Poppe for making my stay most effective and enjoyable. I am most grateful to J. Tricot, P. Verkaeren and R. Claus (K.S. Aardkundige Dienst) and R. Neven (Mine surveyors), for their continuous help and advice during all stages of this project. Dr. R. Flores (U.S.Geological Survey Denver, Colorado, USA) introduced me to the art of interpreting coal-bearing sequences in the field and on logs. Dr. R.L. Austin and Dr. D. Moore (Southampton, U.K.) are thanked for reviewing and editing a draft of the manuscript. Last but not least I would like to thank my collaborators W. Vaesen, J.M. Maquet and J.P. Triplot (ISSeP): without their help the laborious and painstaking selection, input and processing of the numerous geological data would not have been possible.

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Manuscript received on 7.04.1992 and accepted for publication on 28.04.1992.