General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

FE/9036-3
(JPL Publication 78-82)

A Synoptic Description of Coal Basins via Image Processing

Interim Technical Report
Contractor—Jet Propulsion Laboratory
California Institute of Technology

September 1978

Contract No. U.S.D.O.E. ET-76-01-9036

U. S. Department of Energy

Assistant Secretary for Energy Technology

Division of Fossil Fuel Extraction
Mining Research and Development

A Synoptic Description of Coal Basins via Image Processing

K. Winslow Farrell, Jr.
David B. Wherry

ACKNOWLEDGEMENTS

CONTENTS

Table

ABSTRACT

An existing image processing system is adapted to describe the geologic attributes of a regional coal basin. This scheme handles a map as if it were a matrix, in contrast to more conventional approaches which represent map information in terms of linked polygons. The utility of the image processing approach is demonstrated by a multiattribute analysis of the Herrin No. 6 coal seam in Illinois. Findings include the location of a resource and estimation of tonnage corresponding to constraints on seam thickness, overburden, and Btu value, which are illustrative of the need for new mining technology.

SECTION I

BACKGROUND AND OBJECTIVES

This report presents the findings of an attempt to describe a regional coal deposit -- the Herrin No. 6 seam of Illinois. An existing system, originally developed for processing image data from space missions, provided the vehicle for assembling this description. Others have developed computerized descriptions of mineral deposits. However, the flexibility and power inherent in the image processing approach, and particularly the ability of the system to assimilate and rapidly process large amounts of data, encouraged JPL to document this work because of its contribution to geographic information systems as well as overall project goals.

This study of coal basin structure is part of an effort to define and develop advanced systems for mining deep coal seams. Advanced systems are understood to be those which promise (1) a substantial advantage over current technology or (2) the economic extraction of coal from reserves not presently minable. The first steps in undertaking this work on advanced systems have been the development of a set of requirements and an associated methodology for assessing proposed new mining schemes. Each of these efforts requires a description of mining conditions within a broad region. The statement of requirements needs this information in order to alert the designer to the variety and relative importance of physical conditions which the system must either control or avoid. The evaluation methodology also requires similar information in order to estimate the tonnage of reserves/resources exploitable by a new technology, and thus its ultimate commercial potential.

Compiling an aggregate description of a coal basin or larger region by manual analysis of maps and geological reports is a task of major proportions. Coal measures can exhibit a regular structure where erosion and tectonic activity have had little impact. This regularity suggested the possibility of constructing a mathematical model of a coal basin which would permit rough statistical estimates of variables like overburden, seam thickness, pitch, inter-seam distance, etc. If based on a realistic picture of the coalification process and intervening events, such a model should provide information of sufficient accuracy to help set system requirements for a region and make a rough estimate of the tonnage addressed by a candidate system.

The logical first step in constructing such a model is assembling a detailed geological description of a representative coal basin. This description can serve as a laboratory to generate and test hypotheses about overall basin structure, and subsequently, convert these findings into the statistical relationships needed to estimate the tonnage associated with a specified combination of mining conditions. More

particularly, it is hoped that the model will be capable of statements of the form, "40 billion tons (± 10 billion) of resource lie between 800 and 1000 feet, are over 30 inches thick, and pitch less than 5 degrees".

Section II of this report reviews previous work relevant to the description of coal basins and summarizes how image processing differs from other approaches. Section III explains the rationale for choice of the Herrin No. 6 as the target region and discusses the variables to be mapped. Section IV describes the details of adapting an image processing scheme to handle data on coal mining conditions. Section V presents a multiattribute analysis of the Herrin No. 6 seam, in which a tonnage estimate is prepared for a specified set of mining conditions. Section VI concludes the report with a discussion of extensions and plans for future work. The two appendices contain a more technical description of the software and an examination of processing accuracy.

SECTION II

REVIEW OF PREVIOUS WORK

There have been several major studies of coal basins using computer-based descriptive approaches. Carter (1976) is developing a large-scale interactive query system (PACER) for compilation of data on the national coal resources. Bilter and Martin (1977) constructed a map-oriented computer graphics demonstration suitable for both regional and local coal availability studies. Turner (1977) has assembled a highly flexible, interactive system (GMAPS) which appears to have many of the same capabilities as the Bilter and Martin scheme. The following paragraphs describe the salient features of each of these systems.

Designed to be a comprehensive repository of information about the United States coal resources for the USGS, the Program to Analyze Coal Energy Resources (PACER) will be implemented in two phases. Phase I, which is now substantially complete, allows the retrieval and tabulation of summary coal resource data by county or larger area. Primary resource descriptors are seam thickness, overburden, rank, percent sulfur, and tonnage. When implemented, Phase II will store and manipulate point data (from boreholes and field surveys), summarizing this information in the form of isopleth maps. Data is stored in large files that can be searched, retrieved, updated, and summarized in response to specific requests.

In contrast to the USGS computerized coal resource inventory, the system developed by Bilter and Martin is totally map oriented. Based on programs developed at Harvard University, it accepts point data as input and converts it to either a point distribution or an isopleth map depicting a region of interest. Although primarily developed for the description of coal resources, this scheme is applicable to any mineral study for which point data are available.

Turner (1976a, 1976b, and 1977) has developed a highly flexible, interactive system, GMAPS (Generalized Map Analysis Planning System), which accepts map input as a sequence of matrices and produces isopleth or geocoded maps as output. In addition, it is capable of overlay (multiattribute) analysis. The data are organized into 120 x 120 grids which appears to limit the geographic extent of the analysis area or the resolution of the elemental grid cell. A variety of arithmetic and logical functions can be performed on the data, and output can be produced on a lineprinter as a matrix of grey tones.

None of the descriptive schemes discussed above is completely suitable for the sort of coal basin modelling envisaged in the statement of objectives in Section I above. However, each of these schemes has features relevant to the descriptive capability desired by the Advanced Coal Extraction Systems Definition Project. Once the basin modelling effort is well under way, Carter's natural coal resource inventory will be a valuable source of aggregate statistical information. However, the structure of this system as it currently exists is not well adapted to

the kind of map oriented analysis essential to the development of coal basin models. Bilter and Martin's computerized mapping scheme is much closer to the descriptive capability required. However, it has two important limitations: (1) it does not permit multiattribute analysis and (2) it is not well suited to accepting and manipulating isopleth input data. The system developed by Turner has many of the capabilities required for basin modelling. It is map-oriented in both the input and output; it supports multiattribute analysis without producing hard copy intermediate maps; and in addition, it performs statistical tabulations for quantities of interest. Lines, contours, political subdivisions, etc. are represented in terms of polygons, onto which a standard grid is superimposed. To assure low computer run times, the grid size is constrained to fit within core storage along with the necessary processing routines. Depending upon the computer on which the system is implemented, this may limit the scale of analysis that can be performed.

Although very attractive at first glance, systems like GMAPS have certain limitations as a result of the polygonal scheme used to represent map data within the computer. The polygonal representation does permit very efficient use of storage space, since it is necessary to record only polygon boundaries. However, the construction of overlays (multiattribute analysis) requires reformatting the polygonal representation to a grid cell description. The mechanics of this reformatting and subsequent overlay calculations involve a great deal of bookkeeping, which is time consuming and expensive. Thus, polygonal schemes are not well suited to large scale, complex, repetitive multiattribute analysis.

Systems using polygonal data representation have another limitation. Once a data base is formatted to a particular scale, conversion to a larger scale or aggregation into a larger data base requires substantial additional processing. This tends to inhibit the incorporation of new maps into a data base, thereby limiting future applications of the information already assembled.

In contrast to systems using a polygonal data representation, image oriented schemes reduce a map to a matrix of values, where each component of the matrix corresponds to a specified grid cell and thus, x-y location. Consequently, data storage requirements are increased considerably over what is required for polygonal schemes. On the other hand, the matrix representation greatly simplifies the algorithms used in editing; the construction of multiple overlays; and the reformatting involved in changes of scale, aggregation, or adaptation of maps drawn in a different cartographic projection. Processing speed is a direct result of the matrix or fixed grid representation, which enables sequential processing of data files, and as a result, the use of a computer whose core storage is smaller than the map grid size. In summary, it appears that the sort of image-based scheme described in the next section is ideally suited to provide the descriptive component of a coal basin model: it produces complex multiple overlays quickly and cheaply, permits easy reformatting of maps, and facilitates editing.

SECTION III

SELECTION OF A TARGET AREA AND PROPERTIES TO BE MAPPED

There are several reasons why Illinois was chosen as the area to be used in developing a computerized coal basin description. The geology of the basin is straightforward; however, the area is large enough to embrace a spectrum of mining conditions. The basin is almost entirely within the state of Illinois, the state boundaries being nearly coterminous with the coalfield margins. This means that the maps and other data required in the analysis can be assembled from the geological reports of one state. Moreover, the Illinois coal measures have been extensively studied, and the results are readily available in state geological survey circulars. Finally, the deep coal within the Illinois basin appears to be representative of the mining conditions which may be typical of the Midwest near the end of the century — the target time frame for the Advanced Coal Extraction Systems Definition Project.

Within Illinois, the Herrin No. 6 coal seam has been selected as the initial target for analysis. This coal bed is widespread, consistent in thickness, and readily identifiable in the subsurface through studies of drill logs. It is the most important coal seam in Illinois, both in terms of reserves, and in production. According to studies by Hopkins and Simon (1974) and Allgaier and Hopkins (1975), the Herrin No. 6 seam contains 44% of the Illinois reserves and accounted for 75% of that state's production in 1973.

A substantial amount of geological information is needed to pose advanced system requirements and evaluate the breadth of capability of candidate systems. Previous work by the project indicates that the following list of data would be desirable:

- Thickness of coal seam.

- Seam pitch.

- Energy content.

- Percentage of sulfur and ash.

- Depth of overburden.

- Surface topography.

- Seam structure.

- Roof and floor conditions (type of strata).

- Methane content.

- Soil data.

- Water table elevation.

- Land use and land value data.

- Location of coal that has been mined out.

- Location of coal that has been rendered inaccessible because of mining regulations or other restrictions.

As indicated below, considerable effort is involved in getting a map ready for computer processing. Thus, in this initial study, it was decided to limit the analysis to six variables -- thickness, overburden, pitch, energy content, percent sulfur, and roof conditions. Table 1 reports the data source for each variable and indicates how the data were prepared for computer processing.

Table 1. Geological Factors Employed in the Herrin No. 6 Analysis. (Asterisked factors are used in the multiattribute analysis of Section V.)

IBIS Parameter	Origin	Preparation
Thickness of coal seam*	Willman, et al. (1975)	Existing map was digitized.
Energy content measures*	Damberger (1971)	Existing map was digitized.
Percentage of sulfur	Keystone (1976)	Existing map was digitzed.
Depth of overburden to coal seam*	----	Existing seam structure map was subtracted from existing surface topography map.
Surface topography	Willman, et al. (1975)	Existing map was digitized.
Seam structure	Willman, et al. (1975)	Existing map was digitized.
Roof conditions	Cady, et al. (1952)	Map was produced from prose description and digitized.
Seam slope	----	Map was produced from seam structure map and digitized.

DESCRIPTION OF THE IMAGE PROCESSING APPROACH

The approach selected for this initial attempt at coal basin description employs the Image Based Information System (IBIS) developed at the Image Processing Laboratory of JPL. IBIS was conceptualized and implemented by N. Bryant and A. Zobrist (1976,1977) as an extension of a system used to reconstruct and enhance image data obtained from spacecraft. IBIS has seen a variety of applications, including preparation of thematic land cover maps, mineral exploration, assessment of the rooftop area available for solar collectors, and air quality studies. IBIS has the capability of transforming some non-image data into image processing format. Thus, digitized or tabular data, such as borehole records or isopleth maps, can be handled via image processing techniques.

When reduced to its essentials, the approach is quite simple in concept (see Figures 1 and 2 for overview). First, the requisite geological information is assembled in the form of maps which are typically isopleth plots of the salient geological variables -- surface and seam structure, thickness, local slope, roof quality, etc. These maps may be hand drawn summaries, integrating and interpreting data from diverse sources. Next, the maps are put into computer compatible format by digitizing the isopleths. After editing and being transformed into a special data format required for IBIS processing, each map is zoned to portray the data aggregation chosen for analysis. For example, a seam thickness map might be zoned into regions exhibiting thickness values of 0-12 in., 13-30 in., 31-48 in., 49-60 in., and 60 in. +. Finally, the maps are processed to answer questions or to test hypotheses, with the output being maps or tables, at the discretion of the analyst. Section V describes how IBIS was used to locate a coal resource satisfying certain conditions on thickness, overburden, and energy content.

Thus, the scheme permits a highly flexible description of a coal basin which can produce composite maps and conduct analyses, using as input, maps that synthesize available geological information. A representative output is a map showing the location of coal meeting specified conditions on thickness, overburden, roof quality, and surface access -- with a tabular breakdown by township and county. The remainder of this section describes each of the processing steps, illustrating the procedure with results from an analysis of the Herrin No. 6 seam of Illinois.

Preparation of Requisite Geologic Information

IBIS is quite flexible as to the type of information it will accept. Both point data and isopleth data are permitted. Moreover, maps used in a particular analysis may be drawn to different scales or prepared using different cartographic projections. Standard routines

DIGITIZE LINES INTO
X, Y COORDINATES

IDENTIFY EACH DISTINCT
REGION WITH A UNIQUE 'PAINT'
NUMBER OR GREY VALUE

ASSIGN EACH REGION ONE
OF FOUR GREY VALUES FOR
VISUAL DISCRIMINATION
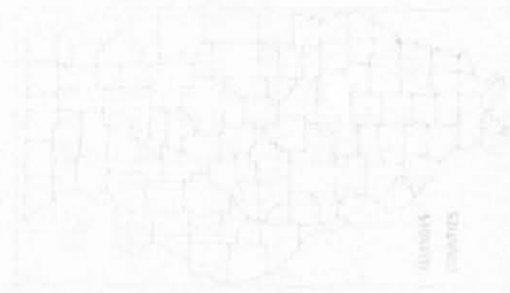
ORIGINAL BASE MAP

IMAGE BASED LINE
MAP

IMAGE PAINTED TO UNIQUELY
IDENTIFY EACH REGION

FINAL IMAGE READY
FOR ANALYSIS

Figure 1. Steps in Converting an Input Map to Image Format:
The Illinois County Base Map

4-2

DIGITIZE LINES INTO
X, Y COORDINATES

IDENTIFY EACH DISTINCT
REGION WITH A UNIQUE
PAINT NUMBER OR GREY VALUE

AGGREGATE THE DATA BY ASSIGNING
A UNIQUE GREY VALUE TO REGIONS
FALLING INTO A SPECIFIED THICKNESS
INTERVAL

FINAL IMAGE READY
FOR ANALYSIS

IMAGE PAINTED TO
UNIQUELY IDENTIFY
EACH REGION

IMAGE BASED LINE
MAP

ORIGINAL THICKNESS
MAP

Figure 2. Steps in Converting an Input Map to Image Format:
A Thickness Isopleth Map of the Herrin No. 6 Seam

for map registratiol and distortion removal ensure that all input maps will be compatible ith a base map.*

In the Herrin No. 6 analysis, all of the maps except those for local coal seam pitch, roof quality, and overburden, were available in isopleth form. The slope map had to be hand drawn using a coal seam structure map as input, and the roof quality map was assembled from prose descriptions in state geological survey reports by Cady (1952) and Allgaier and Hopkins (1975). The overburden map was obtained by differencing the maps of seam structure and surface relief (see Figures 3 and 4). The base map chosen for the Herrin No. 6 analysis was an Illinois county map by Boardman and Young (1953), having a scale of 1:750,000.

Preparation of Digitized Maps and Transformation to Image Format

Mapped information is converted to the format required by IBIS in four steps. First, tiepoints (markers common to all maps) are determined on a base map so that each subsequent map can be registered to those exact locations. Second, key features such as county boundaries or isopleths are digitized. Third, each map is converted to image format and simultaneously registered to the base map. Finally, maps are edited to remove any errors introduced during digitization and map-to-image conversion.

A minimum of three tiepoints is required for registration; the actual number of points needed is a function of both map complexity and amount of distortion removal required for registration. For purposes of aligning planar images, three points are the optimal number for constraining two coordinate directions.

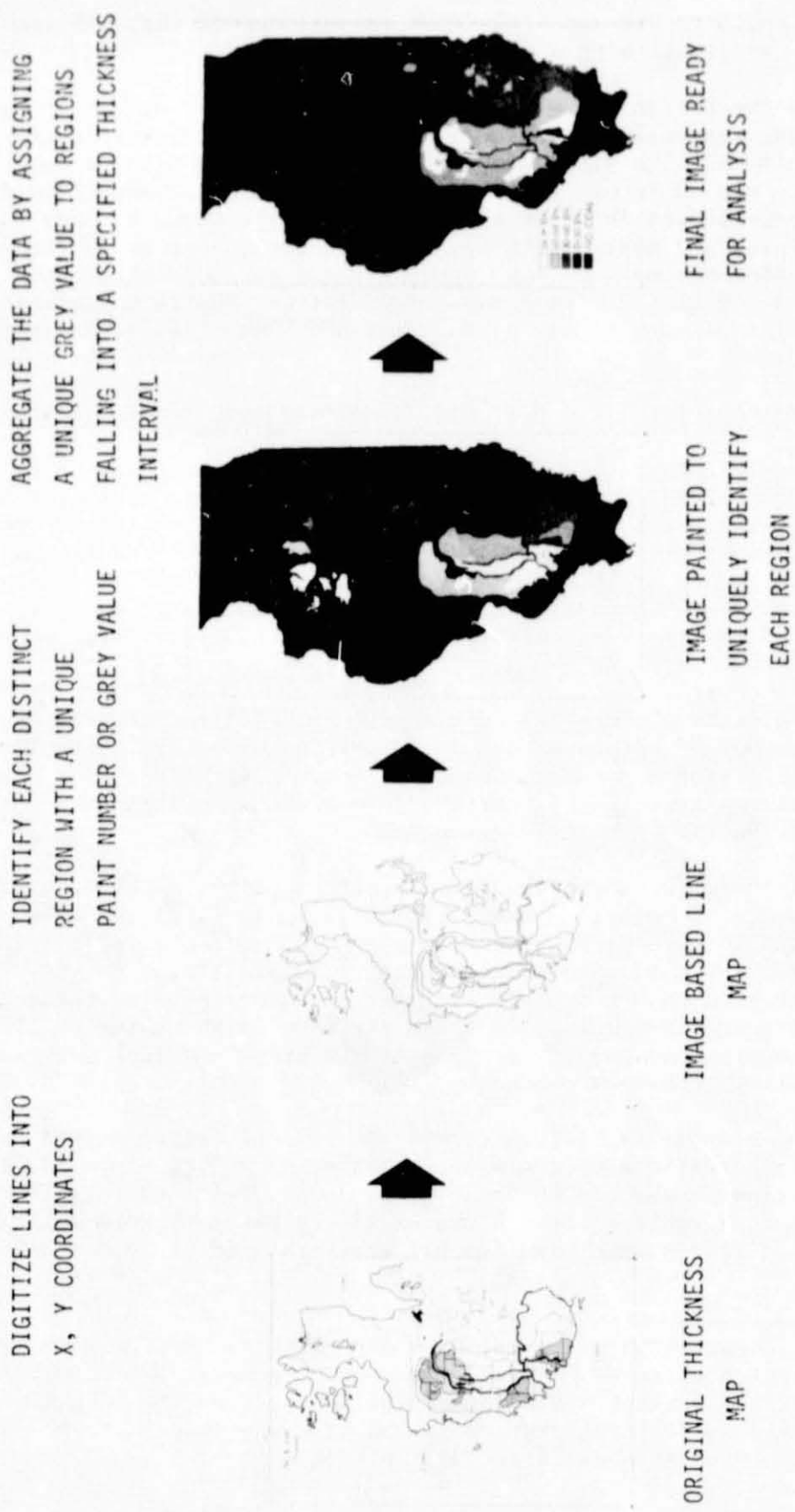Digitization involves recording the x and y coordinates of all key features on magnetic tape. Typically, points, lines, or isopleths are digitized as separate records, although isopleths can be segmented and merged later if this is convenient. In digitizing points, the coordinates of each point are recorded on tape; for line segments, the end-points are recorded. Isopleths are treated as chains of linked line segments. Automatic matching of the first and last points in the chain assures unbroken contours.

For simplicity, let us assume that all of the digitized maps are line representations of geologic variables or political boundaries, as was the case in the Herrin No. 6 study. Conversion to image format involves representing these lines as linked paths of grid cells within the common grid scheme used for all maps. A grid of 1000 x 586 was

---

*Map registration is performed by a mathematical least squares program for coordinate transformation. Distortion removal is accomplished by a piecewise movement and alignment of features on the image-formatted map, based on feature location in the base-map image, or on some common reference grid such as latitude-longitude.

NOTE: The number in a grid cell is the mean elevation with respect to some reference height.

DEPTH OF OVERBURDEN

COAL SEAM ELEVATION

SURFACE TOPOGRAPHY
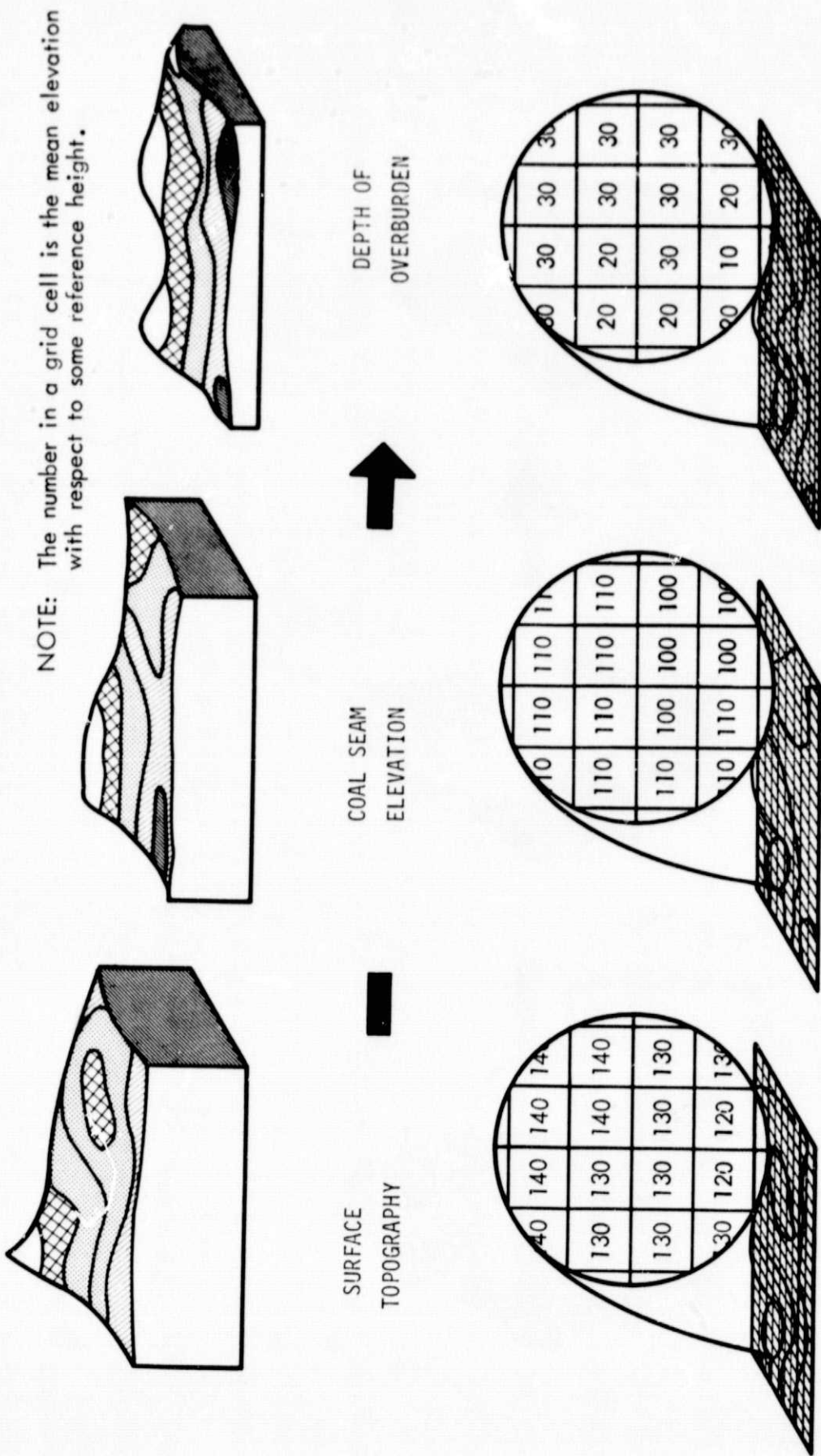
Figure 3. Construction of the Overburden Map via Image Subtraction: Process Overview

SURFACE
TOPOGRAPHY
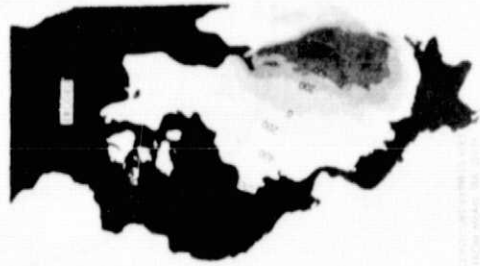
ELEVATION OF
COAL SEAM

OVERBURDEN

Figure 4. Construction of the Overburden Map via Image Subtraction:
Data and Results for the Herrin No. 6 Seam

4-6

chosen for the Herrin No. 6 analysis, resulting in an elemental grid cell area of 0.154 sq mi.

Editing and Painting

It is often necessary to correct errors caused by digitizing or misregistration. In order to do this, the image must be examined via a photograph or CRT display. Editing can be accomplished by correcting either the image or the original file containing the digitized data. Editing of the digitized lines can be simplified by "painting" the image with unique brightness tones or shades of grey and visually inspecting that image for errors.

For ease in interpretation, data are grouped into distinct categories, such as zones of equal thickness or elevation. As in the editing process, zones are identified by giving them unique grey values. For example, in creating the final Herrin No. 6 coal seam thickness image, a shade of grey for each thickness zone was assigned according to the simple relation:

$$\text{if} \quad T_n \leq T < T_{n+1},$$

$$\text{Brightness} = \text{Grey Level } (n+1),$$

where T is the indicated seam thickness on the input map, and T_n and T_{n+1} are the upper and lower limits for a particular analysis category (see Figure 2).

Output Format Options

IBIS permits two types of output -- tables and maps. Tabular output is similar in style and organization to the lists and cross-tabulations common to many kinds of computer analysis. However, the map output is a unique feature of IBIS. Since the results of an analysis are available in image format, these data are immediately and easily convertible into a map image or photograph — a format most convenient for display of geologic information. Finally, these output maps may be retained on tape or disc as input for future analysis in ready-to-compute form.

MULTIATTRIBUTE ANALYSIS OF THE HERRIN NO. 6 SEAM
OF ILLINOIS

Identification of coal reserves or resources which satisfy a
specified list of conditions can be a valuable tool in a variety of
contexts, including assessment of a mining property, mine design,
management of state or regional mineral resources, or the evaluation of
a new mining concept. It was the last interest which stimulated the
work described in this report. For example, suppose one is asked to
judge the attractiveness of a proposed mining technology designed to
exploit thin, multi-seam deposits of coal which are flat-lying and
under moderate cover. Given an inventory of resources containing
deposits of the specified character, a multiattribute analysis can
develop answers to questions of the following genre:

- Does this mining technology address a significant portion
  of the resource?

- What is the tonnage involved and where is it located?

- In view of the locations indicated, what sort of problems
  may be anticipated in construction access, environmental
  impact, and transport of coal to market?

- How may existing leaseholdings and contemplated leasing
  policy affect block size, and thus, the economies of scale
  available to the technology?

The information necessary to answer questions of this sort is easily
handled via IBIS.

Of course, these questions could be answered via a manual overlay
system. Here, the analyst prepares a series of transparent overlays,
one for each attribute of interest. Typically, the overlay would be
colored or cross hatched distinctively to indicate the physical location
of the coal satisfying a particular condition. The analysis would be
completed by carefully superimposing all of the overlays. If a perma-
nent record of the analysis is required, an additional map would be
drawn on tracing paper, or perhaps, another transparency. Tabular out-
put (e.g., a county breakdown of tonnage) would be prepared manually
also, probably by use of a planimeter or another areal estimation
procedure (for an example, see Allgaier and Hopkins (1975)).

The computerized multiattribute analysis addresses the location
and tonnage of Herrin No. 6 coal satisfying the following conditions:

- Thickness of 30 to 60 inches.

- Depth of overburden 1000 feet or more.

- Energy content of at least 12,000 Btu/lb.

This list of specifications describes a portion of the Illinois coal resources which may be attractive to developers near the end of this century.

This resource is located by interpreting the above specifications as a logical intersection of the form, (30 in. < thickness < 60 in.) and (depth > 1000 ft) and (energy content > 12,000 Btu/lb). The first step is to create an attribute window for each term in the intersection by masking out the coal which does not satisfy that condition. For example, all coal that does not satisfy the thickness restriction is colored black on the map image of thickness (Figure 5). In a similar fashion, masks are applied to the depth and energy map images to create windows for those attributes. The three attribute windows are then combined, using the image processing analog of logical intersection. The algorithm which performs this operation constructs the logical intersection by concurrent processing of all relevant maps. Each grid cell is examined in turn. If the cell is unmasked (inside the attribute window) on all maps, it becomes part of the map area satisfying the stated conditions. Currently, the intersection algorithm is able to process 10 maps simultaneously, or an unlimited number of maps sequentially.

The overall logic involved in locating the coal resource described above is presented in Figure 6. Examination of the map showing the location of the resource (Figure 7) and the associated breakdown of tonnage by county indicates an aggregate of 11.64 billion tons, with 6.5 billion tons of this resource residing in Wayne, Clay, Richland, and Jasper counties. This estimate represents almost 8% of the aggregate tonnage of the Herrin No. 6 seam without correction for areas judged to be unminable and for local anomalies such as pinchouts and channel sands.

Clearly, the ease of performing multiattribute analysis is a most attractive feature of the IBIS scheme -- particularly in those applications where a great deal of analysis is contemplated. Once the requisite maps are available in image format, identification of regions satisfying a very complex stipulation of conditions can be done quickly and cheaply. The lengthy process of digitizing and editing the input maps remains a problem. Nevertheless, in those cases where a variety of map scales and cartographic projections are involved, the use of IBIS, with its extensive distortion removal and scale conversion capabilities, remains very appealing.

SEAM THICKNESS MAP
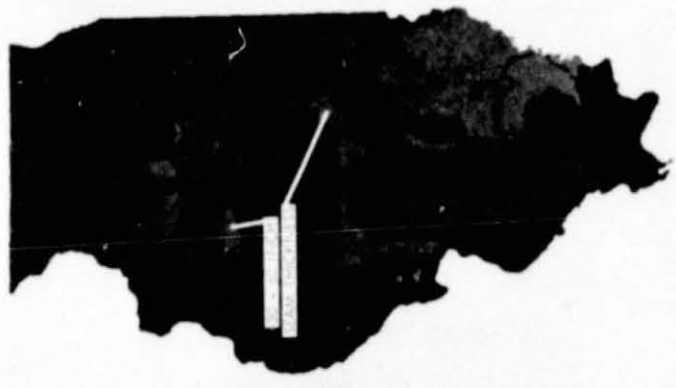
SEAM THICKNESS VALUES
NOT DESIRED ARE BLOCKED
OUT

IMAGE WITH SEAM
THICKNESS ATTRIBUTE
WINDOW

Figure 5. Multiattribute Analysis of the Herrin No. 6 Seam:
Construction of the Attribute Window for Thickness

COUNTY OVERLAY MAP
TABULATION OF
TONNAGE BY COUNTY

COUNTY BASE MAP

MAP OF SPECIFIED
COAL RESOURCE

MAP OF COAL
TONNAGE

MULTIATTRIBUTE
WINDOW

SEAM THICKNESS
ATTRIBUTE WINDOW

BTU CONTENT
ATTRIBUTE WINDOW

OVERBURDEN DEPTH
ATTRIBUTE WINDOW
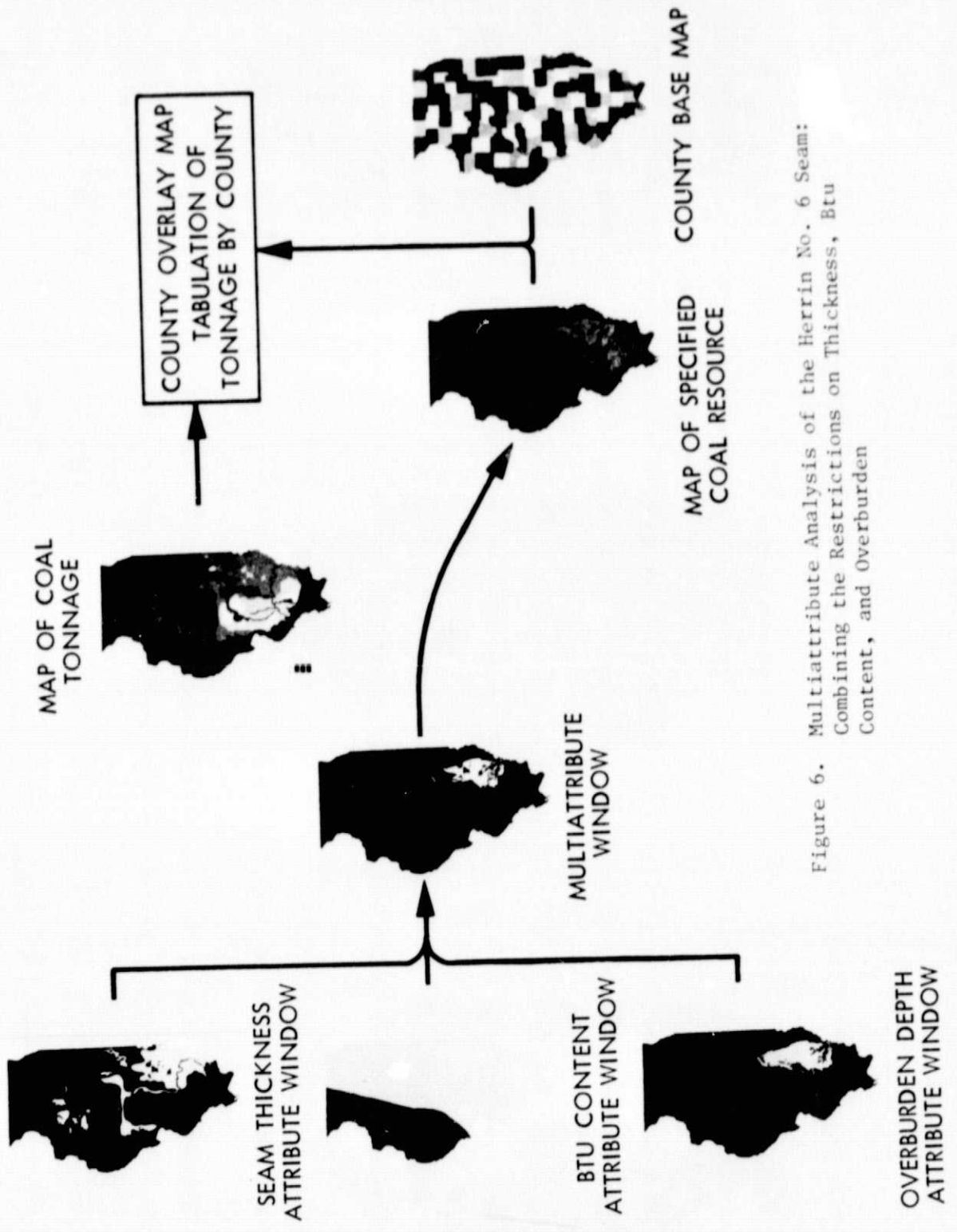
Figure 6. Multiattribute Analysis of the Herrin No. 6 Seam:
Combining the Restrictions on Thickness, Btu
Content, and Overburden

5-4

STATE OF ILLINOIS

COAL RESOURCES BY COUNTY
HERRIN NO. 6 COAL BED

(TONNAGE EXPRESSED IN THOUSANDS OF TONS)

ATTRIBUTES

SEAM THICKNESS - 30 TO 60 INCHES
DEPTH OF OVERBURDEN - 1000 TO 1400 FEET
ENERGY CONTENT - 12,000 TO 14,000 BTU

COUNTY	TONNAGE
CLAY	1734339
COLES	283047
CUMBERLAND	783821
DOUGLAS	44226
EDWARDS	621885
EFFINGHAM	1081155
GALLATIN	2041
HAMILTON	410281
JASPER	1204988
JEFFERSON	491929
MARION	467435
MOULTRIE	124513
PIATT	9525
RICHLAND	1469664
SHELBY	217728
WAYNE	2139857
WHITE	558609
	11645043

(b)

(a)

Figure 7. (a) County Overlay Map of the Herrin No. 6 Resource Which Satisfies the Restrictions on Thickness, Btu Content and Overburden. (b) Breakdown of Coal Tonnage by County for the Herrin No. 6 Resource Which Satisfies Restrictions on Thickness, Btu Content and Overburden.

SECTION VI

SUGGESTIONS FOR FUTURE WORK

This section relates possible future application of the IBIS system to the direction of the Advanced Coal Extraction Systems Definition Project beyond FY 1978, and in addition, identifies ways to enhance processing and analysis capabilities. The discussion concludes by describing possible uses of the IBIS scheme in assessing and developing a broad spectrum of natural resources.

The primary objective of the Advanced Coal Extraction Systems Definition Project for FY 1978-79 is to initiate the conceptualization of advanced mining systems for one target region -- nominally Central Appalachia. IBIS can contribute directly to this objective by (1) producing summary descriptions of mining conditions useful in setting regional geological requirements and (2) estimating the tonnage potentially exploitable by proposed new mining concepts.

It is hoped that applications of IBIS in support of mining system conceptualization will afford an opportunity to take the next step in the development of a statistically oriented coal basin model. This would be done by drawing upon existing phenomenological basin models to pose hypotheses about the properties of coal and adjacent formations which could then be subject to statistical analysis. If successful, the resulting model would permit rapid estimates of the tonnage associated with a specified list of coal properties and mining conditions.

A variety of empirical studies and mathematical tools are available for use in the development of predictive coal basin models. Phenomenological research describes the geological processes for depositional environments in coal basin formation (see Milici (1974); Ferm (1974); Donaldson (1974); Baganz, et al. (1975); and J.C. Horne, et al. (1978)). Certain geomathematical techniques are well adapted to empirical correlation of geologic variables as well as the testing and verification of structural relationships (see Agterberg (1974); Matherton (1963); Briggs and Pollack (1967)). Also of potential interest are probabilistic models which use properties associated with one or more random variables in order to explain statistically the occurrence of aggregate geologic phenomena (Krumbein (1976)).

Phenomenological work is developing some very powerful insights into coal basin structure (e.g., Horne, et al. (1978)). Indeed, current research has produced quantifiable propositions about seam and basin structure which potentially permit the inference of coal thickness, physical and chemical properties, roof and floor conditions, etc. from relatively little data. The challenge is to express these propositions in model format using quantitative tools. In any event, the descriptive capability to be assembled as the first step in basin modelling would have an architecture which permits rich geological characterization and facilitates the statistical analysis of map data.

The potential use of IBIS in these and other applications will depend heavily upon streamlining the procedures for inputting mapped information. The sequence of processing steps which prepares input maps for multiattribute analysis requires a substantial amount of manual processing and editing. In the Herrin No. 6 analysis, an average of one man-week was required to take a map from digitization through the completion of editing and painting. Unless reduced significantly, this requirement for input processing may severely limit large scale applications of the system.

An interactive editing capability has been developed as a partial solution to the input problem. This technique permits one to enlarge a selected region of a map on a CRT display and then visually inspect it for errors. Any errors which remain after the initial edit are quickly pinpointed via an attempt to paint the map as preparation for subsequent analysis. Preliminary testing of this technique indicates a probable 30 percent reduction in editing effort. Additional reductions in processing effort may be possible via the use of digitizing and graphics hardware which permits input and editing in a fully interactive mode.

For coal and other mineral resources such as metals and petroleum, the IBIS system lends itself directly to a diverse set of problems. An obvious application is the estimation of resource location and extent, as in the Herrin No. 6 analysis. This may be done at a regional scale in support of long-range development planning, or at the level of mining property assessment and mine design. In addition to consideration of the customary geological variables, such an analysis could easily incorporate data on transportation corridors, urbanization and land use, and potential environmental impacts. Finally, as indicated in the statement of objectives for this research, the tonnage minable by new mining concepts could be estimated, with a level of detail as complex as the study requires.

REFERENCES

Agterberg, F.P., 1974, Geomathematics, Developments in Geomathematics 1, Elsevier, New York, 596 p.

Allgaier, G.J., and Hopkins, M.E., 1975, Reserves of the Herrin (No. 6) Coal In the Fairfield Basin in Southeastern Illinois, Illinois State Geological Survey Circular 489, 31 p.

Averitt, P., 1975, Coal Resources of the United States: January 1, 1974, U.S. Geological Survey Bulletin 1412, 131 p.

Baganz, B.P., Horne, J.C., and Ferm, J.C., 1975, Carboniferous and Recent Mississippi Lower Delta Plains: A Comparison, Gulf Coast Assoc. Geol. Socs. Trans., v. 25, pp. 183-191.

Bilter, J.R., and Martin, J.D., 1977, Computer Graphics Demonstration: Area Coal Availability Studies, U.S. Bureau of Mines Information Circular No. 8736, 16 p.

Boardman, L., and Young, R., 1953, Geologic Map Index of Illinois, Scale 1:750,000, U.S. Geological Survey.

Briggs, L.I., and Pollack, H.N., 1967, Digital Model of Evaporite Sedimentation, Science, v. 155, pp. 453-456.

Bryant, N.A., 1976, Integration of Socioeconomic Data and Remotely Sensed Imagery for Land Use Applications, in Proceedings of the Caltech/ JPL Conference on Image Processing Technology, Data Sources and Software for Commercial and Scientific Applications, Pasadena, CA, Nov. 3-5, 1976, pp. 9-1 to 9-8.

Bryant, N.A., and Zobrist, A.C., 1977, IBIS: A Geographic Information System Based on Digital Image Processing and Image Raster Data Type, IEEE Trans. on Geoscience Electronics, v. GE-15, no. 3, pp. 152-159, July 1977.

Cady, G.H., et al., 1952, Minable Coal Reserves of Illinois, Illinois Geological Survey Bulletin 78, 138 p.

Carter, M.D., 1976, The National Coal Resources Data System of the U.S. Geological Survey, Computers and Geosciences, v. 2, no. 3, pp. 331-340.

Damberger, H.H., 1971, Coalification Pattern of the Illinois Basin: Economic Geology, v. 66, no. 3, pp. 488-494.

Donaldson, A.C., 1974, Pennsylvanian Sedimentation of Central Appalachians, GSA Special Paper 148, pp. 47-48.

Ferm, J.C., 1974, Carboniferous Environmental Models in Eastern United States and Their Significance, GSA Special Paper 148, pp. 79-95.

Hopkins, M.E., and Simon, J.A., 1974, Coal Resources of Illinois, Illinois Geol. Surv. Min. Note 53, 24 p.

Horne, J.C., et al., 1978, Depositional Models in Coal Exploration and Mine Planning, working paper, Carolina Coal Group, Dept. of Geol., U. So. Carolina (presented at Am. Assoc. of Pet. Geol. annual convention in Oklahoma City, Apr. 1978; abstract published in AAPG Bull., v. 62-3, Mar. 1978).

Keystone Coal Industry Manual, 1976, G.F. Nielson ed., McGraw Hill, New York, pp. 564-572.

Krumbein, W.C., 1976, Probabilistic Modeling in Geology, in: Random Processes in Geology, Springer-Verlag, New York, pp. 39-54.

Matherton, G., 1963, Principles of Geostatistics, Economic Geology, v. 58, pp. 1246-1266.

Milici, R.C., 1974, Stratigraphy and Depositional Environments of Upper Mississippian and Lower Pennsylvanian Rocks in the Southern Cumberland Plateau of Tennessee, GSA Special Paper 148, pp. 115-133.

Turner, K.A., 1976a, Computer-Aided Environmental Impact Analysis, Part 1: Procedures, Colorado School of Mines Mineral Industries Bull., Mar. 1976, v. 19, no. 2, 23 p.

Turner, K.A., 1976b, Computer-Aided Environmental Impact Analysis, Part 2: Applications, Colorado School of Mines Mineral Industries Bull., May 1976, v. 19, no. 3, 16 p.

Turner, K. A., 1977, Applications of Computer-Assisted Composite Mapping System to Energy Development and Environmental Impact Assessment, AAPG Bull., (abst.), v. 65, no. 5, p. 836.

Willman, H.B., Atherton, E., Buschbach, T.C., Collinson, C., Grye, J.C., Hopkins, M.E., Lineback, J.A., Simon, J.A., 1975, Handbook of Illinois Stratigraphy, Illinois Geological Survey Bull. 95.

APPENDIX A

TECHNICAL DESCRIPTION OF IMAGE BASED INFORMATION SYSTEM (IBIS)*

Geologic information systems should satisfy three basic criteria if they are to be useful: (1) they should provide specific point locations, as well as area locations of data; (2) they should provide for variable aggregation (subsetting) of data; (3) they should provide a method for representing spatial mathematical and statistical programs which can be called as needed to aid in the analysis of spatially oriented data. Practitioners of the art of geocoded systems design have progressed with varying degrees of success toward the goals outlined. As a rule, generalized systems have only rudimentary data manipulation capability (i.e., status updating and interrogation by area), while highly specific and specialized systems have progressed further with modelling applications.

In response to the desire to access data for selected areas, polygon and grid-cell geocoded information systems have been developed. Such systems rely on the tabular formatting of the input data, a costly and time-consuming process. Often the system falls into disuse because the updating of major segments of the data base becomes prohibitively expensive. The areas particularly needing improvements are: interactive processing and geocoordinate data entry for map/ picture registration.

A data interface has been provided between image and graphical data sets so that the results of processing can be represented, and image processing analogs have been developed for existing geobase file computational steps (i.e., overlay, aggregation, cross tabulation, etc.). The system makes use of digital image processing technology to perform interactive data base storage, retrieval, and analysis operations. The system provides both rapid up-to-date information access for users' models or the construction of thematic maps, as well as an inexpensive and flexible mode of primary input. The data base design incorporates the interfacing of tabular and graphically formatted geocoding systems with a raster scan formatted geocoding system.

The ease with which an agency can establish a geologic information system is constrained by the level of detail and the computer technology available. With geocoded data, there is a dramatic increase in file size with every added variable and increased resolution. The use of newer generation computers has only moderately improved the overall operation, as the major efforts are involved in both file generation and editing and computer software architecture.

There are a number of ways to encode spatial data. It is possible, however, for illustration purposes, to dichotomize referencing systems into nominal and ordinal ones, and to divide data types into

---

*Adapted from Bryant and Zobrist (1977) with the permission of the authors.

tabular, graphical, and image ones. Ordinal systems reference data by the actual geographical coordinate values. Thus natural resources such as forests, rivers, and geologic formations are mapped with selected identifiers (total area, boundary, centroid) referenced to latitude and longitude or a selected geographic coordinate system. Nominal systems are "name referencing," i.e., information or data are referenced to a name-designating system. Any district-based referencing convention, such as census tract, county, township, or transportation zone, assumes that the operator knows where each administrative area is located and leaves the analysis of contiguity effects, etc., up to the individual.

Of equal concern to the designer of a geologic information system is the incorporation of the various geocoded data types to assure adequate "data capture". It is only through the integration of tabular, graphical, and image data types that geographic information systems achieve the synergistic impact required to offset their initial cost. For instance, tabular files may keep records of individual drilling sites, while graphical files record elevation contours, and image data sets record the distribution of geologic formations. The combination of all three data types would provide analysts with the variety of spatial data needed to model depth to a number of strata within the formations. The need to deliver a uniformly encoded result to the user has been a key element to changes that have occurred in both geocoding approaches and computer system architecture applied to geologic information systems.

There exist three principal geocoding architectures, which have evolved from simple grid-cell systems to complex polygon methodologies, and most recently include the image raster data type (see Figure A-1). Grid-cell methods serve the need to retrieve geo-located data and generate maps through the cross tabulation of variables encoded within a particular cell. Several important drawbacks reduce the overall flexibility of grid cell systems: (1) their spatial resolution is only as accurate as the grid-cell size (usually ranging from 1 acre to 10 sq mi); (2) the systems permit the referencing of data in either a nominal or ordinal manner, never both; (3) the need for manual encoding of the input data files has made updating difficult and even prohibitively expensive and has effectively limited the spatial resolution of grid cells to satisfy the need to achieve regional coverage.

In response to the failings of grid-cell geocoding, polygon systems grew as electronic coordinate digitizers became generally available. Polygon geocoding formats effectively solved the spatial resolution dilemma inherent with grid-cell formats, while coordinate digitizing hardware has permitted rapid encoding of data. Despite these significant achievements, polygon geocoding systems have left the problem of ordinal data updating unresolved and created new challenges inherent in their graphical data structure. These problems include: (1) considerable computational expense associated with file editing; (2) complex topological architectures to achieve efficient data extraction from any given area; and (3) large investments in computer systems to achieve polygon overlay of separate files for encoding ordinal data into nominal encoding formats (e.g., tonnage of coal for each county).
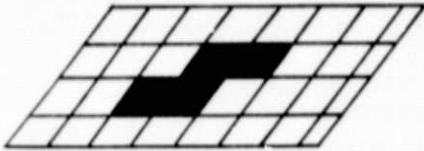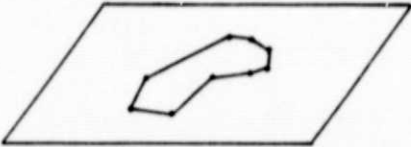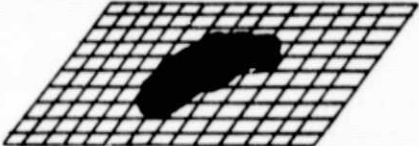
METHOD	COST CONSIDERATION	OVERALL FLEXIBILITY
GRID CELL	MANUALLY OPERATED	SPATIAL RESOLUTION POOR, UPDATING DIFFICULT
POLYGON	EXPENSIVE FOR LARGE DATA SETS	CERTAIN OPERATIONS PROHIBITED
IMAGE RASTER	REQUIRES IMAGE PROCESSING TECHNOLOGY	NEITHER SCALE NOR DATA FORMAT DEPENDENT

Figure A-1. Approaches to Geocoding

Many of these constraints can be mitigated by the use of an image raster encoding procedure and application of digital image processing algorithms to implement geographic information system analyses.

Digital image processing techniques can be applied to interface existing geocoded data sets and information management systems with thematic maps and remotely sensed imagery. The basic premise is that geocoded data sets can be referenced to a raster scan that is equivalent to an ultrafine grid-cell data set, and that images taken of thematic maps or from remote sensing platforms can be converted to a raster scan. A major advantage of the raster format is that x, y coordinates are implicitly recognized by their position in the scan, and z values can be treated as Boolean layers in a three-dimensional data space. Such a system should permit the rapid incorporation of data sets, rapid comparison of data sets, and adaptation to variable scales by resampling the raster scans.

Because the image data type is used, capabilities for digital image file handling, image manipulation, and image processing are required. Thus the IBIS system has been built upon an existing image processing system, VICAR (video image communication and retrieval), developed at JPL. Certain basic image processing operations are absolutely essential. One must accomplish image-to-image registration, whereby images of different scale, rotation, or map projection are superimposed precisely enough so that corresponding pixels represent the same geographic location. Rubber-sheet registration is almost

always necessary to achieve the needed degree of accuracy. On the other hand, it is anticipated that even esoteric image processing operations, such as convolution smoothing, will be useful for certain types of applications. The conclusion here is that any image-based information system must contain a powerful image processing subsystem.

Additional capabilities are then added to the image processing system to convert it into an image-based information system. First, image data must be registered or indexed to spatially referenced tabular data. For example, it may be desired to collate overburden data contained in an image with tonnage data contained in a tabular file aggregated by county. Conceptually, this can be likened to image-to-image registration, except that pixels are aligned with records, not with pixels. Second, a data interface must be provided between the different data types so that the results of processing can be stored. Third, image processing analogs must be developed for existing geo-base file computational steps such as polygon overlay, aggregation, and cross tabulation. For example, the polygon-overlay operation, in which areas of intersections of polygons from two data sets are obtained, is replaced by a two-image histogramming operation.

A user request is given to IBIS by means of a language which is translated into the host machine job control language. The translated code can then invoke system functions or processing modules. This organization makes the system flexible and easily extendable. The system software consists of a number of Fortran modules and a relatively small system nucleus. These characteristics were designed to simplify maintenance and make it easy for new users to understand and apply the system.

APPENDIX B

ACCURACY CONSIDERATIONS

The fidelity of the results produced by the image processing scheme described above depends upon (1) the accuracy of the digitized input maps and (2) the precision of the numerical approximations used in the image processing software. This appendix addresses each of these determinants of accuracy in turn, and then discusses some quantitative measures of accuracy for the analysis of the Herrin No. 6 reported in the text.

Input Accuracy

Accuracy in map preparation is achieved via precision digitizing of pertinent information, careful editing of the digitized products, and controlled registration throughout the procedure. Digitizing errors occur randomly and are commonly associated with gaps where lines are expected, and coalescence of isopleths where separation is desired. Map-to-image conversion can create similar errors, even when based on accurately digitized data. Editing procedures effectively eliminate these random errors.

Registration begins with identification of tiepoints which can be precisely located on all maps used in the analysis. Scale differences between the maps are automatically compensated for by the IBIS scheme. Use of a map created via a different projection from the base map presents a more difficult registration problem. In such a case, IBIS employs a set of so-called "rubber-sheeting" routines which systematically distort the map to achieve the desired cartographic projection.

Processing Accuracy

Processing accuracy depends primarily upon the fineness of the grid used to represent map images during numerical calculations, such as, the tonnage of coal underlying a specified area. The computation of map area contained in a grid cell or picture elemen (pixel) is obtained via a correlation between transects on the original base map and locationally analogous transects on the digitized version. The resulting measure is expressed in linear map units per pixel side, and subsequently converted to map area units per square pixel. In the analysis of the Herrin No. 6, the area of one pixel was equivalent to 0.154 sq mi on the base map. Figure B-1 gives an indication of pixel size, and consequently, the resolution achieved in this analysis.

Accuracy of the Herrin No. 6 Analysis

Two accuracy checks were applied to the results of the Herrin No. 6 analysis, namely, comparisons of computed versus reported surface area and coal tonnage. In each case, the results were encouraging. The surface area comparison was made for the entire state of Illinois,

revealing a -0.18 percent difference between the tabulated value of 56,400 sq mi and the computed value of 56,300 sq mi. A similar high degree of accuracy has been found in other IBIS applications.

In the second accuracy check, a comparison was made between the IBIS determined tonnage estimates and the Herrin No. 6 tonnage reported in the 1976 Keystone Coal Industry Manual. Since terminology is important to adequately define what is being measured, a few definition statements are necessary. The U.S. Bureau of Mines and the U.S. Geological Survey define a resource as a concentration of naturally occurring solid, liquid, or gaseous materials in or on the earth's crust in such a form that economic extraction of a commodity is currently or potentially feasible (Averitt, 1975).

The classification system for resources adopted by these agencies is based on the degree of certainty about the existence of the materials

Figure B-1. An Example of Map-Image Format at the Level of Individual Picture Elements: Herrin No. 6 Structure

and the economic feasibility of recovering them. Thus, hypothesized undiscovered resources are distinguished from identified resources whose location, quality, and quantity are drawn from geologic evidence. That portion of the identified resource from which a usable mineral and energy commodity can be economically and legally extracted at the time of determination is classified as a reserve.

The Herrin No. 6 analysis incorporated both identified and undiscovered resources in the tonnage estimates. The tonnage data were derived from a Herrin No. 6 thickness map published in Willman, et al. (1975). The data from Keystone (1976) also includes all categories of coal resources, plus coal produced as of January 1, 1975. However, the Keystone estimates of resources exclude strippable coal which is less than 18 inches thick and under more than 150 feet of overburden, and deep coal less than 28 inches thick. Willman's data incorporate no restrictions on thickness.

In the Herrin No. 6 analysis, coal tonnages were determined for four thickness intervals:

Interval Limits, in.	Average Thickness Used in Calculations, in.
0-30	15
31-60	45
61-84	72
85 +	92

The average value used in tonnage calculations for the first three intervals is merely the arithmetic mean of the interval limits. The value of 92 inches for coal over 84 inches was based on an aggregate assessment of the seam description in Willman, et al. (1975), plus other published data on the Herrin No. 6 seam.

There is a considerable difference between the 64.8 billion tons of Herrin resource estimated by Keystone (1976) and the 98.5 billion tons which resulted from the image processing analysis reported here. Examination of Table B-1, which provides a county-by-county comparison, indicates that in 57 out of 64 coal bearing counties the IBIS tonnage estimate was higher than the value published by Keystone. As Table B-2 indicates, percentage differences between IBIS estimates and Keystone become much less important as the tonnage within a county increases.

In the seven counties where the IBIS tonnage was less than the Keystone figure, the aggregate discrepancy was 1.06 billion tons, with 986 million tons of the deficit occurring in Gallatin, Vermilion, and White counties. Reexamination of the source data on the Herrin No. 6 in these three counties suggests that unfortunate choices for average thickness probably accounts for the bulk of the discrepancy.

Counties where the IBIS estimates exceed the Keystone tonnages present a more serious problem. However, almost 10 billion tons of the 33.7 billion ton difference can be attributed to Keystone not counting the tonnage in seams of less than 28 inches. The remainder of the discrepancy undoubtedly results from a combination of factors, of which the most prominent are reductions in resources due to:

- State regulations prohibiting coal mining in the proximity of oil and gas production;

- IBIS maps ignoring local channel sands, sand lenses and other anomalies, which have substantial impact in the aggregate;

- IBIS maps failing to reflect all of the recently mined out areas; and

- Keystone's estimates incorporating more recent information than the IBIS maps.

Of all these factors, the restrictions on mining in the vicinity of oil and gas wells is felt to be the most important. An estimated 2000-3000 sq mi area is affected by mining restrictions necessitated by oil and gas production. According to Allgaier and Hopkins (1975) the plugging of oil and gas wells in Illinois is required to protect coal miners working in the vicinity of a well. Heavily drilled areas are excluded from coal resource estimates because it is felt that protective measures taken in the past are probably not adequate, with coal under 1000 feet of overburden being especially hazardous to mine.

County	0-30"	31-60"	61-94"	95+"	IBIS Total	Keystone Total	Tonnage Difference
			Estimated Coal Resource in Millions of Tons				
Bond	--	--	2.302	0.123	2.425	2.452	-0.027
Bureau	--	1.017	--	--	1.017	0.645	0.372
Champaign	0.036	0.101	0.208	--	0.345	0.182	0.163
Christian	0.016	0.527	1.000	2.996	4.539	3.437	1.102
Clark	0.608	0.352	--	--	0.960	0.012	0.948
Clay	0.012	1.883	0.215	--	2.110	0.917	1.193
Clinton	--	--	2.951	0.358	3.309	3.233	0.076
Coles	0.519	0.651	--	--	1.170	0.154	1.016
Crawford	0.138	1.556	--	--	1.694	0.572	1.122
Cumberland	0.153	1.051	--	--	1.204	0.162	1.042
De Witt	0.607	--	--	--	0.607	0	0.607
Douglas	0.080	0.470	0.432	--	0.982	0.698	0.284
Edgar	0.666	0.578	--	--	1.244	0.721	0.523
Edwards	--	0.935	--	--	0.935	0.684	0.251
Effingham	0.266	1.231	0.161	--	1.658	0.622	1.036
Fayette	0.293	0.663	2.447	0.253	3.666	2.774	0.892
Ford	0.059	--	--	--	0.059	0	0.059
Franklin	--	--	1.315	1.765	3.080	1.933	1.147
Fulton	--	0.331	--	--	0.331	0.242	0.089
Gallitin	--	0.795	--	--	0.795	1.312	-0.517
Greene	--	0.125	--	--	0.125	0.097	0.028
Grundy	0.126	--	--	--	0.126	0	0.126
Hamilton	--	0.676	2.033	--	2.709	2.612	0.097
Henry	0.234	--	--	--	0.234	0.260	-0.026
Jackson	--	--	--	0.306	0.306	0.204	0.102
Jasper	0.001	1.573	0.999	--	2.573	1.862	0.713
Jefferson	0.007	0.938	1.795	0.246	2.986	2.700	0.286
Jersey	--	0.204	--	--	0.204	0.071	0.133
Knox	--	0.335	--	--	0.335	0.214	0.121
La Salle	0.165	0.319	--	0.069	0.553	0.217	0.336
Lawrence	--	1.587	--	--	1.587	1.187	0.400
Livingstone	1.379	0.081	--	--	1.460	0.355	1.105
Logan	0.641	--	--	--	0.641	0	0.641
Macon	0.633	0.692	0.001	--	1.326	0.163	1.163
Macoupin	--	1.094	3.511	0.931	5.536	3.932	1.604
Madison	--	0.090	3.341	--	3.431	1.918	1.513
Marion	0.246	1.121	1.029	--	2.395	1.216	1.179
Marshall	0.297	0.271	--	--	0.568	0.010	0.558
Mc Lean	1.280	--	--	--	1.280	0	1.280
Menard	0.277	--	--	--	0.277	0	0.277
Monroe	--	--	--	--	0	0.007	-0.007
Montgomery	--	--	1.057	3.211	4.268	3.721	0.547
Morgan	0.002	1.655	0.041	--	1.698	0.622	1.076
Moultrie	0.348	0.385	--	--	0.733	0.356	0.377
Peoria	--	1.120	--	--	1.120	1.044	0.076

Table B-1. County Coal Tonnages for the Herrin No. 6 Seam: IBIS Results Compared with Keystone (1976) Estimates (contd)

	Estimated Coal Resource in Millions of Tons						
County	0-30"	31-60"	61-84"	85+"	IBIS Total	Keystone Total	Tonnage Difference
Perry	--	--	2.025	0.509	2.534	2.107	0.427
Piatt	0.107	1.556	--	--	1.663	0	1.663
Putnam	0.023	0.465	--	--	0.488	0.079	0.409
Randolph	--	--	0.417	--	0.417	0.424	-0.007
Richland	--	1.564	0.083	--	1.647	1.192	0.455
Saline	--	0.330	1.091	--	1.421	1.328	0.093
Sangamon	0.652	0.765	1.078	1.083	3.578	2.140	1.438
Scott	--	0.038	--	--	0.038	0.006	0.032
Shelby	0.603	0.842	0.576	0.535	2.554	1.184	1.370
St. Clair	--	--	1.225	1.944	3.169	2.279	0.890
Stark	--	0.550	--	--	0.550	0.428	0.122
Tazewell	--	0.226	--	--	0.226	0.070	0.156
Vermilion	0.016	0.438	0.108	--	0.562	0.698	-0.136
Wabash	--	0.930	--	--	0.930	0.576	0.354
Washington	--	--	2.270	1.303	3.573	3.462	0.111
Wayne	--	2.809	0.136	--	2.947	2.350	0.597
White	--	2.028	--	--	2.028	2.364	-0.336
Williamson	--	--	0.465	1.080	1.545	0.635	0.910
Woodford	0.036	--	--	--	0.036	0	0.036
Totals	10.290	37.184	34.314	16.722	98.510	64.840	33.670

Table B-2. Discrepancies Between the Keystone Tonnage Estimates and Results of the IBIS Analysis, as a Function of Indicated County Tonnage

	Amount of Coal Tonnage within a County (Keystone, 1976) -- million tons					
	0-100	101-500	501-1,000	1,001-2,500	2,501 +	Totals
Aggregate of Keystone County Estimates (million tons)	352	3,361	7,390	27,868	25,871	64,842
Aggregate Difference between Keystone Estimates and IBIS Analysis (million tons)	6,946	5,603	6,985	9,416	4,715	33,665
Aggregate Difference as a Percent of Keystone Estimate	1,973	167	95	34	18	52