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Guides to exploration for coal deposits in Permo-Carboniferous rocks in São Paulo State, Brazil

by

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INTRODUCTION

A 2-week visit (July 3-18, 1982) was made to São Paulo, Brazil, to advise the Carvão Group of Pró Minério, Instituto de Pesquisas Tecnologicas (IPT) on exploration for economic deposits of coal in Permo-Carboniferous rocks in the State of São Paulo (fig. 1). The objective was to use depositional modeling methods as a guide for coal exploration. Lithologic variations, internal structures, trace fossils, and facies sequences and associations of strata were observed along road cuts and drainages in the vicinities of Piracicaba, Cirquilho, Tiete, Tatui, Capão Bonito, Taquarituba, Itaporanga, Buri, Itapeva, and Itapetininga (fig. 1). Data for the modeling study of the coal-bearing Itararé Formation and lower parts of the Tatui and Rio Bonito Formations (fig. 2) were collected during an 8-day field trip and during office discussions with five Pró Minério geologists headed by Mr. Siuzi Nakano (Chief Geologist, Carvão Group). A separate field trip was made to study a thick accumulation of peat along the floodplain of Rio Paraiba near Taubate (fig. 1). Full-diameter cores from drill holes in the vicinity of Buri were also examined. A summary of the field trip and the discussions was presented to Dr. Erasto Boretti de Almeida, Vice President, Pró Minério, on the last day of the visit. This report is an expansion of the administrative report submitted to Dr. Almeida and Mr. Nakano.

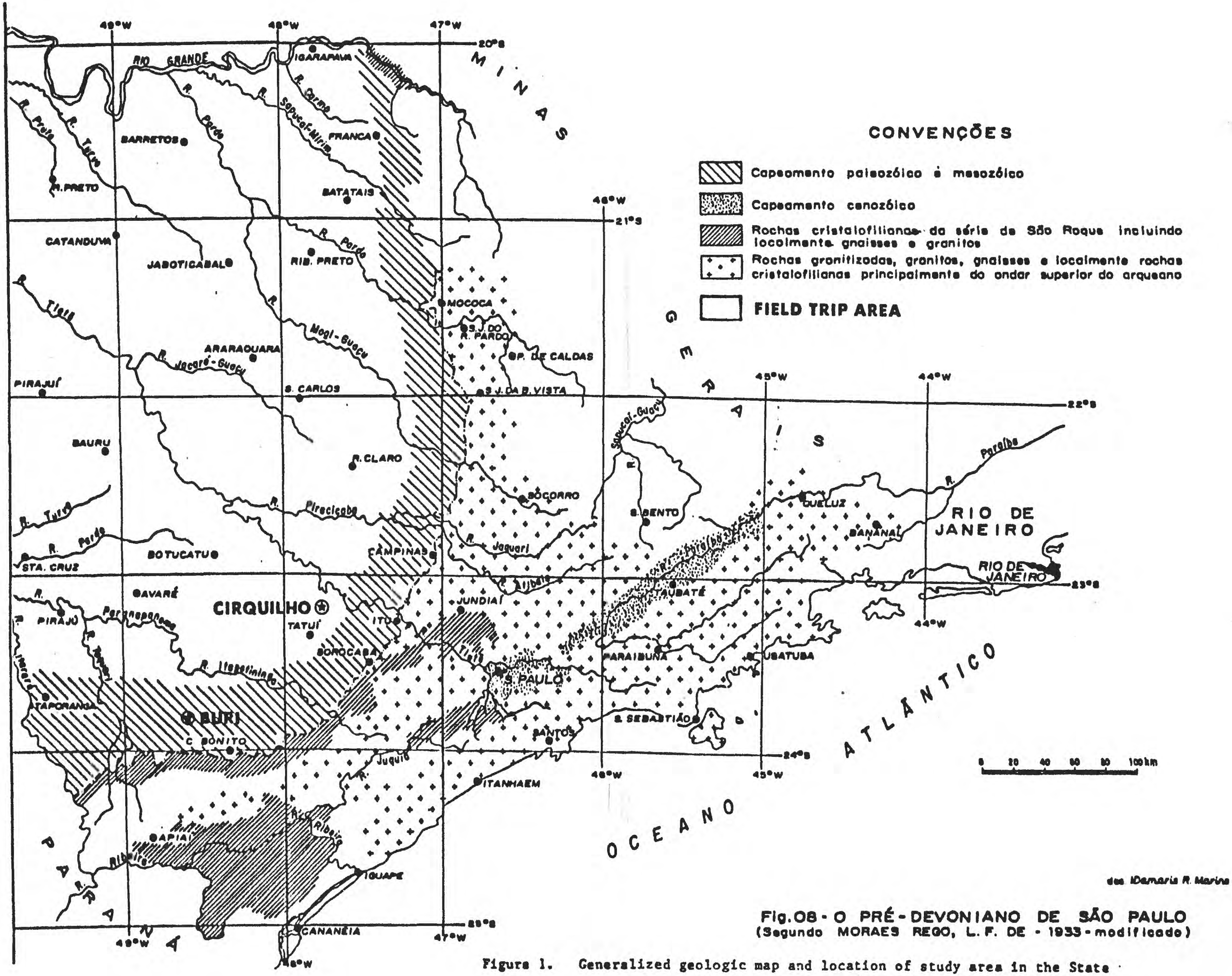
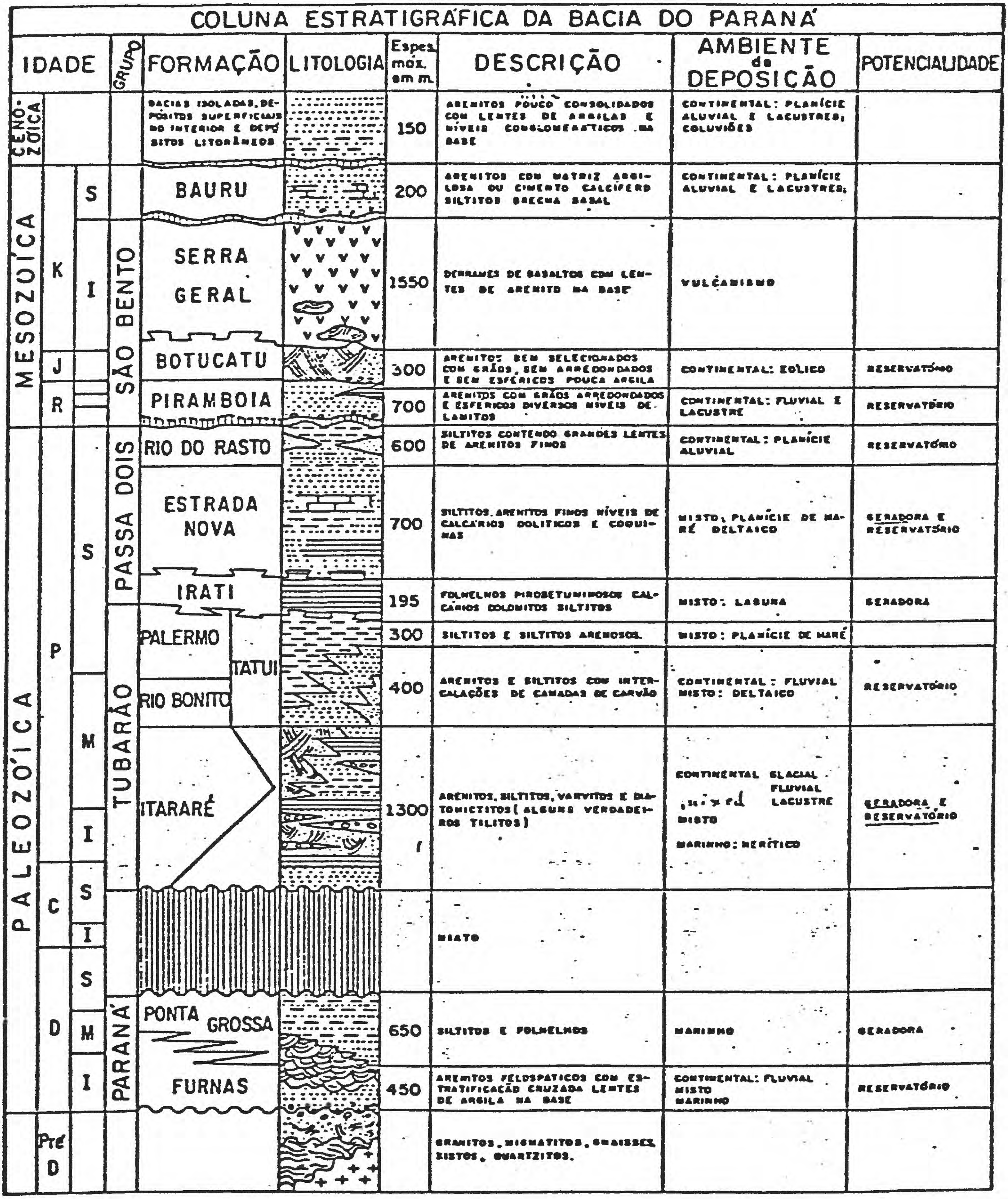


Figure 1. Generalized geologic map and location of study area in the State of Sao Paulo, Brazil. Modified from IPT, 1981.



COLUNA ESTRATIGRÁFICA DA BACIA DO PARANÁ

IDADE			GRUPO	FORMAÇÃO	LITOLOGIA	Espes. máx. em m.	DESCRIÇÃO	AMBIENTE de DEPOSIÇÃO	POTENCIALIDADE
CENOZÓICA				BACIAS ISOLADAS, DEPÓSITOS SUPERFICIAIS DO INTERIOR E DEPÓSITOS LITORÂNEOS		150	ARENITOS POUCO CONSOLIDADOS COM LENTES DE ARGILAS E NÍVEIS CONGLOMERÁTICOS NA BASE	CONTINENTAL: PLANÍCIE ALUVIAL E LACUSTRES; COLUVIÕES	
MESOZÓICA	K	S		BAURU		200	ARENITOS COM MATRIZ ARGILOSA OU CIMENTO CALCIFERO SILTITOS BRECHA BASAL	CONTINENTAL: PLANÍCIE ALUVIAL E LACUSTRES;	
		I	SÃO BENTO	SERRA GERAL		1550	DERRAMES DE BASALTOS COM LENTES DE ARENITO NA BASE	VULCANISMO	
	J			BOTUCATU		300	ARENITOS BEM SELECIONADOS COM GRÃOS, BEM ARREDONDADOS E BEM ESFÉRICOS POUCA ARGILA	CONTINENTAL: EÓLICO	RESERVATÓRIO
	R			PIRAMBOIA		700	ARENITOS COM GRÃOS ARREDONDADOS E ESFERICOS DIVERSOS NIVEIS DE LAMITOS	CONTINENTAL: FLUVIAL E LACUSTRE	RESERVATÓRIO
PALEOZÓICA	P	S	PASSA DOIS	RIO DO RASTO		600	SILTITOS CONTENDO GRANDES LENTES DE ARENITOS FINOS	CONTINENTAL: PLANÍCIE ALUVIAL	RESERVATÓRIO
				ESTRADA NOVA		700	SILTITOS, ARENITOS FINOS NÍVEIS DE CALCÁRIOS OOLITICOS E COQUINAS	MISTO; PLANÍCIE DE MARÉ DELTAICO	GERADORA E RESERVATÓRIO
				IRATI		195	FOLHELHOS PIROBETUMINOSOS CALCÁRIOS DOLOMITOS SILTITOS	MISTO: LAGUNA	GERADORA
			TUBARÃO	PALERMO TATUI		300	SILTITOS E SILTITOS ARENOSOS	MISTO: PLANÍCIE DE MARÉ	
		M		RIO BONITO TATUI		400	ARENITOS E SILTITOS COM INTERCALAÇÕES DE CAMADAS DE CARVÃO	CONTINENTAL: FLUVIAL MISTO: DELTAICO	RESERVATÓRIO
	P C	M I S		ITARARÉ		1300	ARENITOS, SILTITOS, VARVITOS E DIAMICTITOS (ALGUNS VERDADEIROS TILITOS)	CONTINENTAL GLACIAL FLUVIAL LACUSTRE mixed MISTO MARINHO: NERÍTICO	GERADORA E RESERVATÓRIO
	C D	I S					HIATO		
	D	M	PARANÁ	PONTA GROSSA		650	SILTITOS E FOLHELHOS	MARINHO	GERADORA
		I		FURNAS		450	ARENITOS FELDSPATICOS COM ESTRATIFICAÇÃO CRUZADA LENTES DE ARGILA NA BASE	CONTINENTAL: FLUVIAL MISTO MARINHO	RESERVATÓRIO
	Pré D						GRANITOS, MIGMATITOS, GNAISSES, XISTOS, QUARTZITOS.		

Figure 2. Composite stratigraphic section of the Precambrian and Paleozoic rocks in the State of Sao Paulo, Brazil. Study interval is the Itarare Formation. Adopted from IPT, 1981.

This report was prepared for IPT, São Paulo, Brazil. The author is grateful to the following officials and geologists of IPT for their expert assistance, stimulating discussions, and gracious hospitality: Dr. Erasto Boretti de Almeida (Vice President, Pro Minerio), Mr. Siuzi Nakano (Chief Geologist, Carvão Group), Mr. Marsis Cabral, Jr. (Geologist, Carvão Group), Mr. Carlos Alberto Ciantelli, Jr. (Geologist, Carvão Group), Mr. Jose Francisco M. Motta (Geologist, Carvão Group), and Ms. M. Rita Caetano Chang (Consulting Geologist, Rio de Janeiro). The kind and essential assistance of support personnel of IPT is also gratefully acknowledged.

DEPOSITIONAL MODELING METHODS FOR COAL EXPLORATION

Depositional modeling as a method of identifying areas likely to contain minable coal resources must be approached logically and systematically. The first phase of exploration should consist of the following:

1. Identification of potential coal resource areas by search of the literature, examination of outcrops, and exploratory drilling.
2. Geologic reconnaissance mapping (1:250,000 scale) to establish areal extent, distribution of rock types, and structural features of coal basins or coal fields.
3. Detailed geologic mapping (1:25-50,000 scale) of known coal basins or coal fields that contain near-surface deposits of coal.
4. Establishment of a general lithologic sequence of the coal-bearing strata.
5. Reconnaissance exploratory drilling.

The second phase of exploration should consist of a step-by-step synthesis of stratigraphic and sedimentologic information as follows:

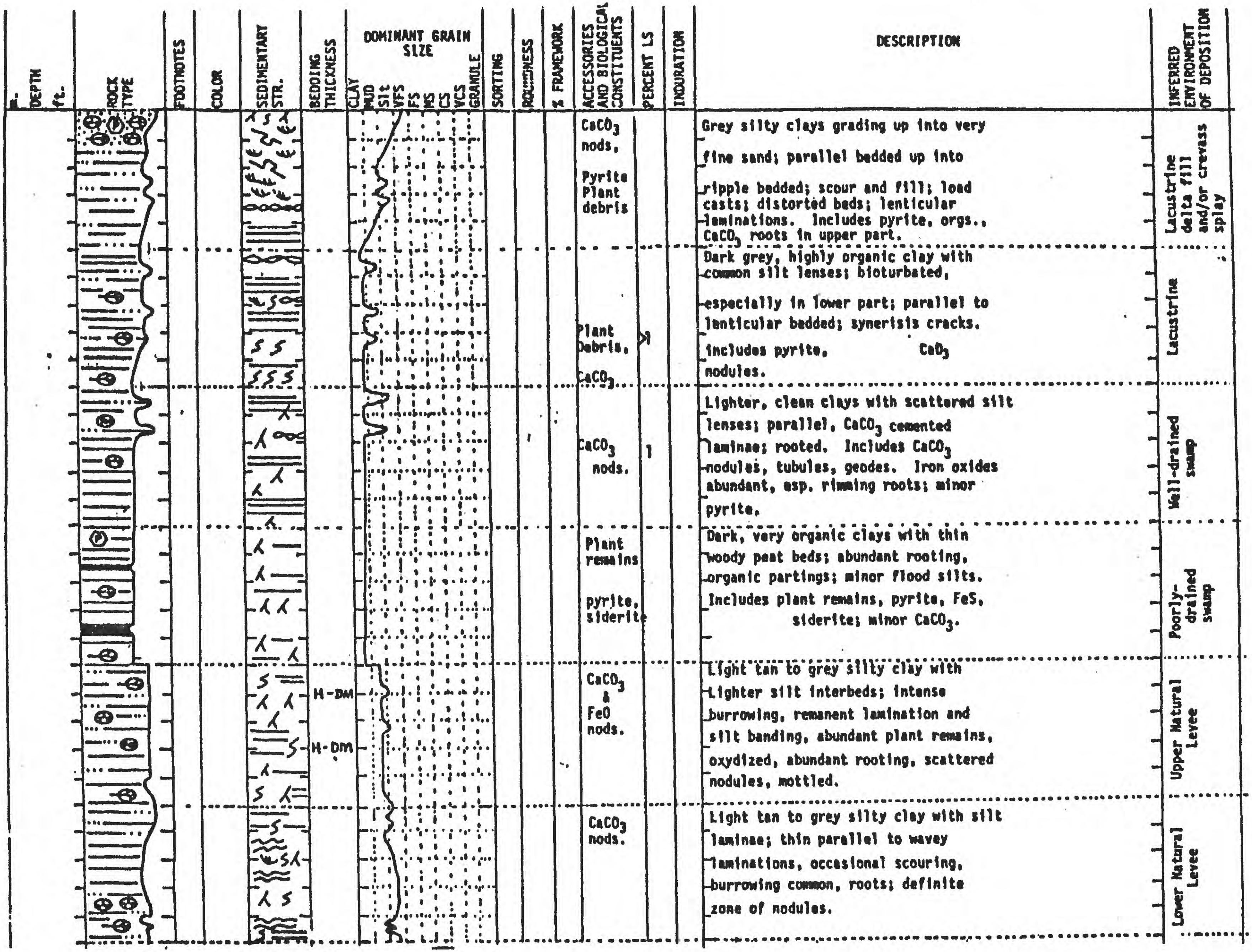
1. Synthesis of stratigraphic (local and regional framework) data.
2. Synthesis of sedimentologic (physical and biological properties) data.

3. Synthesis of facies (sequences, associations, and relationships) data.
4. Facies mapping and paleogeographic reconstruction.

The tasks of the first phase of the exploration were partly completed by the initial geological work of Prô Minèrio prior to my visit. Included were stratigraphic and sedimentologic investigations of the coal-bearing rocks. A remaining task to be accomplished in the first phase of exploration is detailed mapping (1:25-50,000 scale) of the coal beds known from outcrops and drilling. A topographic base map with a contour interval of 2 to 5 m should be used to show elevations, the thickness and areal extents of coal beds, and local structures in the Buri and Cirquilho coal fields. It will also facilitate projection of coal beds into unknown areas. These data can be then used for estimating coal resources. A guideline to this type of mapping is included in the Appendix. Because the data base has been compiled, only the detailed mapping remains to be done before the second phase of exploration could be implemented.

STRATIGRAPHIC SYNTHESIS

Stratigraphic data can be collected in several ways: 1) measurement of outcrop sections; 2) description of cores from exploratory drill holes; and 3) lithologic interpretation of geophysical logs from exploratory drill holes. These stratigraphic data should be compiled and recorded as graphic logs. Data from continuous cores should be plotted in graphic lithologic logs following the example in figure 3. Stratigraphic data from outcrops and data interpreted from geophysical logs should be plotted in graphic logs following the example in figure 4. These graphic logs are the principal method of constructing environmental-stratigraphic cross sections.



Grey silty clays grading up into very fine sand; parallel bedded up into ripple bedded; scour and fill; load casts; distorted beds; lenticular laminations. Includes pyrite, orgs., $CaCO_3$ roots in upper part.

Dark grey, highly organic clay with common silt lenses; bioturbated, especially in lower part; parallel to lenticular bedded; synerisis cracks. Includes pyrite, CaO_3 nodules.

Lighter, clean clays with scattered silt lenses; parallel, $CaCO_3$ cemented laminae; rooted. Includes $CaCO_3$ nodules, tubules, geodes. Iron oxides abundant, esp. rimming roots; minor pyrite.

Dark, very organic clays with thin woody peat beds; abundant rooting, organic partings; minor flood silts. Includes plant remains, pyrite, FeS, siderite; minor $CaCO_3$.

Light tan to grey silty clay with lighter silt interbeds; intense burrowing, remanent lamination and silt banding, abundant plant remains, oxydized, abundant rooting, scattered nodules, mottled.

Light tan to grey silty clay with silt laminae; thin parallel to wavey laminations, occasional scouring, burrowing common, roots; definite zone of nodules.

Figure 3. Lithologic log and inferred paleoenvironments for the Wasatch Formation Wyoming, United States. Adopted from Deutsch and others, 1979.

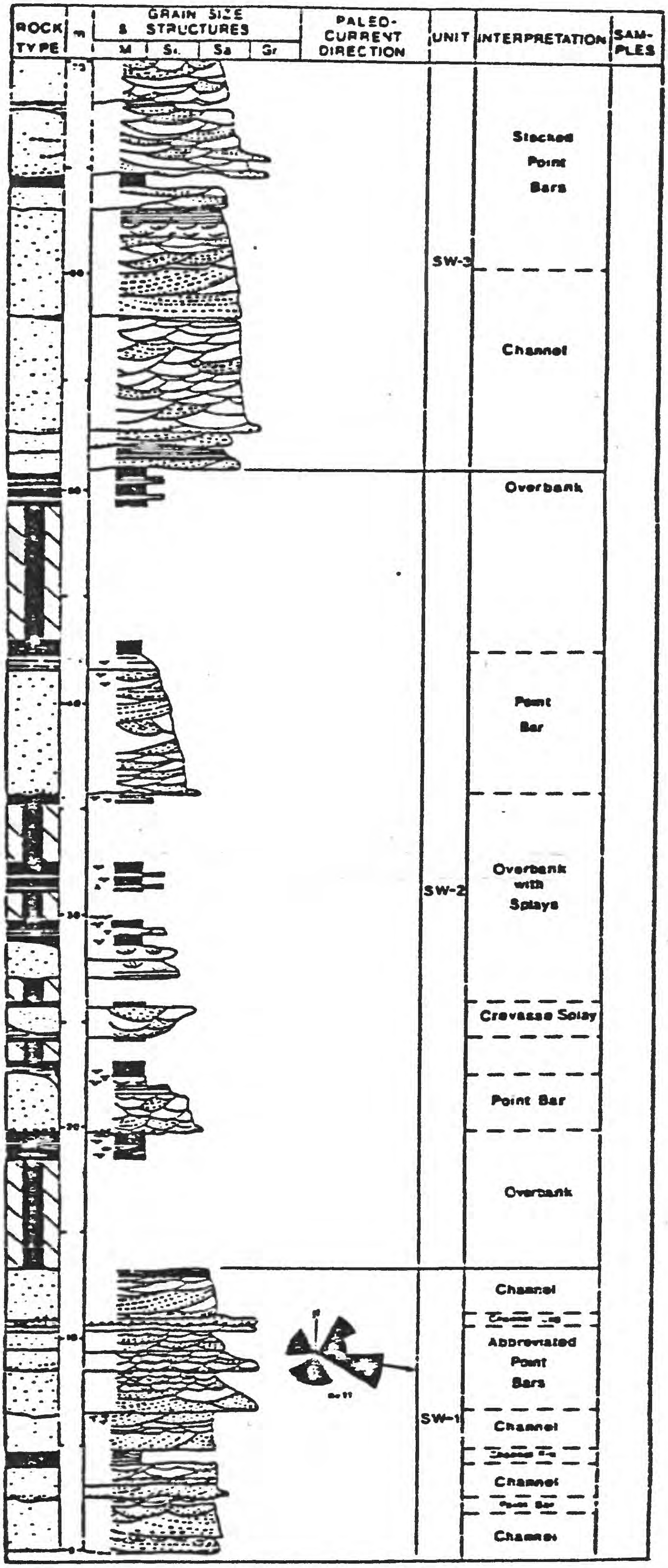


Figure 4. Detailed lithologic log and interpretation of a measured section. Parts of the core which were not recovered were not described. Adopted from Ethridge and others, 1980.

The cross-sectional panels should be constructed by using a best-fit method, which takes into consideration differential compaction and lithofacies relationships. The correlation between measured sections and core holes is made by tracing several key beds such as coal, sandstone, and limestone along the outcrop from one section to the adjacent section or by comparison of logs of core holes. If key beds are not present, a generalized facies correlation may be attempted on the basis of rock types that are deemed to be in the same stratigraphic interval (for example, lower, middle, upper parts of formations). A deltaic facies may be correlated with a fluvial facies in its landward direction and to a prodelta-offshore marine facies in its seaward direction. In more specific cases, a working facies model such as a fluvial channel sandstone may be correlated with floodplain-backswamp deposits; or in a deltaic interval, a distributary channel sandstone may be correlated with interdistributary bayfill-swamp deposits. Figure 5 is an example of the best-fit method of correlation.

Constructions of cross sections should be presented in networks of panels (e.g., west to east, north to south, northeast to southwest directions). These cross-section panels can show facies changes and 3-dimensional vertical and lateral variations of the rock types. In addition, the cross-section panels can be used to determine geographic changes in lithology with time and to prepare facies maps and paleogeographic reconstructions. Cross sections should be constructed for each local area of interest as well as for the entire region. Regional cross sections (e.g., from Itaporanga to Buri) can be established from composite stratigraphic sections. These regional cross sections are useful in determining the facies changes which must be recognized if basin facies analysis is to be successful.

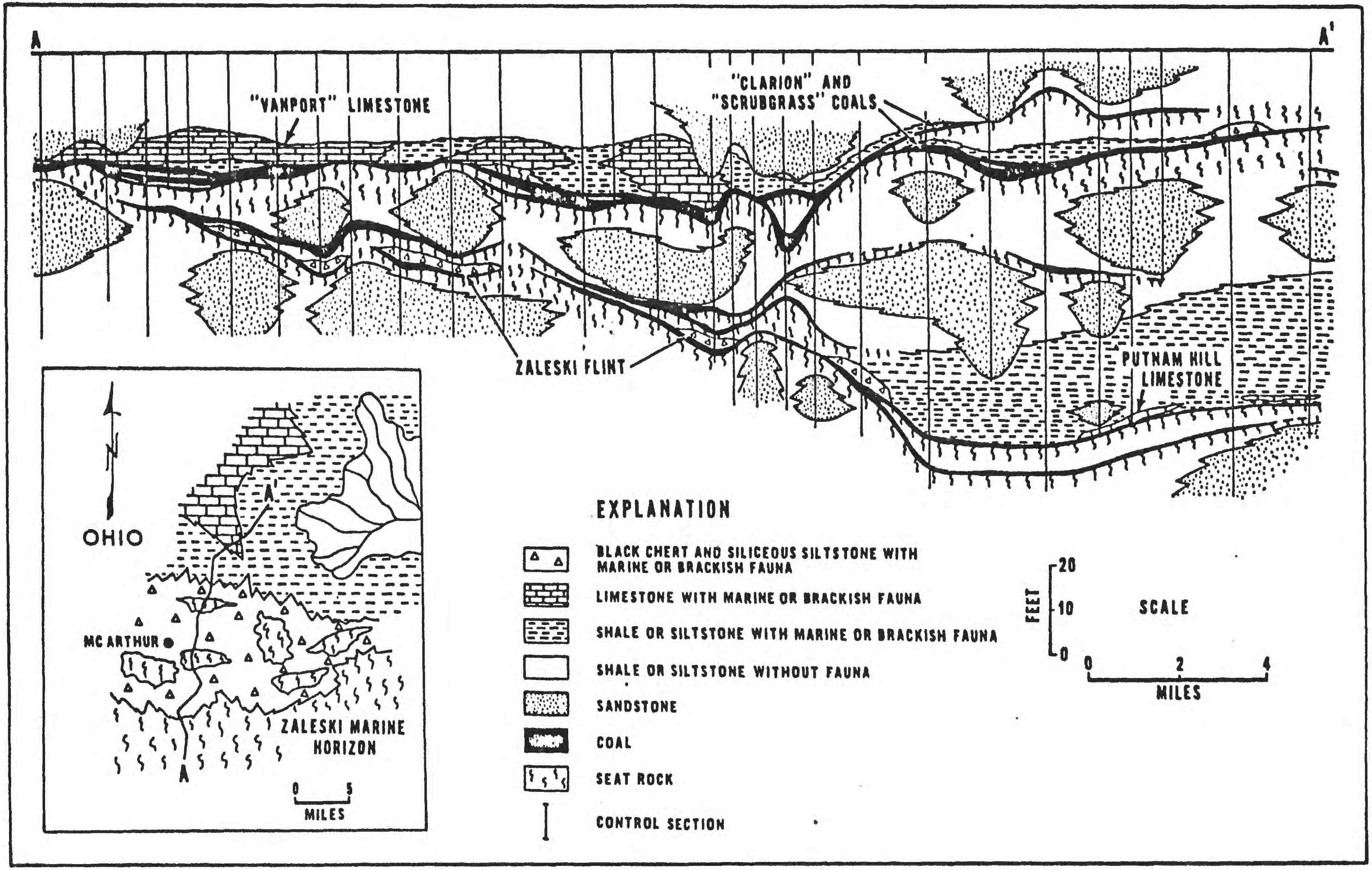


Figure 5. Environmental-stratigraphic cross section of the lower part of Allegheny Formation in Ohio, United States. Adopted from Cavaroc and Ferm, 1968.

SEDIMENTOLOGIC SYNTHESIS

Collection of sedimentologic data (table 1) on the physical and biological properties of sedimentary rocks should be integrated with the stratigraphic data. The physical properties that provide important clues to rock genesis include mineral composition, grain size, sorting, and internal structures. These petrographic features are genetically diagnostic in sandstones and can be determined from field observations and petrographic study of thin sections. The petrography of the sandstone indicates the nature of the source area of the sediments as well as the conditions of their transport. Field investigation of grain-size distribution (that is, coarsening-upward or fining-upward sequence) through a vertical section may also yield important information relative to environments of deposition. Study of internal structures consists of identification of the types of cross stratification (for example, festoon crossbeds, planar crossbeds, ripple laminae, or convolute laminae) of rocks as well as the nature of vertical arrangement of cross-stratification types (for example, festoon crossbeds grading upward into ripple lamination or vice versa, fig. 6). Internal structures of rocks including surface markings and imprints, scour marks, tool marks, and syndepositional structures are useful indicators of sedimentary processes. Syndepositional structures formed during deposition such as diapirs, mudlumps, slumps, microfaults, contorted bedding, and ball-and-pillow structures are indicative of slope processes (delta front, prodelta). Paleocurrent patterns (fig. 4) derived from cross stratifications can also be very useful in facies interpretation. Measurement of the dip of crossbeds and pebble imbrication indicate current flow and directions.

Table 1.--Sedimentological criteria for recognition of environments of deposition

Petrographic	Internal structures	Syndepositional structures	Biologic
Mineralogy	Festoon crossbeds	Diapirs	Fossil shells
Grain size	Planar crossbeds	Mudlumps	Fossil casts
Sorting	Ripple laminae	Slumps	Fossil molds
	Convolute laminae	Microfaults	Trace fossils-- horizontal and vertical burrows
		Contorted bedding	
		Ball-and-pillow structure	

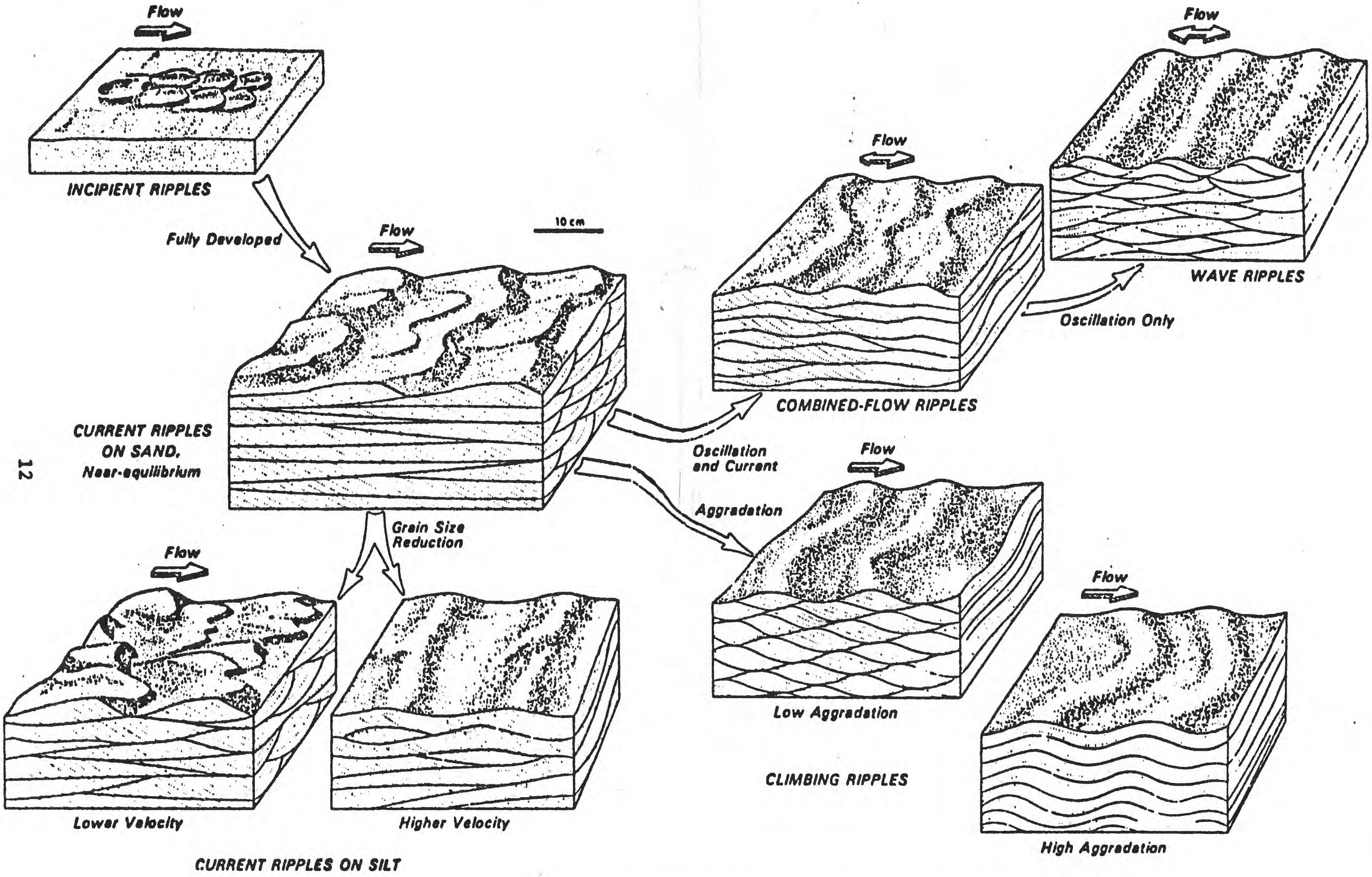


Figure 6. Cross-stratification types related to a range of flow conditions, grain size, and aggradation rate. Adopted from Harms and others, 1975.

Marine fossil remains are an important key to environments of deposition. In the absence of body fossils, trace fossils, such as burrows of bottom-dwelling animals, provide the next best biological evidence of the environment of associated sediments. The patterns of burrows, that is, whether they are horizontal or vertical, may serve to indicate the nature of water energy in the environment; bottom animal grazers that produce horizontal burrows commonly live in quiet, deep water. In contrast, animals that ingest sediments of the substrate in high-energy, shallow-water environments build vertical-escape structures.

The petrology, texture, internal structure, and biological characteristics are combined to serve as a tool in interpreting specific environments of deposition of a rock type or sequences of rock types (fig. 3). A rock type, such as a sandstone, deposited in a specific environment may be identified as channel, crevasse splay, or distributary mouth bar facies. A burrowed shale grading upward into rippled and burrowed siltstone may be identified as a bayfill facies.

FACIES SYNTHESIS

A facies is a body of rock having physical and biological properties that are characteristic of a specific environment of deposition (for example, channel, crevasse splay). A body of rock or suite of rocks thought to have formed in one environment (table 2) can be grouped as a facies (fluvial facies, deltaic facies, shallow marine facies). These different definitions and uses of facies are justified as long as one is aware of how the term is used. A facies can be characterized on the basis of its sequences, associations, and relationships.

Table 2.--Classification of environments of deposition (modified from LeBlanc, 1972).

HIERARCHY OF ENVIRONMENTS				
Continental	Alluvial (Fluvial)	Alluvial Fans (Apex, Middle & Base of Fan)	Stream Flows	Channels Sheetfloods Sieve Deposits
			Viscous Flows	Debris Flows Mudflows
		Braided Streams		Channels (Varying Sizes) Longitudinal Bar Transverse Bar
		Meandering Streams (Alluvial Valley)	Meander Belts	Channels Natural Levees Point Bars
			Floodbasins	Streams, Lakes & Swamps
	Eolian	Dunes	Costal Dunes Desert Dunes Other Dunes	Types: Transverse Seif (Longitudinal) Barchan Parabolic Dome-Shaped
Transitional	Deltaic	Upper Deltaic Plain	Meander Belts	Channels Natural Levees Point Bars
			Floodbasins	Streams, Lakes, & Swamps
		Lower Deltaic Plain	Distributary Channels	Channels Natural Levees
			Inter-distributary Areas	Marsh, Lakes, Tidal Channels, & Tidal Flats
		Fringe	Inner Delta Front	River-Mouth Bars Beaches & Beach Ridges Tidal Flats
		Distal	Outer Delta Front	
	Coastal Inter-Deltaic	Coastal Plain (Subaerial)	Barrier Islands	Back Bar, Barrier, Beach, Barrier Face, Spits & Flats Washover Fans
			Chenier Plains	Beach & Ridges Tidal Flats
			Tidal	Tidal Flats Tidal Deltas
			Lagoons	Shoals & Reefs
		Subaqueous	Tidal Channels Small Estuaries	
Marine	Shallow Marine	Shelf (Neritic)	Inner Middle Outer	Shoals & Banks
	Deep Marine	Canyons Fans (Deltas) Slope & Abyssal Trenches & Troughs		

A facies can represent a single depositional phase, such as a coarsening-upward sequence (e.g., crevasse splay, bayfill, and delta front facies) or a fining-upward sequence (e.g. channel facies). Facies may be vertically stacked such as channel-overbank facies overlain by crevasse splay and backswamp facies. These stacked facies can be cyclically repeated vertically. A facies sequence that has a single process interpretation reflects a specific environment. A coarsening-upward sequence indicates increased waterflow, and fining-upward sequence indicates decreased waterflow. Such waterflow conditions suggest a shallowing crevasse, deltaic environment, and a migrating point bar in a river channel.

Facies associations are genetically related groups that grade or merge into each other, both laterally and vertically. Thus, within an alluvial or delta plain, the facies association may consist of channel-overbank facies laterally grading on either side into floodplain deposits consisting of crevasse splay-lake-backswamp facies (fig. 7). The alluvial facies associations can be repeated upward with the same lateral arrangement; however, the channel-overbank facies may overlie the older floodplain facies. Similar patterns of facies association may be true of a group of deltaic deposits in which the distributary channel-overbank facies is flanked by interdistributary bay-crevasse splay-swamp facies. This facies association may be repeated upward in sequences in which the distributary-overbank facies overlies the older interdistributary bay-crevasse splay-swamp facies. Thus, the nature of a vertical sequence and arrangement of a group of laterally associated facies are controlled by the depositional processes.

The observation of lateral and vertical successions of facies (associations) permits appraisal of their relationships. The patterns of lateral passing of a particular facies into another and the nature of

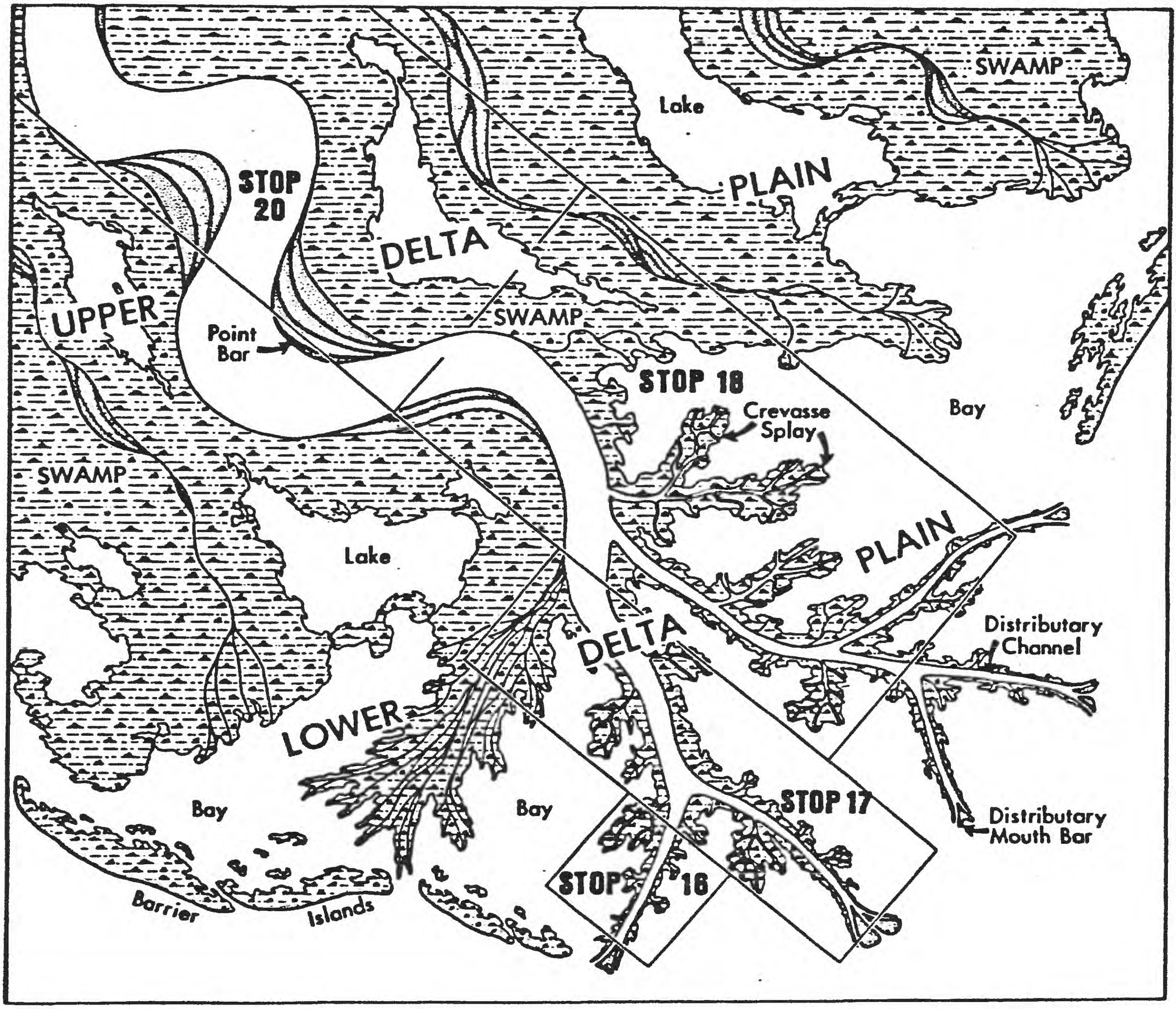


Figure 7. Diagrammatic reconstruction of coal-forming swamps and facies relationships in a delta-plain environment in Pennsylvanian rocks of West Virginia, United States. Stop numbers are itinerary for a field trip in the study area divided into 4 blocked areas. Adopted from Flores and Arndt, 1979.

arrangement of overlying and underlying facies reflect juxtaposition of interrelated depositional environments. Understanding these relationships is critical in constructing facies and paleogeographic maps.

FACIES AND PALEOGEOGRAPHIC MAPPING

Interpretations of facies sequences, associations, and relationships serve as guides in the construction of facies maps and reconstruction of the paleogeography of the study area. A facies map illustrates the gross areal distribution of observable properties (such as lithology, thickness, etc.) of different rock types within a stratigraphic interval. Facies maps are constructed by drawing lines of equal magnitude that represent measurements of rock properties or by employing different patterns to indicate major changes in the geographical distributions of lithology of rock types. Types of facies maps include isofacies or lithofacies, isolith, percentage, and ratio maps. These maps are:

1. An isofacies or lithofacies map (fig. 8) is a map that shows the distribution of one or more facies or lithologies within a designated stratigraphic interval.
2. An isolith or isopach map (fig. 9) is a facies map that depicts the net thickness of a single rock type in a given stratigraphic interval.
3. A percentage map (fig. 10) is a facies map that illustrates the relative thickness of a single rock type with respect to the total thickness of a given stratigraphic interval.
4. A ratio map (fig. 11) is a facies map that shows the proportional thicknesses of rock types, such as sandstone-shale, in a given stratigraphic interval.

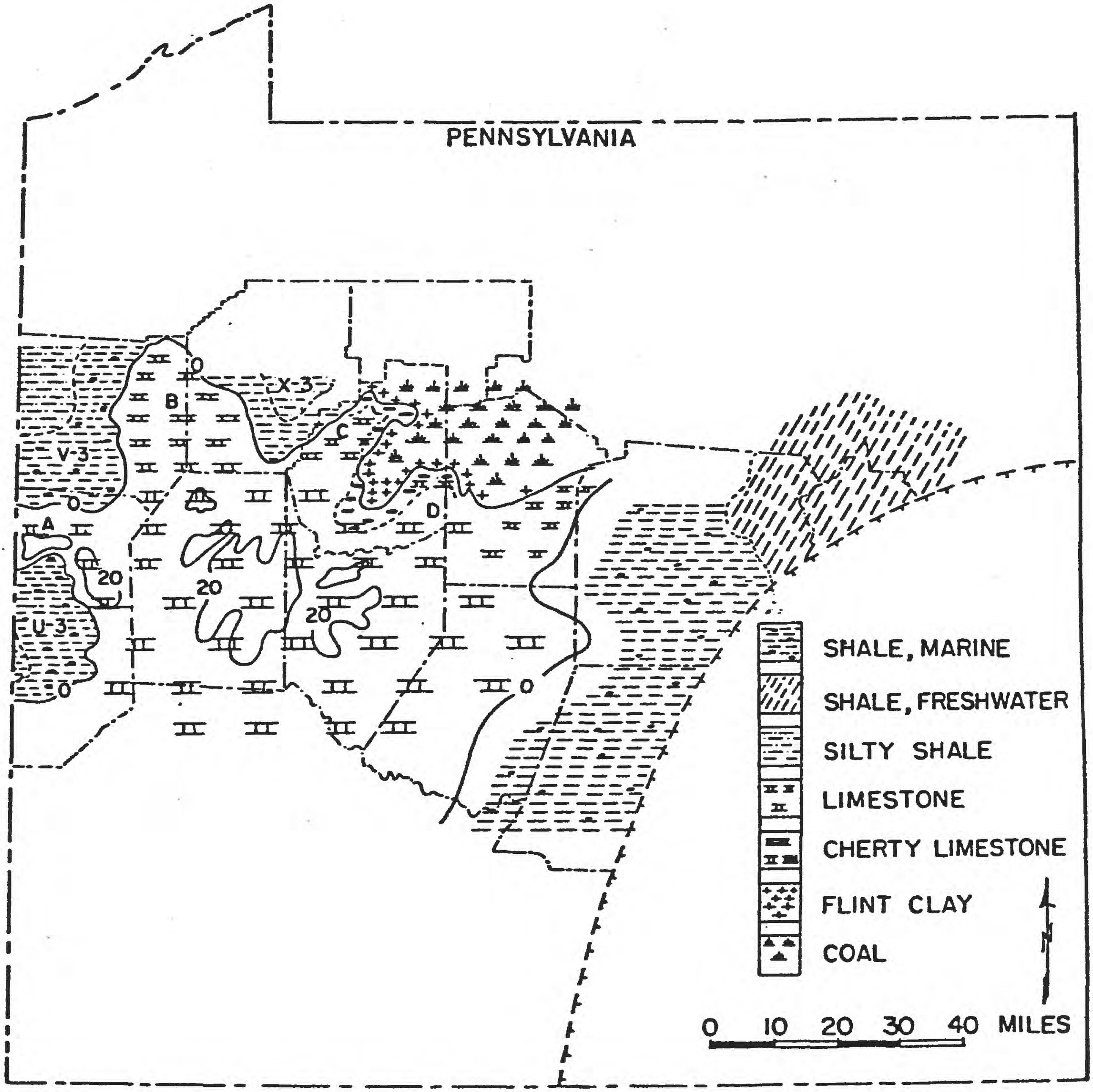
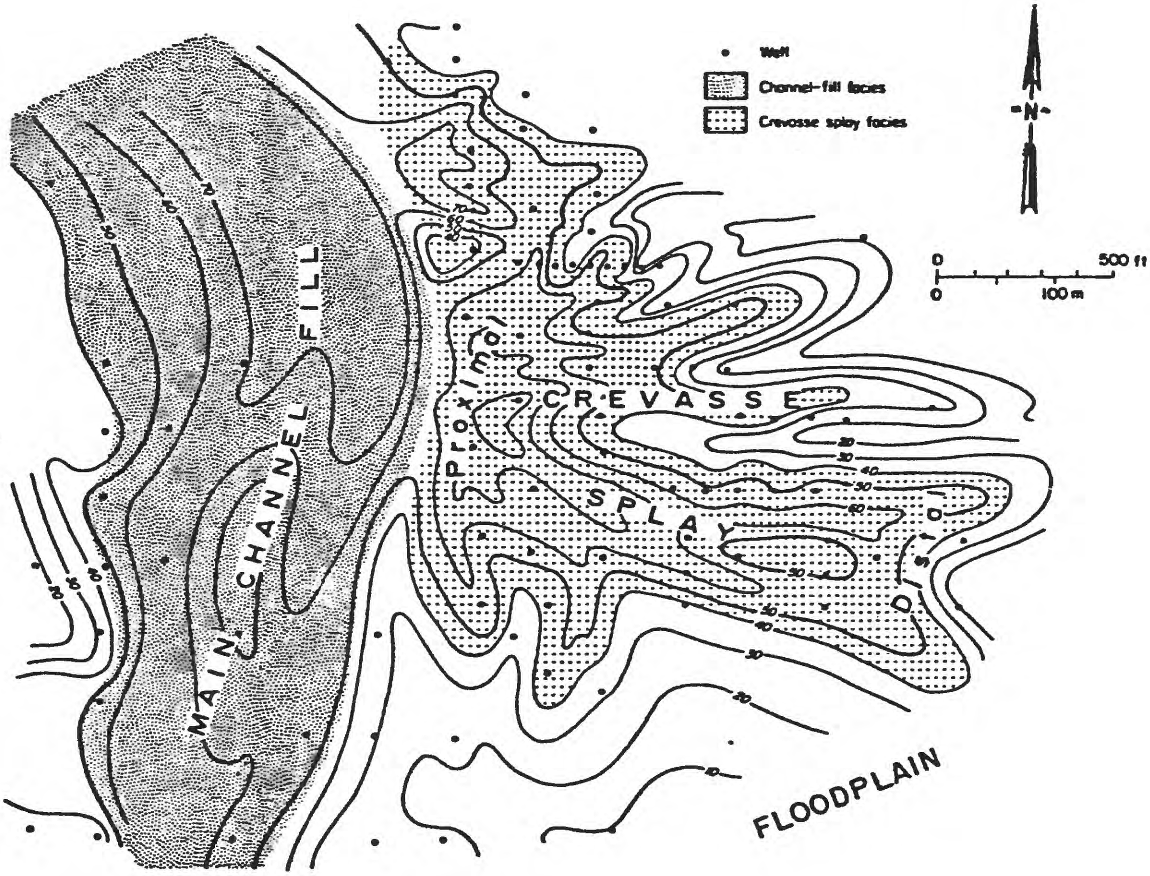


Figure 8. Facies map of lower part of Allegheny Formation in western Pennsylvania, United States. Isopach interval is 20 ft. Adopted Williams and Ferm, 1964.



Isopach interval in ft

Figure 9. Isopach and facies maps of Cenozoic fluvial deposits in the Texas Gulf coast, United States. Isopach lines are in ft. and isopach interval is 10 ft. Adopted from Galloway, 1981.

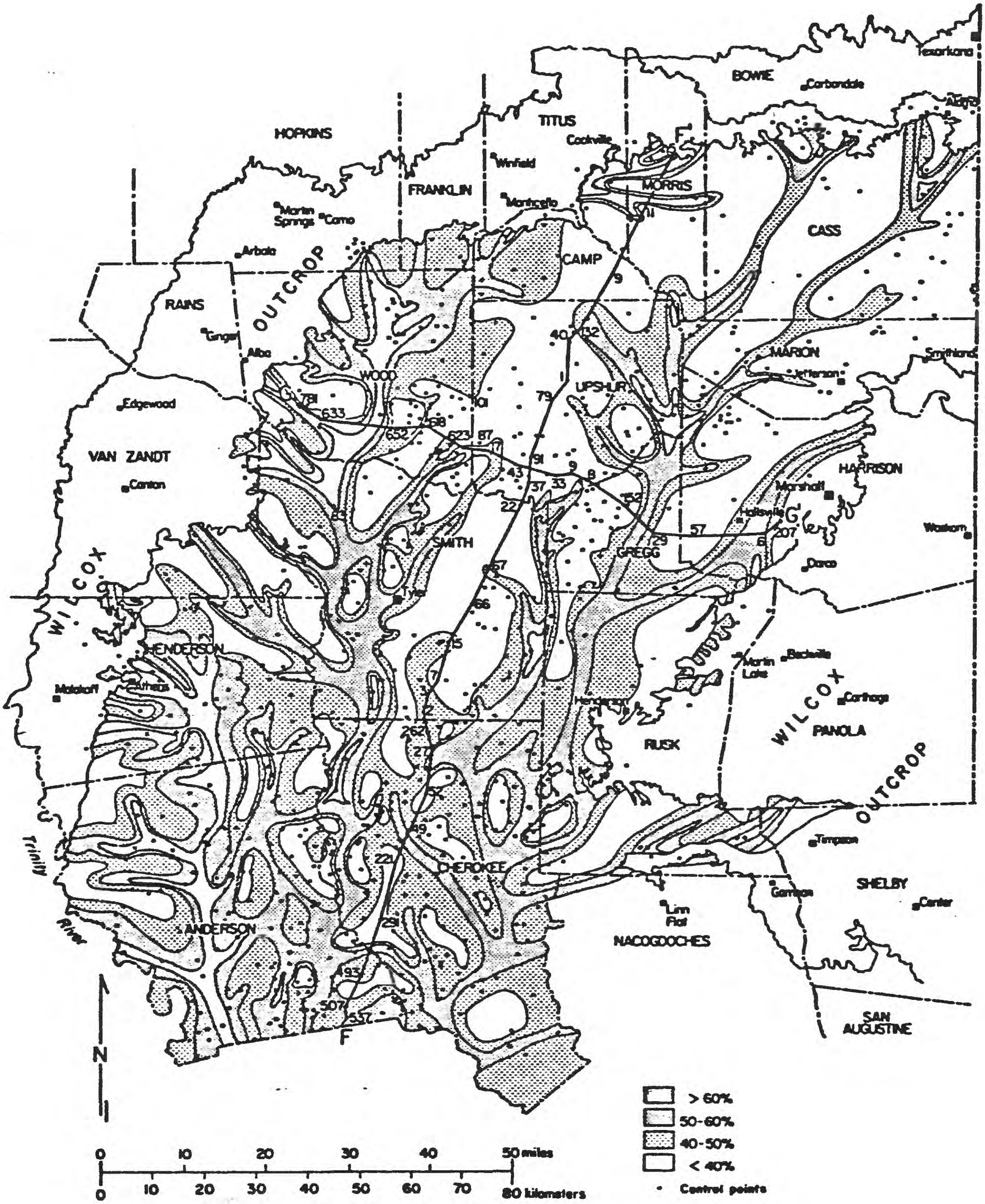


Figure 10. A sand percentage map of Eocene fluvial deposits in Texas Gulf coast, United States. Adopted from Kaiser and others, 1978. The lines of cross sections (F-F' and G-G') constructed from subsurface data (for example 7, 66, 221, etc.) are shown in this reference.

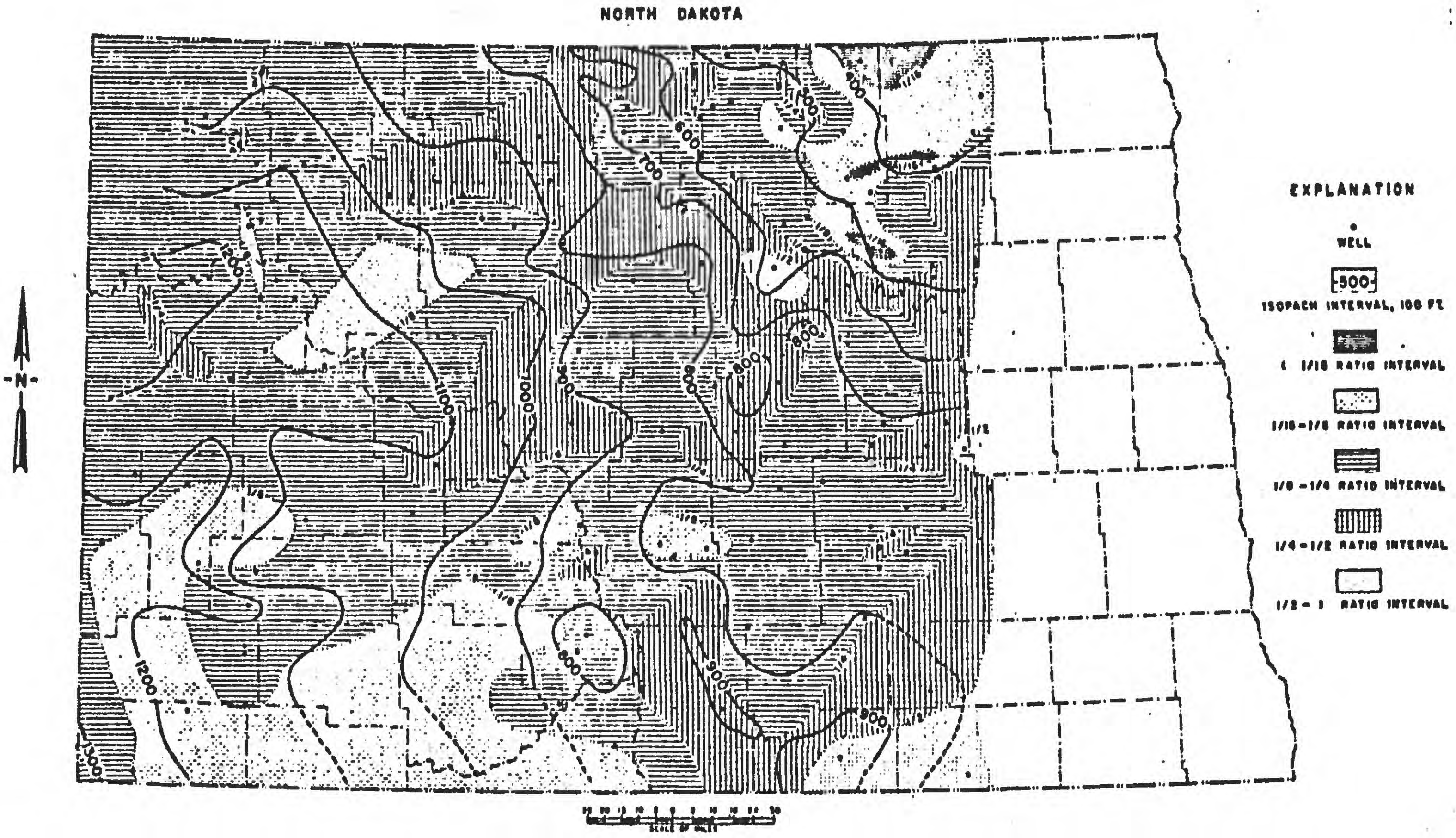


Figure 11. A ratio map of the interval from upper Cretaceous Greenhorn Formation to lower Cretaceous Lakota Formation in North Dakota, United States. Adopted from Hansen, 1955.

In contrast a paleogeographic map illustrates the reconstructed physical geography at a particular time in the geologic past. Paleogeographic maps include either the generalized former distribution of land and sea, or more specifically in local areas, the orientation and location of interrelated environmental belts such as in fluvial, deltaic, and coastal zones (fig. 12). For example, locations of channels can be identified and mapped with respect to locations of laterally equivalent floodplain or interdistributary environments. The position of the floodplain or interdistributary environments on a paleogeographic map aids in exploration for coals formed in swamps associated with these environments. In addition, it more closely defines the locations of poorly drained swamps where thick coals accumulated in the distal part of a floodplain, and of well-drained swamps where thin coals accumulated in the proximal part of a floodplain adjacent to channel areas. Thus, such coal-forming environments can be established by depositional modeling based on stratigraphic and sedimentologic data.

IMPLEMENTATION OF DEPOSITIONAL MODELING OF THE ITARARÉ FORMATION AND ASSOCIATED ROCK UNITS

The step-by-step method of depositional modeling described above can be used for the coal-bearing Itararé and Tatui-Rio Bonito Formations. The coal beds are locally concentrated in the middle-upper Itararé Formation in the Buri coal field. The uppermost part of the Itararé Formation or lowermost part of the Tatui Formation contains coal beds in the Cirquilho coal field. These two coal fields make up the major coal-prospecting areas; however, coal is present in the middle-upper part of the Itararé Formation at Monte Mor, and in the upper part of the Itararé Formation north of Itaporanga. The coal beds in the Buri and Cirquilho coal fields are as much as 55 cm thick in the Itararé Formation. The coal beds are bituminous in rank; total sulfur content

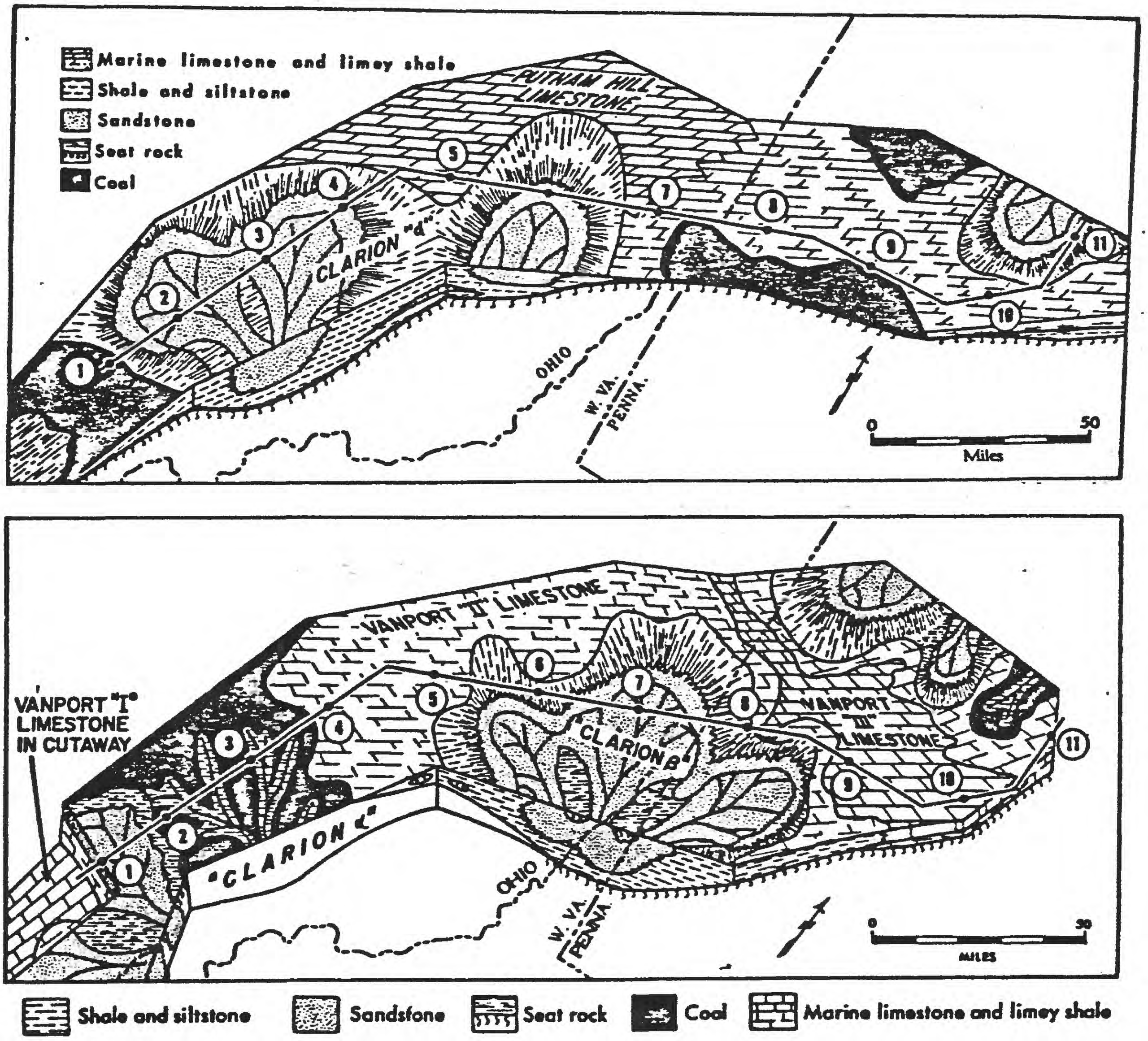


Figure 12. Coal-forming swamps in fluvio-deltaic environments of the Allegheny Formation in Ohio, Pennsylvania, and West Virginia, United States. Adopted from Ferm, 1970. The lines of cross sections constructed from stratigraphic sections (for example 1, 2, 3, etc.) are shown in this reference.

ranges from 0.4 to more than 10.5 percent, and ash is about 20 to 33 percent (these analyses based on weathered samples).

Preliminary geological work by the Carvão Group of Prô Minério, in the Buri coal field, determined that the Itararé coal beds accumulated in coastal-deltaic swamps. Data from measured sections taken during my field trip in the coal field support a deltaic origin. Outcrops along the drainage of Córrego do Fazenda Velha west of Buri indicate that two coal beds (7 and 10 cm thick) are overlain by bayfill deposits. These deposits consist of highly bioturbated shale and siltstone overlain by flaserlike, ripple-laminated silty sandstone typical of interdistributary bayfill deposits. This coarsening upward sequence is very similar in characteristics to bayfill deposits in the lower delta plain environment (fig. 7) that is characteristic of Pennsylvanian coal-bearing deposits in the northern Appalachian region of the eastern United States (for example, Kentucky, Ohio, Pennsylvania, and West Virginia; Ferm, 1970). Thus, on the basis of the similarity of the bayfill deposits and associated coal facies, it is suggested that the coals exposed in the Córrego do Fazenda Velha may have accumulated in interdistributary swamps in a lower delta plain environment. However, unlike the deltaic deposits in the northern Appalachians, the deltaic deposits in the Buri coal field contain a large amount of glacial debris as indicated by deposits of dropstones, tillites, and diamictites. The latter two deposits, which consist of pebble-, cobble-, and boulder-size Precambrian rocks floating in a sand-size matrix, can also be interpreted as deposits derived from an anastomosed fluvial system resulting from ice melting, a possible landward depositional continuum of the deltaic environment. However, the glacial influence on the depositional systems in the Itararé Formation is recorded all the way into the shallow marine-prodelta deposits which include pebble to boulder size dropstones.

In the Buri coal field, initial deposition modeling can be performed by using all measured sections, cores of drill holes, and geophysical logs as a stratigraphic data base. The first stage of modeling, which consists of stratigraphic synthesis, includes analysis of all vertical facies changes in all measured sections. In addition, all the cores should be described so that downhole lithologic changes can be plotted in graphic logs (see fig. 3). Geophysical logs also should be redescribed in as much detail as possible to record downhole lithologic changes. This work should be followed by preparation of plotted sections that incorporate lithologic logs of rock types and rock sequences (fig. 4) based on their physical properties (internal structures) and evidence of biological activity (burrows). This synthesis serves as the data base for interpreting the environment of deposition or facies of the rock types and rock sequences.

Rock types and rock sequences interpreted for each section, core, and geophysical log form a base for construction of network of cross sectional panels (see fig. 5). The depositional environments of rock types and sequences in each section, core, and geophysical log in cross section panels are then utilized to establish facies associations by comparing and contrasting the vertical and lateral variations of the sequences. The facies associations of each cross section panel, in turn, can be interrelated to other cross sectional panels in the same area, so that facies relationships (fig. 13) in the Buri coal field can be determined.

On the basis of the variations in vertical facies sequences observed in Buri, it is hypothesized that the coal beds in the vicinity of the Córrego do Fazenda Velha probably are associated with lower delta plain deposits. Previous studies of similar deltaic deposits in the central Appalachians of the United States have demonstrated that the economically thick coal beds

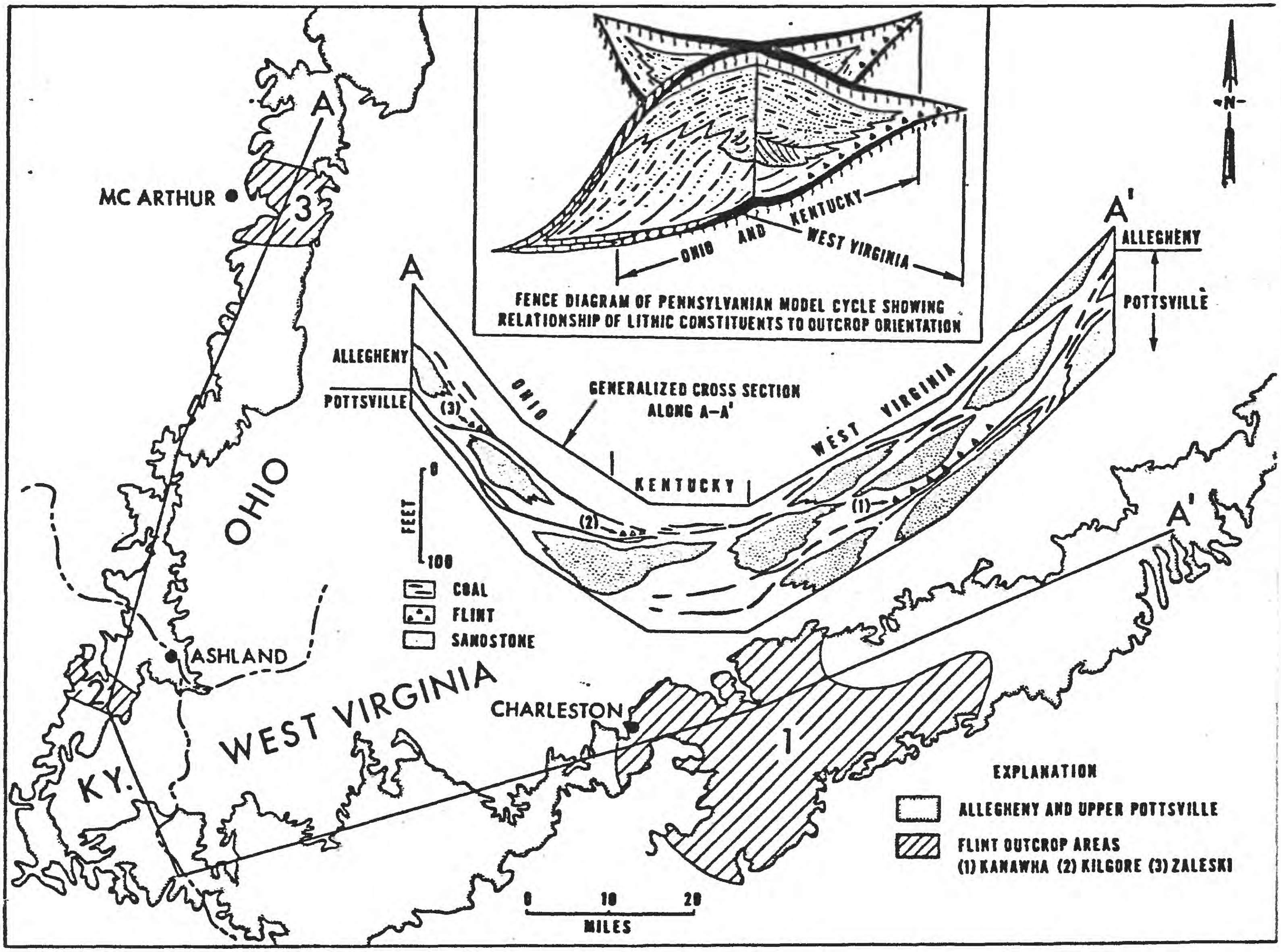


Figure 13. Facies associations and relationships of the Allegheny Formation in Ohio, Kentucky, and West Virginia, United States. Adopted from Cavaroc and Ferm, 1963.

accumulated in the upper delta plain and fluvial environments. Thus, in order to develop a predictive model to explore for minable coal beds in the Buri coal field, it is imperative to employ facies mapping and paleogeographic reconstruction in a second stage of depositional modeling. Percentage maps of sandstone (channel sandstone or channel sandstone and crevasse-splay sandstone) and ratio maps of sandstone-shale are the most important facies maps (figs. 9 and 11) as aids in the modeling work. The areas where sandstone is concentrated will delineate major areas of deposition of the sediments in channels and associated overbank areas as well as the location of floodplains (fig. 9). In contrast, shale areas will define major areas of deposition of the sediments away from channels and overbank areas. Coal beds are preferentially accumulated as thick deposits in fluvio-deltaic, poorly drained swamps (fig. 12) far removed or isolated from major detrital influx (away from channels). Identification of areas of major sandstone and shale accumulations can focus coal exploratory efforts. Isolith or isopach maps of total coal thickness (fig. 14) may delineate the coal basin. Such a map will aid in pinpointing orientation, distribution, and shape of the floodbasin in which the coal accumulated and areas of thick and thin coal, as projected from known and coal-thickness data. These different facies maps can be compared with accompanying isofacies maps that show distribution of all facies types found in interrelated environments. Paleogeographic maps, which (fig. 12) show locations of channels, interdistributary bays, and floodplains, are critical to recognizing seaward and landward related environments. Knowledge of directions of transport of sediments from crossbedding measurements may help to make this observation. Identification of seaward and landward directions from west Buri is particularly significant because the landward upper delta plain-fluvial environments are the target areas for exploration for economic

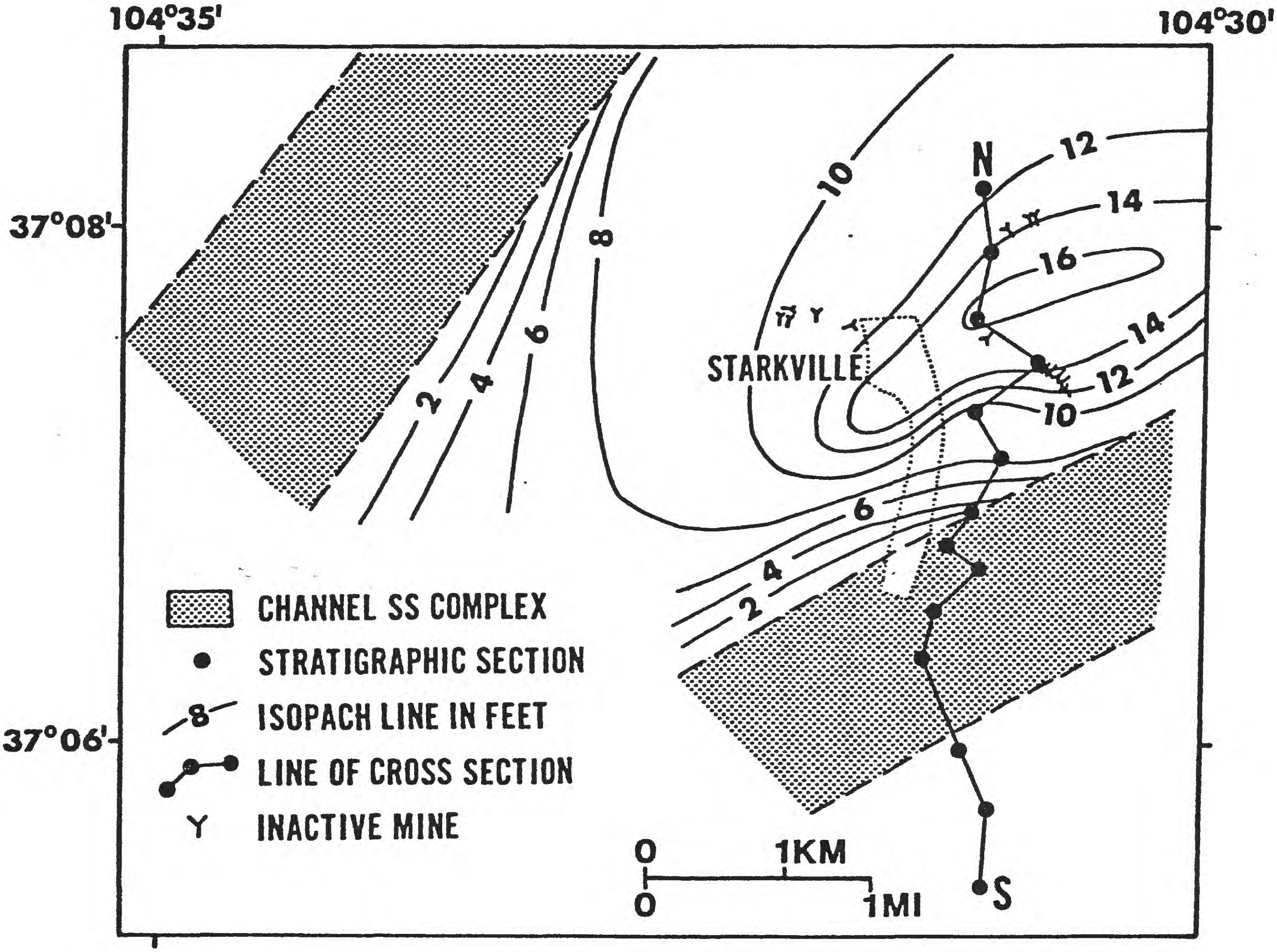


Figure 14. An isopach map of total thickness of coal beds and adjoining distributary channel sandstones in the Vermejo Formation, Raton Basin, Colorado, United States. Adopted from Flores and Tur, 1982. The line of cross section constructed from stratigraphic sections (large dots) are shown in this reference. Area bounded by small dots is the town of Starkville.

deposits of coal. Thus, the paleogeography of the area provides a basis for defining or predicting the boundaries of environments in which minable deposits of coal were formed.

The step-by-step geological method that has led to depositional modeling in the Buri coal field can be implemented in the Cirquilho coal field. However, there are fewer stratigraphic and sedimentologic data for the Cirquilho coal field than for the Buri coal field. Presently in the Cirquilho coal field, subsurface geophysical logs and cores are the only data available for depositional modeling. The geophysical logs and cores need to be reinterpreted and redescribed and plotted on graphic logs. Outcrop sections remain to be measured, described, and plotted in graphic logs.

My observations of the coal-bearing deposits in the Cirquilho coal field brought out two important aspects. Although exposures of coal have not been observed, mine reports and coal tailings from mining activity indicate the presence of a minable coal bed, perhaps as much as 50 cm thick, in the Cirquilho coal field. A few kilometers from the old mine area, rocks that probably overlie the minable coal bed are exposed in roadcuts; these rocks have interdistributary, lower delta-plain characteristics similar to those in the Buri coal field and in the central Appalachian region, United States. These two observations suggest that, on the basis of facies associations, the coal beds in the Cirquilho coal field may have been deposited in a delta plain environment. The coal deposits in the Cirquilho coal field, however, are stratigraphically higher in the Itararé, Formation or younger in age, than those in the Buri coal field. Whether or not the thick, minable coal bed at Cirquilho coal field is an upper delta plain coal can be determined by facies analysis of additional stratigraphic data. Facies modeling of the rock types in the Cirquilho coal field may help in locating areas of thick, minable coal beds and to delineate the coal body of the Cirquilho mine so that its coal resources can be estimated.

Coal exploration in the Buri coal field should begin by implementation of depositional modeling in the Itararé Formation and associated Tatui-Rio Bonito Formations and later be extended to the Cirquilho coal field. The coal-bearing area in the Monte Mor and the area north of Itaporanga, should be investigated later. The stratigraphic, sedimentologic, and facies data collected in these areas should be utilized to establish a regional facies model of the Itararé and associated formations, which in turn, may provide clues of additional coal-bearing areas.

COAL GEOCHEMISTRY AND QUALITY

The geochemistry, especially the sulfur and ash contents of the coal beds in the Buri and Cirquilho coal fields, is directly influenced by their environments of deposition. Previous studies (Williams and Keith, 1963) of mid-continent and Appalachian coal beds in the United States suggest that coal deposits overlain by brackish-water and marine rocks generally contain high amounts of sulfur (fig. 15). In contrast, coals overlain by continental rocks have low sulfur contents. The high sulfur content of coals derived from brackish-water and marine conditions is probably due to increased activity related to sulfur-reducing bacteria. The ash content of coal is controlled mainly by influx of clays and silts into the swamps from channels during flooding or from tidal currents influenced by daily marine processes. Ideally, swamps far removed from centers of active detrital sedimentation will yield lower-ash coal deposits.

It is imperative that only fresh coal samples obtained by trenching or coring be submitted for geochemical and ultimate-proximate analyses. Guidelines on collecting coal samples for geochemical and ultimate-proximate

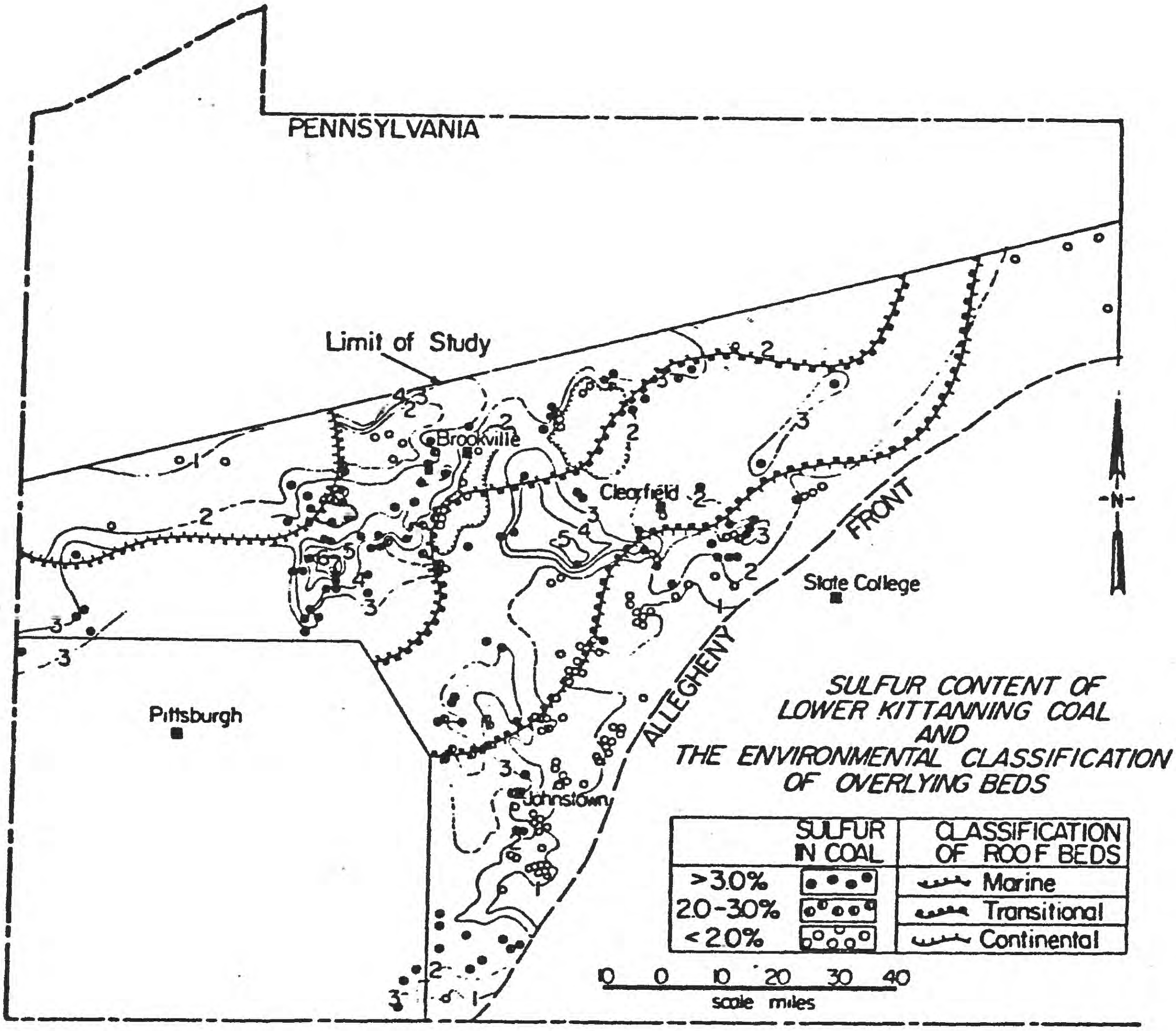


Figure 15. A map showing relationship of sulfur content of lower Kittaning coal and environments of overlying beds in western Pennsylvania, United States. Adopted from Williams and Keith, 1963.

analyses are listed in Appendix I. The analysis of the geochemistry and quality of Itararé coals in the Buri coal field as presented to the author by the Carvão Group of Pró Minério was based mainly on samples collected from outcrops. Previous studies have proved that weathered coal samples do not provide a realistic analysis because mineral matter as well as coal macerals have been exposed to prolonged oxidation. In addition, original moisture, volatile matter, and free carbon in the coal have been liberated during weathering.

APPENDIX I

GUIDELINES ON COLLECTING COAL SAMPLES FOR CHEMICAL ANALYSIS

By V. E. Swanson and C. Huffman, Jr. (1976)

Cut-and-dried instructions on the type, number, and distribution of samples to be collected cannot be given, but some general guidelines should be followed:

1. The judgment of the geologist must be applied toward obtaining samples which will be most representative of the coal bed.

2. Only samples of fresh or unweathered coal should be submitted for analysis, preferably taken from a newly exposed mine face or from cores. The samples should be shipped within a few days after collection to minimize the effect of oxidation and exposure to air on moisture content and forms of sulfur.

3. The objective should be to obtain a complete channel sample of the minable bed; if the coal bed is more than 5 feet thick, a good rule-of-thumb is to collect one sample of each 5-foot interval of coal (for example, four samples of a bed 20 feet thick). Special-type samples will also be analyzed, at the discretion of the geologist.

4. Generally, 4 to 5 pounds of coal should be included in each sample.

5. Plastic bags (10 in. x 15 in. or larger) should be used, and care should be taken to avoid contact of the coal with metal during and after collecting sample (the use of a geologic hammer, of course, cannot be avoided); sample number, date of collection, and key description should be written with a magic marker (permanent ink) on each bag, <u>and</u> on a label attached to the tie on the bag.

6. A rule-of-thumb should be never to collect a single sample from one locality--always collect two, or if a mine face is several hundred yards long,

collect three channel samples; the main reasons for this collecting of two or three samples are that short-distance composition changes can be assessed, and that possible analytical errors can be spotted.

7. Core samples of coal are better than samples of weathered coal, but contamination by drilling fluids generally makes trace-element analyses unreliable. Name and composition of drilling fluids used should accompany list of core samples submitted for analysis.

8. Shale splits, siltstone partings, or bone coal less than a few inches (5-10 cm) generally should be included in a channel sample if it is probable that this material will be included in mined coal; special samples of these materials should also be collected, based on the judgment of the geologist, to determine their contribution to abnormal element concentrations.

9. If project objectives include the obtaining of knowledge of coal shipped or of plant feed, extra care should be taken to collect at least two representative raw coal, cleaned coal, blend-pile, and conveyor-belt samples; such sample sets should include, where possible, representative samples of furnace-bottom ash, and fly ash from precipitator/scrubber units.

10. If permission to sample is obtained from a company, the offer should be made, and promise kept, to provide a copy of the analytical results to the company; where possible, obtain available analytical data from the company for comparison with your analyses.

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