STRATIGRAPHY OF THE COAL-BEARING STRATA (MIOCENE)

IN THE CARBONERAS REGION,

IZABAL, GUATEMALA.

By

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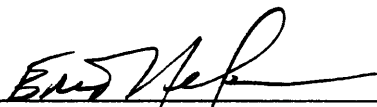
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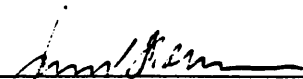
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ABSTRACT

The Lake Izabal basin comprises an area of about 2,000 square kilometers in the eastern Guatemalan Departamento de Izabal. The basin is associated with the eastern portion of the Cuilco-Chixoy-Polochic fault system; a pull-apart environment is suggested by the geologic and tectonic setting.

Paleogene sedimentary rocks within the basin and its surroundings accumulated in a complex depositional setting. Only the Oligo-Miocene Río Dulce Formation, the studied section, and other similar strata seem to be areally limited to the Lake Izabal basin. A 367 m thick section exposed along the Carboneras River was measured and interpreted to formulate a generalized model for the development of the southern margin of the basin. The section, which is dissimilar to other age-equivalent (?) formations in the region is informally named Carboneras formation. The measured section is characterized by an accumulation of sandy-argillaceous and rudaceous strata, and carbonaceous beds in a rapidly aggrading alluvial environment with predominance of flood plain deposits and lack of marine influence. Sediment input was supplied by a main longitudinal river, an isolated volcanic event, and perpendicular gravity flows and alluvial fans emanating from the surrounding mountains. A strong tectonic control on sedimentation is indicated by the attributes of the rock succession.

Powder X-ray diffraction analyses indicate that the sandy-argillaceous deposits are mainly composed of clays of the smectite group, quartz, and in some cases calcite. The rudaceous deposits were derived from the mountains bordering the edge of the basin.

Coal beds with a total thickness in excess of 15 m are present in the measured section. Physical, chemical and petrographic analyses of coal samples indicate a

maturity rank of lignite, high ash and sulfur content, and an origin derived from terrestrial plants.

The relatively low specific energy of the lignite and its high sulfur and ash content constrain its potential applications. High-scale burning of lignite without reducing its sulfur and ash content may raise environmental hazards and technical difficulties with intervening equipment. The severe climate, steep dip of the strata, and hydrologic complexities of the region suggest that opencut mining may be the only feasible high-scale mining method. Approximately five million cubic meters of lignite could be mined considering these limitations. The argillaceous deposits, some of which are interbedded with the lignite beds, are an additional economic prospect; their exploitation, in conjunction with the lignite, may increase the economic potential of any future operation.

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INTRODUCTION

Coal deposits in the Lake Izabal region of Guatemala have long been recognized as a potential fuel source. The structural and hydrological complexities, severe climate, and paucity of roads, among other factors hindered earlier attempts to explore and exploit these resources that may help to reduce the dependence of Guatemala on imported fuels, especially for industrial applications. Relatively new accesses to the region have improved the economic potential and feasibility of exploration, but the virtual absence of detailed geologic information has complicated current exploration efforts.

The Lake Izabal basin (hereafter abbreviated LIB) is intimately associated with the eastern features of the Cuilco-Chixoy-Polochic (CCP) fault (Kesler, Josey, and Collins, 1970). In western Guatemala, structural complexities of the fault have prevented the determination of the total lateral displacement along the fault. The LIB represents a pronounced change from the structural style in western Guatemala. Despite the complications caused by the dense vegetation, detailed observations of the stratigraphic succession may provide additional information to better understand the history of the fault.

The purpose of this study is to construct a detailed stratigraphic section of the coal-bearing and associated strata cropping out along a portion of the Carboneras River, interpret their depositional environments, formulate a generalized model for the development of the southern margin of the LIB, and provide a basic reference for outcrop correlations in coal exploration. The specific objectives are: 1) measurement and interpretation of the stratigraphic section; 2) identification of the main structural features of the area; 3) interpretation of the stratigraphic and structural history of the area and their relation to the regional geologic framework.

LOCATION

The study area lies in the eastern Guatemalan Departamento de Izabal, within the administrative jurisdiction of the Municipio de Livingston. The area is covered by the Instituto Geográfico Militar topographic map reference 2462 IV Castillo San Felipe, scale 1:50,000. Figure 1 is an index map showing the location of the study area.

The central part of the study area is located 11.5 km east of Lake Izabal and 7.5 km south of El Golfete. Elevations range from a few meters above sea level in the vicinity of the lake up to 200 meters at the foothills of Cerro San Gil. Quaternary gravel deposits, mainly composed of chalcedony, are present in the lower elevations, specially near the lake and its drainage. No strong geomorphic division exists between the Cerro San Gil and Montaña del Mico; the name Cerro San Gil is customarily used by the peasants in the neighborhood of the LIB, while Montaña del Mico is applied to the mountain at the Motagua valley side.

The area is accessible from the paved road leading to Modesto Mendez via a dirt road to Lote Seis and Los Angeles villages. Vehicular travel is difficult and limited, especially during the rainy part of the year. The best exposed coal outcrop is accessible by a dirt road built and maintained to transport bulk coal samples.

All of the land is privately owned; most of the forest has been cleared for pasture or rudimentary cultivation of corn and black beans.

EARLIER INVESTIGATIONS

The existence of coal in the study area has been known at least since early this century. The suggestive name "Carboneras" (colliery in English) is the name of the river that drains the area exposing the best coal beds. Compañia Centram, a subsidiary of the International Nickel Company, and other U. S.-and Canada-based geology and
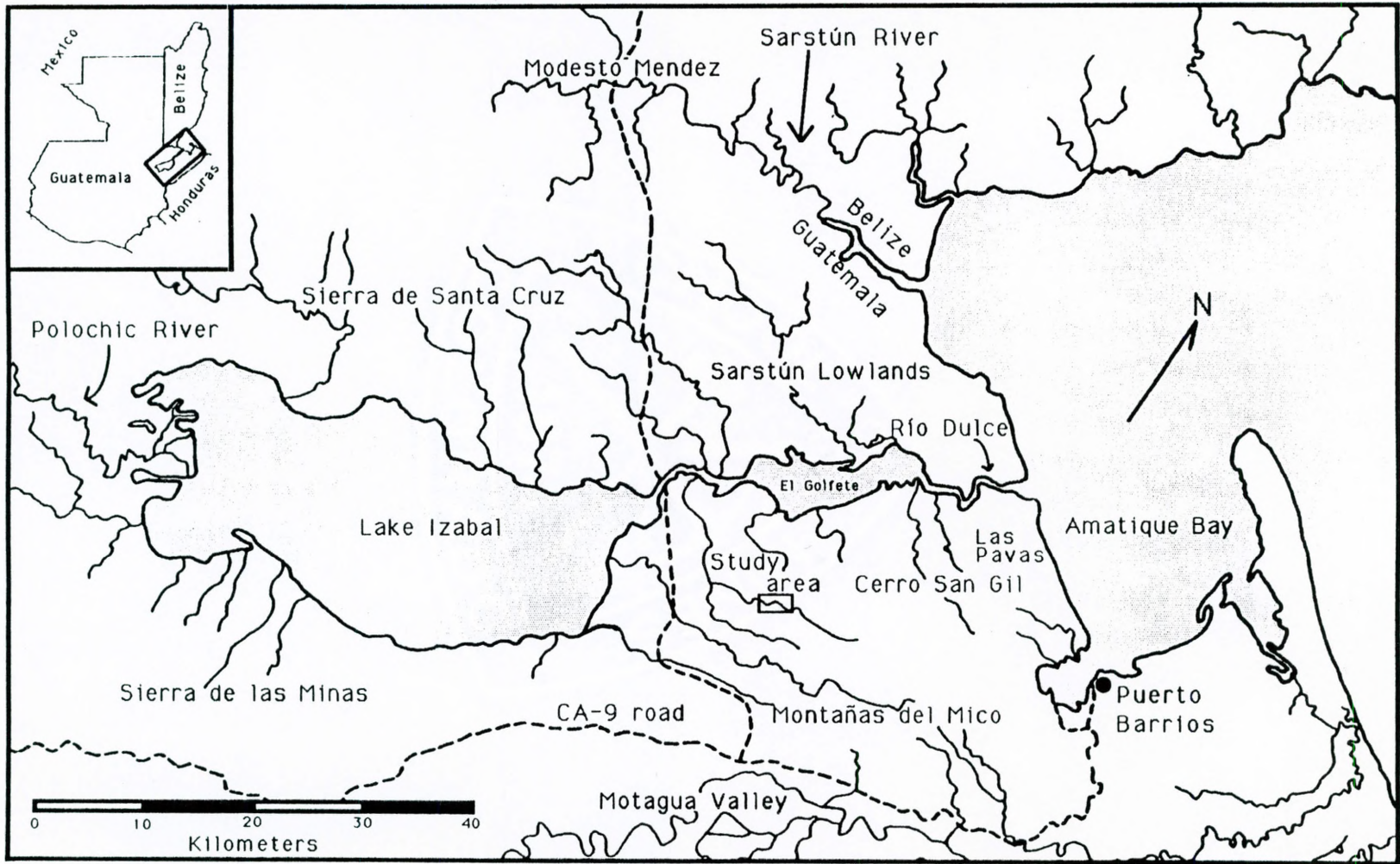
Figure 1.   Generalized index map of the Departamento de Izabal showing the geographic features mentioned in the text.

mining consulting companies conducted extensive geological reconnaissance studies during 1968, 1969, and 1970 in the Departmento de Izabal specifically directed toward the location of fuel sources. Exploration efforts were concentrated during the last two years in the Carboneras region evaluating the potential of the coal beds; the general geological features of the area are described in the annual reports rendered to the Guatemalan government. Although many companies have explored the basin for its nickel, coal, magnesite and oil resources, the resulting geological information, when existing, is confidential or highly unreliable due to its legally compulsory origin. The government of Guatemala does not have a specific "Geology" bureau and most of the geologic knowledge of the country is dispersed in the geology-related divisions of the General Directorates of Mining, Petroleum, and the Military-Geographic (IGM), Seismology, Volcanology, Meteorology and Hydrology (INSIVUMEH) Institutes. Hornos de Cal, S. A. (Horcalsa), an associated company of Cementos Progreso, is presently evaluating the coal potential of the area and this study was carried out in coordination with their efforts.

METHODOLOGY AND PROCEDURES

The geologic information concerning the area of this study was obtained through the Guatemalan Mining Bureau and private companies that kindly provided access to their files. Because of the improved road access to areas surrounding Lake Izabal, reconnaissance trips were made to verify the reported occurrences of coal-bearing strata throughout the basin and to determine the feasibility of measuring the coal-bearing section in Río Carboneras. The defined type-section and areal occurrences of the Herrería Formation, which is generally accepted as containing the lignite, were also field checked. In general, the actual characteristics of the strata in the type section and areal occurrences strongly disagree with their definition or are too poorly exposed to be studied.

FIELD METHODS

The stratigraphic section was measured using a Brunton compass and a measuring tape. Samples of each lithology were collected at the outcrops and sealed in plastic bags for further analysis and description. A hand lens and a comparison chart were used to determine rock textures. The predominance of poorly-indurated, argillaceous, and swelling rock types required repeated outcrop examinations before and after rain precipitation in order to observe the sedimentary structures and bedding features.

The existing geologic map of the locality was field-checked to assess its reliability; this was done with the help of a 1:50,000 scale topographic map and the assistance of local dwellers familiar with the area; this activity was facilitated by the extensive deforestation that has occurred since the original map was done and the severe drought that affected the region during the summers of 1988 and 1989.

LABORATORY METHODS

Thin sections were prepared from the outcrop samples collected during the field work and studied under a petrographic microscope to supplement the petrographic descriptions. Fossils collected in the field were identified by Cary Madden (proboscideans), Richard Forrester (ostracodes and charophytes), and Barry Roth (mollusks).

Other laboratory studies consisted of qualitative determination of minerals in argillaceous samples using powder X-ray diffraction methods. Chemical, physical, and petrographic analyses were made on selected lignite samples. Appendix B presents a description of the laboratory techniques and the results of the ultimate, proximate, and ash analyses; as well as selected examples of X-ray diffraction patterns of the argillaceous rocks analyzed.

GEOLOGIC AND TECTONIC SETTING

The name Lake Izabal basin (LIB) is used here to refer to the northeast trending, elongated intermontane basin containing Lake Izabal, the Río Dulce, the lake's drainage into the Amatique Bay, and El Golfete, the shallow water body in which the Río Dulce broadens halfway to the sea. The basin encompassed about 2,000 square kilometers and is located at the eastern end of the Cuilco-Chixoy-Polochic (CCP) fault zone (figure 2).

The LIB is bordered to the northwest by the Sierra de Santa Cruz; to the northeast by the Sarstún lowlands and the Cerro Sarstún; to the south by the Sierra de las Minas, Cerro San Gil, and Montaña del Mico. To the northeast, it borders the Amatique Bay of the Gulf of Honduras, a shallow marine embayment whose genetic association to the rest of the defined area is little known. To the northwest, the basin terminates in a structural wedge filled by the Polochic River delta. Figure 3 is a portion of the geologic map of the basin and the sorrounding mountains. The Lake Izabal covers approximately one third of the LIB; the main features of the contemporary LIB are listed in appendix A.

The CCP fault zone is a sharply-defined linear feature traceable across middle Guatemala (about 350 km), continuing into Mexico and the Pacific Ocean (Burkart, 1978; Schwartz, Cluff, and Donelly, 1979). The CCP, Motagua, and probably the Jocotán-Chamelecón fault systems are considered to accommodate the displacements between the North American and Caribbean plates (Schwartz, Cluff, and Donelly, 1979) but the strong east-west component in the strike of other fault systems in Guatemala, Belize, Honduras, and Nicaragua suggest that the strains have been accommodated in a broader area. The CCP, Motagua, and Jocotán-Chamelecón fault systems are also thought to be the landward extension of the Cayman trough.
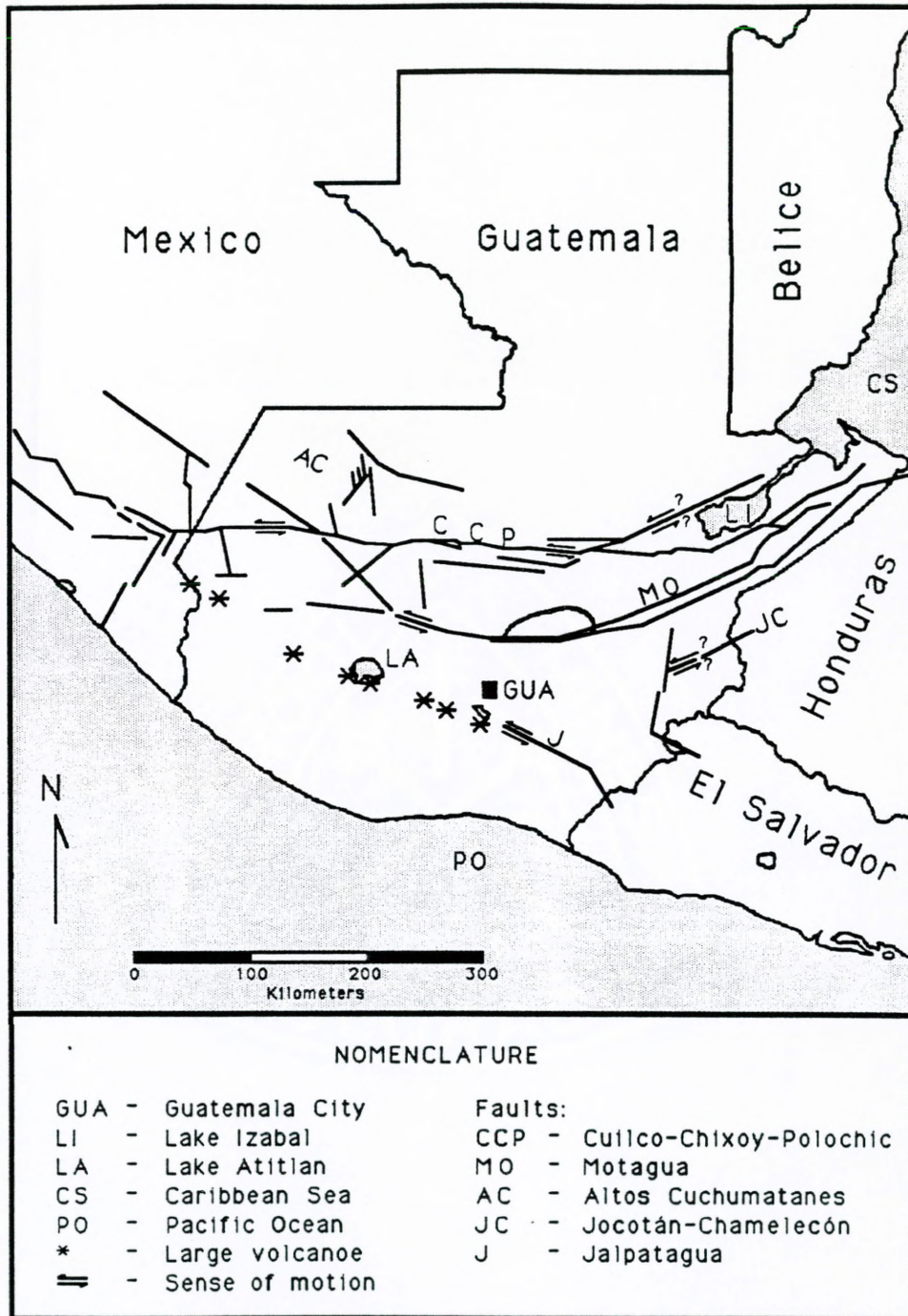
Figure 2. Outline map of Guatemala showing some linear features observed on Skylab
photographs. CCP and Motagua fault systems are the most prominent linear
features. Modified from Muehlberger and Ritchie, 1975.

LEGEND

Qa — QUATERNARY ALLUVIUM

Tsp — UPPER TERTIARY OLIGOCENE-PLIOCENE
Mainly continental: includes Cayo, Armas, Caribe, Herreria, Bacalar, and White Marls Formations.

Tsd — UPPER TERTIARY OLIGOCENE-MIOCENE
Rio Dulce (limestone), Lacantun (red beds), and Desempeño (conglomerate) Formations.

KTsb — CRETACEOUS-EOCENE
Subinal Formation (red beds, mainly Tertiary).

KTs — CRETACEOUS--TERTIARY
Sepur Formation, Cammpanian-Eocene. Mainly marine clastic sediments. Includes Toledo, Reforma, and Cambio Formations, and Verapaz Group.

Ksd — CRETACEOUS
Neocomian-Campanian carbonate. Includes Cobán, Ixcoy, Campur, and Sierra Madre Formations, and Yojoa Group.

Pc — PERMIAN
Chóchal Formation (carbonate).

CPsr — CARBONIFEROUS-PERMIAN
Santa Rosa Group (shale, sandstone, conglomerate, and phyllite). Includes Santa Rosa, Sacapulas, Tactic, and Macal Formations.

IGNEOUS AND METAMORPHIC ROCKS

Qp — QUATERNARY
Thick pumice fills and mantles of diverse origin.

π — Ultrabasic rocks of unknown age. Mainly serpentinite. In part pre-Maestrichtian in age.

Pzm — PALEOZOIC
Undivided metamorphic rocks. Phyllite, chlorite and garnet schist, quartz-mica-feldspar schist and gneiss, marble and migmatite.

/ — Fault

Facing page figure 3.
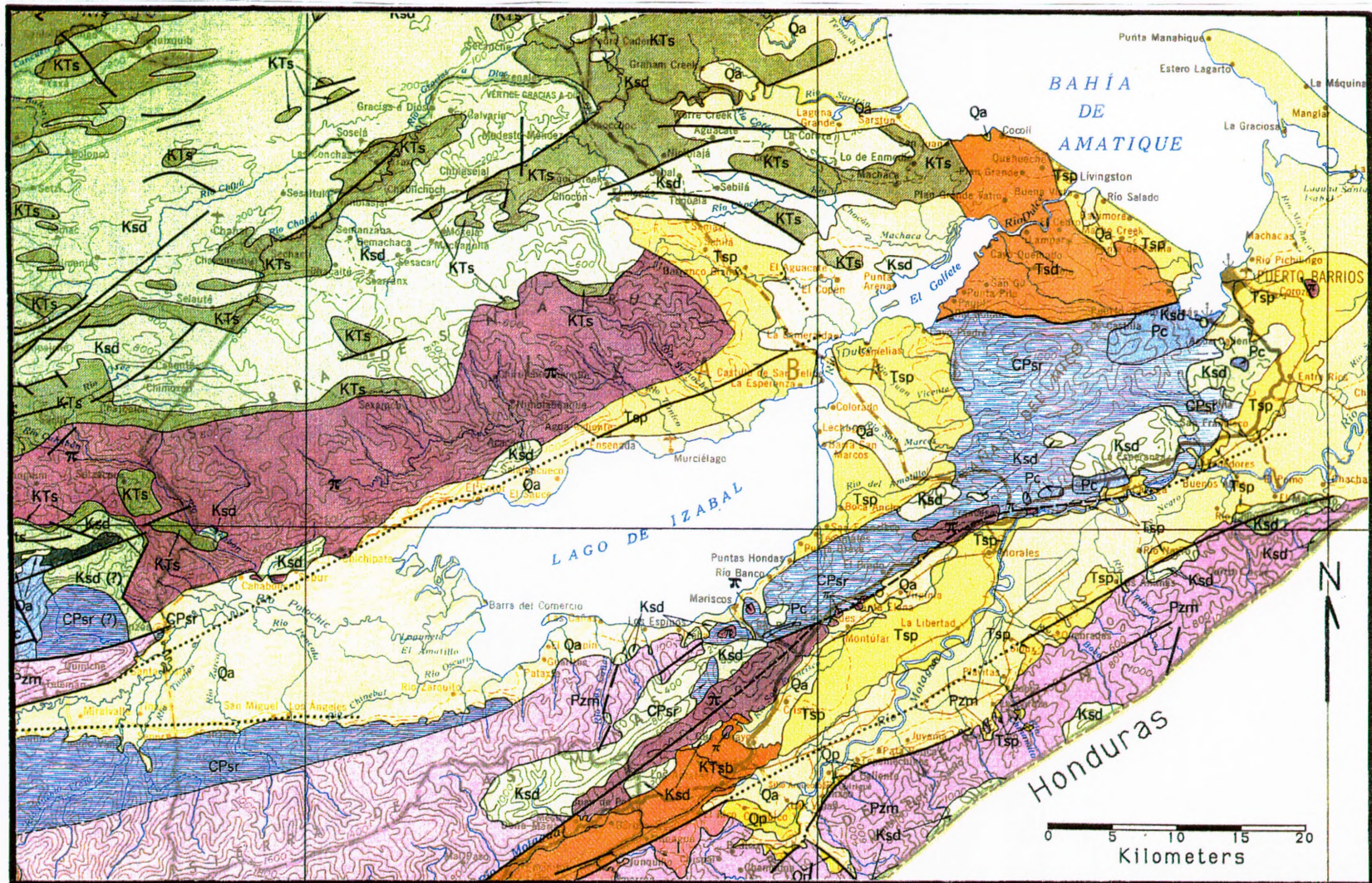
Figure 3.   Generalized geologic map of a portion of the Departamento de Izabal.   Reproduced with modifications from Bonis, Bohnenberger, and Dengo, 1970.

The location of the contact between the North American and Caribbean plates is associated with the CCP-Motagua fault systems and is a matter of bitter controversy and speculations. Preliminary studies of basement rocks exposed to the south and north of the Motagua fault zone in western and central Guatemala suggest that the fault zone represents a late-Cretaceous suture between two lithospheric plates (Schwartz and Newcomb, 1973; Lawrence, 1976; Sutter, 1979). However, as Lawrence (1976) indicates, the orientation of the subduction zone and location of the associated volcanism is still to be determined. Late Cretaceous to early Tertiary allochthonous masses derived from south of the CCP fault are present along the northern edge of the eastern part of the CCP fault system in Guatemala (Anderson, Erdlac, and Sandstrom, 1985; Dengo 1986). Similar structures have been recognized in Chiapas, Mexico (Carfantan, 1977 cited by Anderson, Erdlac, and Sandstrom, 1985). In the northern edge of the LIB, interpretation of aeromagnetic data indicate a depth to magnetic basement in the eastern part of the mafic-ultramafic, partly serpentinized, Sierra de Santa Cruz Mountain of 4.2 to 4.9 km (Williams, 1975) suggesting that it moved onto its present stacked position by gravity sliding, thrusting, or a combination of both. The flysch-like strata of the Sepur Formation, a member of the Campanian-Maestrichtian Verapaz Group (Vinson, 1962) that are present in an east-west trend north of the CCP fault, suggested to Wilson (1974) that they are associated with the emplacement of these allochthons in late Cretaceous time. Rocks of the Verapaz group crop out in the western Cuchumatanes Mountains in Guatemala (more than 3,000 m high), indicating strong post-emplacement uplift of the block north of the Polochic fault in western Guatemala.

Field studies in western Guatemala show that the CCP fault has a Cenozoic left-lateral strike-slip displacement with a small up-to-the-north component (Schwartz, Cluff, and Donelly, 1979). Quaternary displacements are suggested by left-lateral

stream offsets of less than one km along the west and central part of the fault (Anderson et al.,1973; Kupfer and Godoy, 1967). Recent displacements in the LIB are not apparent in the faults that bound it.

Estimates of the rates of slip along the Caribbean-North American plate boundary range from 0.4 cm/year (Perfit, 1977) to 2.2 cm/year (Holcombe, 1973). Variable interpretations have been proposed of its onset and behavior through geologic time. The history and total amount of left-lateral displacement along the CCP fault system is not known and additional controversy has arisen due to the different approaches that have been used to predict and quantify its features. The evidence of sea floor spreading in the Mid-Cayman Rise (Holcombe et al.,1973) and the need to accommodate large displacements has led to reconstructions that imply more than 1,000 km of left-lateral movement of the associated plates (Wadge and Burke, 1983). These displacements should be manifested in the landward extension of the Cayman trough, but no conclusive evidence has been provided. Some models suggest a displacement of about 130 km along the CCP fault (Burkart, 1978; Wadge and Burke, 1983; Deaton and Burke, 1984) but do not provide accurate matches of the displaced lithology; in part, this may be due to the poor, unreliable time-stratigraphic information available for most of the country. Late Cretaceous allochthons and Neogene strata which do not record large displacements obscure pre-existing traces of the fault in western Guatemala (Erdlac and Anderson, 1982; Anderson, Erdlac, and Sandstrom, 1985). Despite many individual efforts, no conclusive information is currently available on the CCP, Motagua or Jocotán-Chamelecón fault systems to fully demonstrate left-lateral strike-slip displacements of more than one kilometer.

Whereas a substantial amount of information exists on features of the western portion of the CCP fault, the present knowledge of its eastern characteristics, e. g. the

LIB, are poorly known. The area has not been thoroughly mapped and the only published

geologic map (Bonis et al., 1970) despite its scale, lacks substantial features that have

been observed by the author and the exploration team of Horcalsa. Dengo and

Bohnemberger (1969) described the most prominent structural features in the eastern

part of the LIB as follows:

> "Current evidence permits only speculation on the direction of movement
> along the Polochic Zone in the area between Lake Izabal and Amatique Bay.
> Here the Miocene Río Dulce Formation and younger sediments have been
> folded in a pattern completely different from that that resulted during the
> Laramide orogeny. The Río Dulce Formation was deposited in a small
> embayment bounded on the north and south by faults of the Polochic zone.
> The formation was folded during late Miocene or Pliocene time as a result
> of movement along these boundary faults. The deformation was local,
> because there is no evidence of regional post Miocene folding in Northern
> Central America. A series of inverted, open, S-shaped folds was formed.
> In general they trend NW-SW, almost at right angles to the faults. These
> folds show effect of drag close to the faults and thus may have resulted
> from left lateral movements along the faults which produced NE-SW
> compression in the enclosed embayment."

Aydin and Nur (1982), in a theoretical study on the evolution of pull-apart basins

and their scale independence, without providing supportive evidence identified the LIB as

being a rhomb graben or pull-apart basin. The Guatemalan Ministry of Energy and

Mines, in a brochure about petroleum exploration opportunities in the country

(Ministry of Energy and Mines, 1987), indicates that the basin comprises a group of

Tertiary pull-apart basins, but due to the promotional character of the publication, no

further information is provided. No conclusive evidence is available to demonstrate that

the LIB is a pull-apart basin or group of sub-basins, but its known tectonic, morphologic and stratigraphic features, as well as the regional geologic and tectonic setting seem to indicate so.

LOCAL STRUCTURAL FEATURES

A series of west-plunging folds with a rather constant tilting along the fold axes characterize the area where the section was measured (figure 4). Minor folds, slickenslides, and small-displacement normal faults are present in two outcrops, where the relatively incompetent coal beds are exposed at the crest of the antiforms. High angle normal faults perpendicular to the fold axes are present at the base of the Cerro San Gil. The unconformity between the measured section and the basement is obscured by these faults.

Centram (1970) drilled a series of shallow wells using a hand auger to determine the location of the coal-bearing strata where they were not exposed. The resulting maps show the coal beds in an inclined band with a marked sinuosity, likely caused by folding.
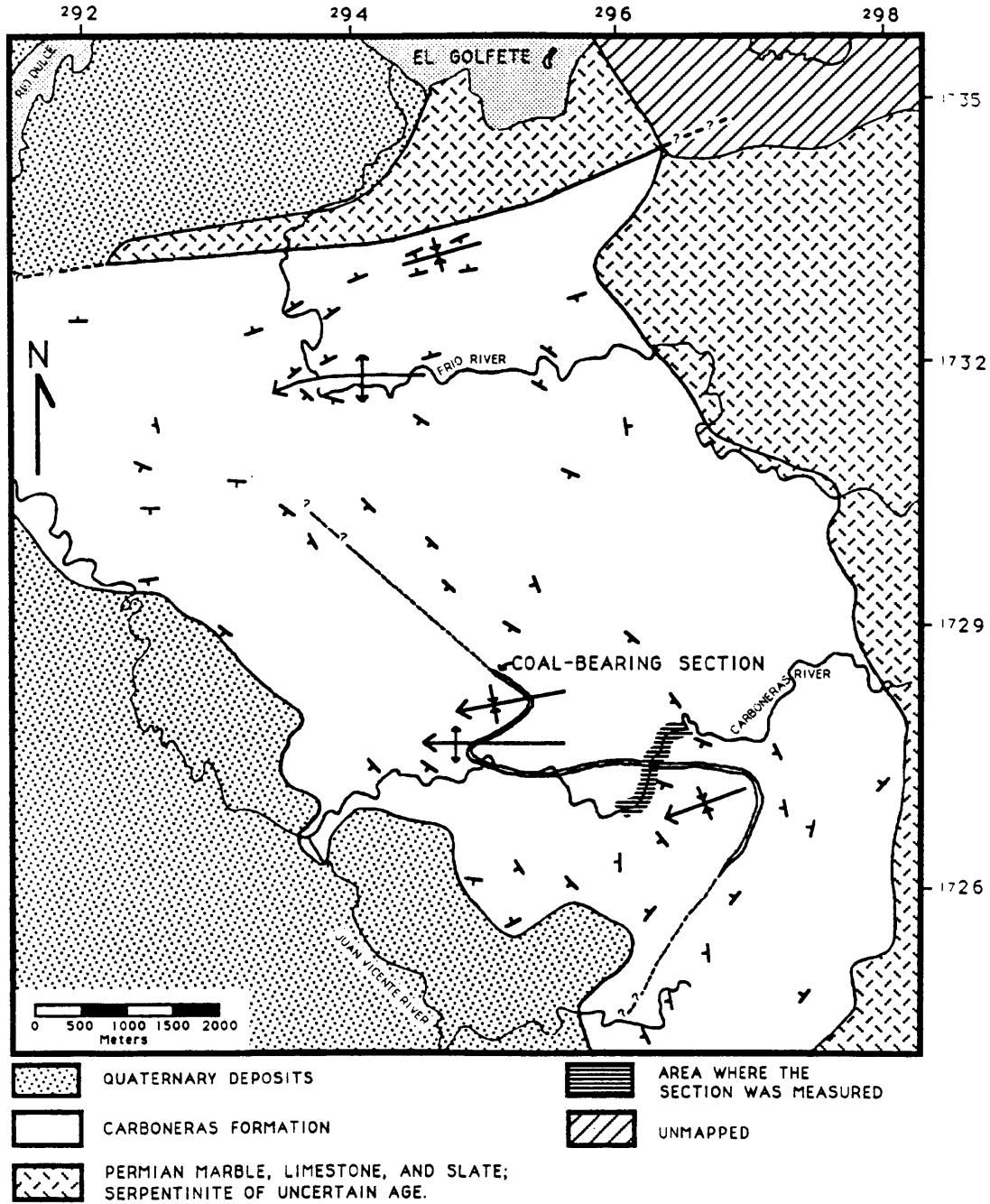
Figure 4. Geologic map of study area. Modified from Centram, 1970.

STRATIGRAPHY

The rocks exposed in the LIB and surrounding mountains range from Carboniferous to Quaternary in age but undifferentiated metamorphic Paleozoic rocks are also present and could extend the age span to the lower Paleozoic.

The evolution of the CCP and Motagua fault zones in eastern Guatemala is poorly understood; the pre-Tertiary sedimentary stratigraphy of the LIB is mostly based on extrapolations of similar rock formations in northern and western Guatemala and are not described in detail here because they form the basement of the basin. Figure 5 is a simplified time-rock columnar chart of the stratigraphy of Guatemala, north of the Motagua fault with emphasis on the strata present in the LIB.

BASEMENT ROCKS

The measured section lies unconformably on highly-deformed, massive-bedded, dark gray to black carbonate rocks with intercalations of slate (figure 6). This association is typical of the Permian carbonate strata exposed in the vicinity of Puerto Barrios that may be equivalent to the Chochal Formation of western Guatemala. A high angle normal fault (figure 7) exposes conglomeratic strata readily distinguishable from the overlying volcaniclastic beds by the absence of volcanic rock fragments and intense induration. The clasts in these conglomerates are composed of quartz and highly silicified limestone and intrusive rocks, resembling the basal part of the Jurasic Todos Santos Formation. However, because similar conglomeratic strata have been described in members of the Carboniferous Santa Rosa Group, also mapped in the area, an unequivocal identification is not possible. The Río Dulce Formation is not exposed in the

Figure 5.   Simplified time-rock columnar chart of the stratigraphy of the Lake Izabal Basin (LIB). Modified from Vinson, 1962.

Figure 6. Folded carbonate rocks with intercalations of slate exposed at the foothills of Cerro San Gil. These rocks may be equivalent to the Chochal Formation (Permian). Geologist is circled for scale.

Figure 7. High-angle normal fault at the base of Cerro San Gil. Exposed rocks are intensely indurated and readily distinguishable from the overlying volcaniclastic strata.

Carboneras region. Discrete, unmapped serpentinite bodies are present in the vicinity of the Cerro San Gil, but the outcrops do not allow determination of their relation to the rest of the basement rocks.

The Carboneras river discontinuously follows an underground drainage at the base of the Cerro San Gil, overflowing surficially only during flood periods. The Juan Vicente and Frio ("cold" in English, suggestive of its underground origin) rivers that also drain the region, originate at caverns at the base of the Cerro San Gil.

The edge of the basin associated with the measured section is here considered as being the base of the Cerro San Gil, where high angle normal faults expose the basement rocks described above. Volcaniclastic strata are present as erosional remnants on the mountains throughout the entire region, including the Sierra de Santa Cruz where euhedral, doubly terminated quartz crystals typical of some pyroclastic deposits were observed mixed with upper laterite strata (Fred Barnard, personal communication, 1989).

The Sierra de Santa Cruz comprises mafic to ultramafic rocks, partly serpentinized and heavily weathered. Tertiary clastic strata overly the ultramafic rocks at the foothills of the mountain. Cretaceous and early Tertiary carbonate strata are also reported in fault-bounded areas.

The Sierra de las Minas is composed of Paleozoic undifferentiated rocks, Permian limestone, Carboniferous clastic rocks of the Santa Rosa Group, Cretaceous (Neocomian and Campanian) carbonate rocks, and late Cretaceous to Eocene red beds; undefined Tertiary strata and serpentinite of uncertain age have also been mapped.

The Cerro San Gil and Montaña del Mico are comprised Carboniferous clastic rocks of the Santa Rosa Group, Permian slate and dark limestone and marble, Cretaceous carbonate rock, and Tertiary undefined strata. Serpentinite of uncertain age are also

present and, in some areas, are "intruding" the sedimentary and metamorphic rocks (Bryson and Williams, 1970). Large portions of the Cerro San Gil and Montaña del Mico are covered by virgin jungles and are very difficult to access. The large amount of pyroclastic deposits within the measured section suggest a source that could be buried in these fantastic, largely unknown mountains.

The age of the serpentinite present along the basin margins is uncertain but due to the presence of Cretaceous carbonate strata (Lee Mosheim, personal communication, 1989) capping some of the outcrops and the stratigraphic position of the surrounding strata, a late Cretaceous age is generally accepted. Despite some isolated studies and some geophysical data, no conclusive information is available to prove their origin and mechanisms of emplacement.

TERTIARY ROCKS

The Tertiary rocks in the LIB comprise the Toledo, Río Dulce, Herrería, and "Barrios" formations, along with the Carboneras formation (informally defined below) which corresponds to the measured section. The Tertiary rocks attain a maximum thickness of as much as 5 km but all this rock cover is unlikely to be present at any single place (Bryson and Williams, 1970). All the contacts between the Tertiary formations described below are unconformable.

The California #1 wildcat that was drilled on the crest of the Livingston anticline (see figure 8) during 1958 and 1959 bottomed at about 2,400 m after crossing a 475 m interval of Cretaceous (Maestrichtian ?) limestone and a thick Eocene to Miocene sequence resembling the Toledo Formation in the lower part; the upper part was clearly the Río Dulce Formation (Horcalsa, 1987; Richard Bryson, 1989, personal communication). The Toledo Formation is confined to the area between the Maya

Mountains of Belize and the Sierra de Santa Cruz and Montaña del Mico in Guatemala. The Sarstún saddle, a structurally caused drainage divide, separates the Toledo from equivalent Formations of southwestern Peten (Vinson, 1962). Although the Río Dulce Formation has a much broader distribution than stated by Vinson, as discussed below, its areal extent seems to be limited to the LIB. Furthermore, the strata of the Herrería Formation and other very similar strata, also discussed below, are confined to the LIB. This information suggests that the early Tertiary history of the LIB should be considered as part of a much broader basin, whose depocenter was located north of the LIB in a probable different tectonic setting, while the Oligo-Miocene to Quaternary events suggest a reduction of the depositional area to the LIB as defined here. In any case, what is presently published about the region only allows to speculate since many varying tectonic controls may have affected the deposition of the whole Tertiary sedimentary cover.

No Tertiary rocks older than Eocene are reported in the LIB but the Lacandon Formation that was assigned by Vinson (1962) to the Maestrichtian, crops out in extensive areas to the north and northwest. Bryson and Williams (1970), assigned the prominent pinnacle reef-like limestone present at Punta Gorda (Belize, just north of the Guatemalan border) to the Lacandon Formation and suggested a Paleocene age to the formation in this area, largely based on stratigraphic position.

TOLEDO FORMATION

Vinson (1962) proposed the name "Peten Group" to distinctly recognizable and mapped rock units, early Eocene in age, present in Guatemala and Belize (figure 8). Some of the Formations in the group are differentiable facies within a single basin but the Sarstún saddle confined the strata of the Toledo Formation to the area between the
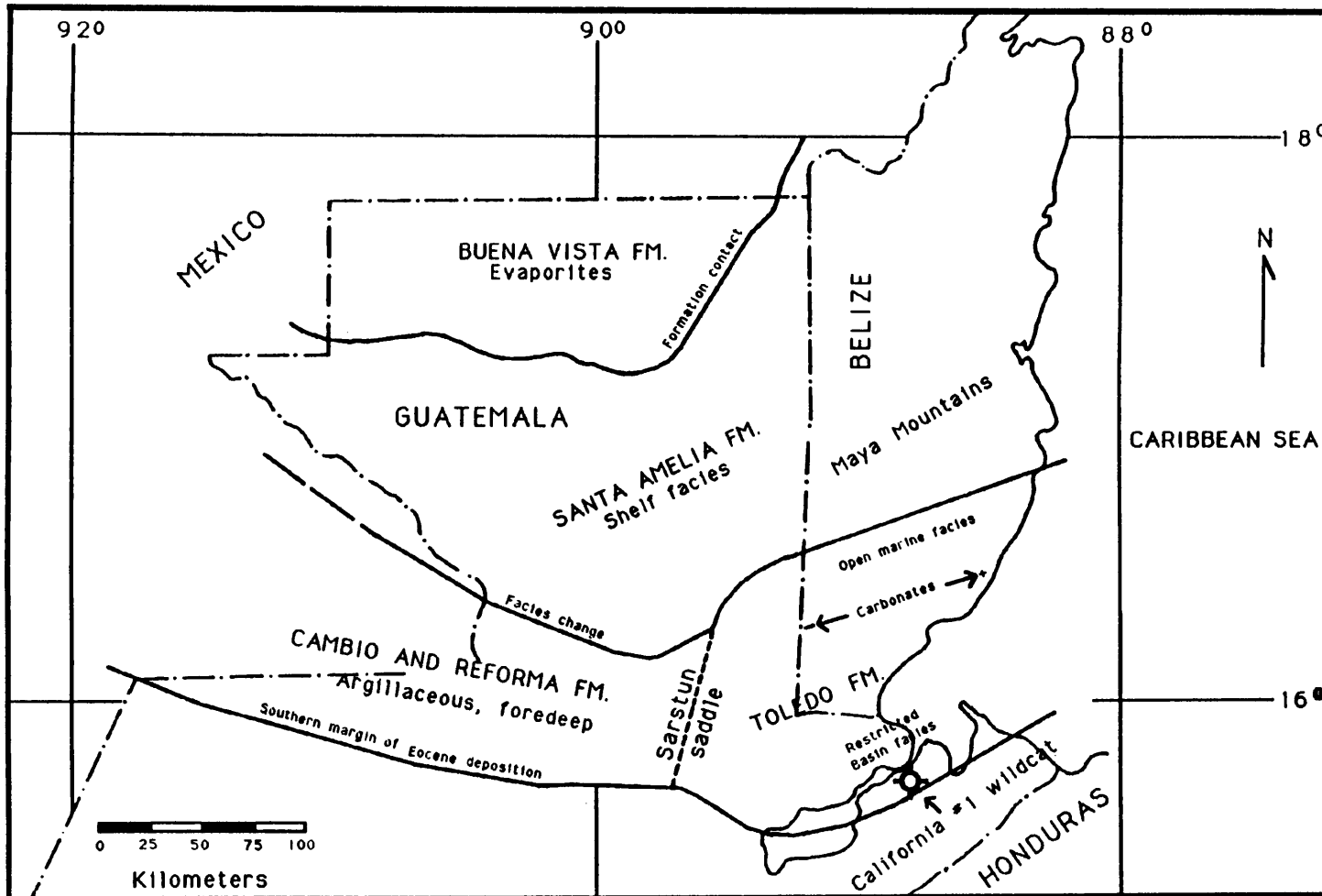
Figure 8.   Areal distribution of formations of Petén Group (early Eocene) showing dominant facies characteristics. Note location of California #1 wildcat. Modified from Vinson, 1962.

Maya Mountains in Belize, and the Sierra de Santa Cruz and Montaña del Mico in
Guatemala.

Ower (1928) studied and named a series of shale, mudstone, calcareous sandstone
and limestone after the District of Toledo (Belize) but did not define a type section.
Dixon (1957) described this formation as a series of thin bedded shale and mudstone
with blue calcareous sandstone and, based on the work of Paul Bronniman, a
paleontologist working for Gulf Oil Corporation and Standard Oil in Central America and
the Caribbean, assigned the Toledo Formation a lower Eocene age. Bryson and Williams
(1970) mapped a sequence of red mudstone and shale, limestone and marl, and some
gypsum, east of the Sierra de Santa Cruz. This sequence was dated as Eocene based on
macrofossils and thus referred as part of the Toledo Formation. Bryson and Williams
also observed that the California #1 wildcat shows an entire Eocene section with
restricted or euxinic basin facies, different from the open marine facies exposed in
western Toledo where the percentage of carbonate strata increases near the coast and
turbiditic strata are also reported. The reported facies changes in this formation
indicate that the depocenter of the corresponding Eocene basin was located north of the
LIB. The tectonic reasons for these features have not been studied. The extensive,
concave-to-the-south faults present in the southern part of the Maya Mountains suggest
that the Eocene basin could be related to strike-slip movement along the CCP fault
system, in which case, the left-lateral displacement in the fault would be older than
currently speculated. The basin also could be associated to an elongated depression
present north of the CCP fault in late Cretaceous time during the emplacement of the
allochtons mentioned in the discussion of the geologic and tectonic setting of the LIB
(Wilson, 1974).

The total maximum thickness of the Toledo is not known but it has been estimated to exceed 2,000 m. In the California #1 wildcat, the total thickness is 1,280 m; in Belize the clastic facies range form 0 to 610 m thick (Bryson and Williams, 1970).

RIO DULCE FORMATION

The Río Dulce Formation (Powers, 1918) is characterized by massive to thick bedded, varicolored fossiliferous limestone. Reefal facies can be observed, especially along the Río Dulce gorge as it crosses the Livingston anticline. The formation was considered to be early Miocene in age by Vinson (1962), but paleontological studies on surface samples and cuttings from the California # 1 wildcat indicate an Oligo-Miocene age (Bryson and Williams, 1970). According to Vinson, the formation is exposed in a limited area surrounding the east end of Lake Izabal, El Golfete and the Río Dulce, but very similar rocks have been observed farther west on the northern side of Lake Izabal by the author and Fred Barnard (personal communication, 1989) suggesting a broader depositional setting, likely covering most of the here defined LIB. The Sarstún saddle separates the Río Dulce Formation from other time-equivalent strata in Guatemala (e. g., the Caribe Formation in southwest Petén) and no time correlation has been made with similar rocks in Belize. Nevertheless, if the Río Dulce Formation is confined to the LIB as considered above, the abundant stenohaline marine fossils that characterize this formation indicate that the main modern fresh water source to the basin, the Polochic river (see appendix A), was likely absent or much smaller, posing interesting possibilities to explain the onset of the left-lateral strike-slip in the CCP fault and the formation of the LIB basin.

HERRERIA FORMATION

This formation was defined by Vinson (1962) based on the descriptions given in a private oil company report. It was defined as comprised of poorly cemented clastic and marly strata overlying the Río Dulce Formation, exposed in a "long, narrow, gentle dipping north-south strip", paralleling the shoreline of the Amatique Bay, east of the Río Dulce gorge, at the southern margin of the outlet of the river into the ocean. Due to similarities with the upper section of the Armas Formation, that is present along the Motagua valley across the Montaña del Mico, Vinson implied that the Herrería could be "Pliocene or Pleistocene", the age span assigned to The Armas Formation by Powers (1918). These similarities led Vinson to suggest, for future use, the group name "Puerto Barrios" or "Izabal".

Bryson and Williams (1970) mapped both, the Armas and Herrería Formations of Vinson, as "Barrios Formation". According to them it consists, in general, of a monotonous sequence of nonmarine redbeds with deltaic to partially marine characteristics in the upper part; coal beds in the lower third of the section; and marine facies in the area between the Livingston anticline and the shoreline of the Amatique Bay.

The exploration team of Horcalsa is presently prospecting for coal in the area of their exploration licence denominated Las Pavas, located between the Livingston anticline and the Amatique shoreline. The structural complexities of the region, in contrast to the gentle dips assumed by Vinson, together with the heavy vegetation have made it very difficult to correlate the scarce outcrops. The clastic strata in Las Pavas and the area of this study show very similar petrographic facies, especially fine-grained deposits with a distinct sky blue color that turns to light brown when heavily weathered. Biotite flakes, slate, limestone, serpentinite, and quartz fragments are also common constituents of the clastic strata in both areas.

During reconnaissance trips to Las Pavas it was observed that, as stated by Bryson and Williams, marine facies are present in Las Pavas (figure 9). Additionally, petrologic studies on polished coal samples show very high amounts of pyrite (up to 30 %) in the coal measures of Las Pavas without a clear association to carbonate strata; this is typical of marine-influenced peat deposition environments (Stach et al., 1982, page 28).

The Herrería, "Puerto Barrios," and the Carboneras formations (the last informally defined below) have petrologic similarities and may be lateral or vertical facies variations of a genetically associated group of strata. Their association along the CCP fault system in a probable strike-slip basin-margin setting indicates that they should not be considered as a single stratigraphic unit due to the characteristics of such basins described elsewhere. These include basin asymmetry, episodic rapid subsidence, pronounced topographic relief with abrupt facies changes, contemporaneous crustal extension and shortening in different parts of the basin, and differences in facies geometry and unconformities at basin margins (Christie-Blick and Biddle, 1985).

QUATERNARY DEPOSITS

Unnamed alluvium deposits are present throughout the basin; in the vicinity of the study area they are mainly composed of chalcedony clasts ranging in size from coarse sand to boulders. These deposits have been interpreted as product of the lateritization of serpentinite (Lee Mosheim, personal communication, 1988), but the occurrences of serpentinite in this part of the basin are relatively few to account for the volume of the deposits. Devitrification of volcaniclastic rocks within the measured section may as well be the source. The contact between the Quaternary deposits and older rocks is inferred to be uncoformable.

Figure 9. Fossil oyster bed beneath a coal bed exposed along the San Carlos River, Las Pavas, Izabal.

DESCRIPTION AND INTERPRETATION OF THE MEASURED SECTION

All the measured section is exposed along the Carboneras River. The river flows almost due south in the surroundings of the best exposed coal outcrops; since beds strike N.90°E. and are dipping 22° to 31° to the south, excellent outcrops are available for about one kilometer. However, the intense weathering and erosion and heavy vegetation prevented observations outside the river outcrops. The measured section has an almost unidimentional character, with few exceptions where some continuous outcrops allowed lateral variations to be described.

Powder X-ray diffraction analyses, discussed in appendix B, indicate that the argillaceous and fine grained deposits are mainly composed of smectite-group clays, quartz, and in some cases calcite; two samples were found to contain palygorskite. The presence of Tertiary volcaniclastic erosional remnants on the mountains throughout the basin and smectite-rich sedimentary deposits is suggestive of a primary volcanic origin (tuff or ash fall) for the argillaceous and fine grained deposits. The rudaceous deposits likely were derived from the mountains bordering the southern edge of the basin.

The section was divided into 9 different facies for purposes of description and interpretation; these divisions are based on shared lithology, sedimentary structures, organic features, overall stratigraphic position, and interpreted depositional processes. Letters A through I arranged in a succession, where A corresponds to the lowermost facies and I to the uppermost, identify the individual associations; appendix C displays the complete measured section.

AGE

The molars of two different Old World species of proboscideans, common in Europe, Asia and North Africa but relatively rare in North America, were collected in a prolific, megafossil-bearing section near the exploration camp of Horcalsa (base of facies H). The first is a worn, upper first molar identified as Gomphotherium angustidens; the second species is a juvenile dentition comprised of upper tusk, fourth premolar, and first and second molars, all of the right upper jaw of a Zygolophodon tapiroides (figure 10). Both specimens were identified by Cary T. Madden (Center for Mastodon and Elephant Research, personal communication, 1989). The temporal ranges of both species are identical; from the later early Miocene to earlier late Miocene. G. angustidens has been identified from the early and middle Barstovian of Maryland and Texas; Z. tapiroides has been identified from the early Barstovian of Nevada (Madden and Mota, 1989). The occurrence of both species in the same section is indicative, due to the relatively fast evolution to new species in migrant faunas, of the earliest dated occurrence in the New World; in the present case, early late Miocene, or about 16 million years. Nevertheless, the measured section is more than 360 m thick and the indicated age can only be taken as indicative for the general stratigraphic position of the section.

Other fossils identified in the measured section (ostracodes, gastropods, and pelecypods; see page 51) have long stratigraphic ranges and are not diagnostic.

NOMENCLATURE

The rocks exposed in the Carboneras region have never been formally described. Centram (1970) assigned the rocks to the Puerto Barrios (or Izabal) group proposed by Vinson (1962) to refer to the Armas and Herrería Formations due to their similarities.

Figure 10.   Molars of <u>Zygolophodon</u> <u>tapyroides</u> collected at the base of facies H. From left to right: fourth premolar, first molar, second molar; all from upper right jaw. Tusk is not shown.

This study shows that the Tertiary rocks in this part of the LIB have some similarities with the Herrería, Armas and "Barrios" formations but significant lithological and sedimentary differences exist; therefore, the name Carboneras formation is here informally assigned to the Tertiary strata outcropping in the study area and used throughout the text.

FACIES A

Description. Facies A corresponds to the lowermost part of the measured section. It is composed of claystone, siltstone, and massively-bedded, poorly-sorted silty pebbly mudstone (figure 11). Individual strata range from 30 cm to 2.5 m in thickness, the siltstones being the thinnest; the total thickness of this facies is 11.5 m. Massive bioturbations are present at the base and top of claystones; vertical branching disorganized burrows are present in the middle parts (figure 12). The fill of the burrows is white-colored and calcareous; the sustrate is a slightly indurated noncalcareous bluish-colored claystone that weathers out in concentric shells when dried. Distinct plant remains such as leaves, twigs, and dispersed fine-grained carbonaceous debris are present in most of the individual beds, especially at the top which has clear pedogenic features: oxidized rootlets, darker color, and fern-like plant remains. Coarser-grained beds are composed of angular to well rounded coarse sand to granule fragments of dark brown mudstone in a structureless muddy matrix.

Interpretation. Massive or apparently structureless bedding may represent very uniform sedimentation over a short time, or may result from bedding destruction by burrowing organisms (Reineck and Singh, 1980, page 130; Potter, Maynard, and Pryor, 1980, page 25). Original bedding planes in muds may also be destroyed by

Figure 11.   Bioturbated claystone overlain by massively-bedded pebbly mudstone at the base of facies A.

Figure 12.   Vertical burrows in the middle part of claystone in facies A. Bar scale
            is approximately 15 cm. long.

penecontemporaneous mobilization, one expression of the rheotrophic behavior of some muds. This is especially true for smectite-rich muds that rapidly become fluid when disturbed, returning to a gel state when the disturbance ceases (Greensmith, 1978, page 103). Loss of electrolytes may also lead to clay fluidization (Nair, 1976). Water loss on standing, accompanied by contraction after fluidization (syneresis), may also add disturbing elements to cause a massively bedded claystone (Leeder, 1982, page 112). The deceptive lack of bedding in the claystone in facies A in outcrop and thin section is most likely associated with extensive bioturbation. The massive bedding of the siltstone and pebbly mudstone is interpreted as a product of rapid sedimentation, since bioturbation is not evident.

The extremely fine-grained texture of the claystone is indicative of a primary sedimentation where flocculation was important; this may occur in a wide variety of environments, but the relatively small amount of organic material and presence of bioturbation suggest a well-drained, aerobic environment. In a small basin like the LIB, lacustrine and well-drained swamps may produce similar deposits. The alternation of extremely fine-grained claystone, massive siltstone, and pebbly mudstone with soil forming features, is related to sedimentation in well-drained swamps subject to both aerial exposure and flooding by streams ladden with suspension sediments; a mudflow (Bull, 1972) origin could also be feasible in the case of the pebbly mudstone, since bedding and sorting are not evident and a debris flow overlies this facies. A shallow subaqueous setting cannot be ruled out with the available evidence, in which case, the coarser strata in this facies would likely be formed by subaqueous fine-grained debris flows. Bioturbation by burrowing organisms occurred following clay sedimentation; similar burrowings caused by small crabs are present in muddy sediments in the modern lake Izabal flood areas.

FACIES B

Description. An 8.75 m thick bed of massive, matrix-supported conglomerate overlies facies A. The base of this bed, about 70 cm thick, is composed of well sorted, inversely-graded clasts ranging from granule to pebble. Fern-like plant remains are present at the base in one of the outcrops (figure13); rootlets and plant debris were observed in the underlying bed at another location. The base has a sharp transition to an unsorted, matrix-supported conglomerate containing large boulders up to 40 cm in length (figure 14). The matrix is almost exclusively pumice fragments ranging in size from fine ash to lapilli, and a small fraction of clay produced by pumice weathering. Coarser clasts are volcanic rock fragments (basalt, andesite, rhyolite, and dacite; in some cases vesiculated), slate, and serpentinite; the last two are most abundant. Clasts vary from very angular to well rounded, and lack internal stratification and fabric. The upper part, about 90 cm thick, changes transitionally to normally graded.

Interpretation. Unsorted conglomerate without internal stratification and fabric is characteristically formed by gravity flows of rock fragments and soil, such as subaerial or submarine debris flows. Facies B contains the first clear indication of volcanic activity in the LIB; none of the stratigraphically-lower Tertiary formations in the LIB show evidence of volcanic activity. The source of the tephra is not known and, although it could be located within the Cerro San Gil-Montaña del Mico, it could be on the Motagua valley.

Distinction between subaerial and subaqueous debris flow deposits is difficult. In the present case, a subaerial origin is more plausible since the conglomerate overlies a strata with pedogenic features, and no typical subaqueous features like turbidites or soft sediment deformation are present underneath. Nevertheless, a strata with very similar

Figure 13.   Fern-like plant remains at the base of facies B.

Figure 14.   Middle part of facies B. Hammer is resting on largest clast observed.

characteristics was identified in the field about 3 km north of the Carboneras river, suggesting that this gravity flow deposit may have covered a relatively broad area. Interfingering with subaqueous deposits may occur in the distal parts of the flow if the appropriate basin morphology existed.

The erosive power of debris flows can be relatively negligible (Kukal, 1971, page 297; Nemec and Steel, 1984), and the good preservation of underlying features like the rootlets and fern-like plant remains described above is not unusual. The sorting and inverse grading of the basal part of this facies suggest that it was likely deposited by a waxing turbulent flow and was immediately preserved by the succeeding debris flow. Subaerial debris flows may follow or cut across preexisting fluvial channels, and capture well rounded fragments incorporating them into the resulting conglomerate along with angular immature clasts. The normal grading of the upper part of this deposit may be associated, as Nemec and Steel (1984) propose for similar deposits, with a turbulent flow or heavily sediment ladden stream flow following the debris flow.

FACIES C

Description. Facies C is 32.28 m thick and is the best exposed part of the measured section; an almost vertical cliff about 45 m high and 160 m long exposes facies C, D, and a small part of facies E along the Carboneras River (figure 15). Nevertheless, the poor induration and predominant fineness of these strata creates a sticky mud that deeply impaired observation of the strata.

This facies is characterized by remarkable lateral continuity and parallelism of beds along the outcrop. Beds range from 20 cm to 6 m thick. Thicker beds show a 20-25 cm thick poorly-sorted, normally-graded base composed of imbricated, well rounded, even and parallel bedded altered pumice and tabular bone fragments in a muddy

Figure 15. Cliff exposing facies C, D, and the lowest part of facies E along the Carboneras River.

matrix (figure 16). The base is transitionally overlaid by upward-fining, poorly sorted, muddy sandstone that contains randomly distributed granule-sized clasts. The tops of the thicker beds are composed of extremely fine claystone that weathers in concentric shells when dry, and have plant debris and occasional rootlets.

Less abundant beds are composed of massive, muddy, poorly-sorted sandstone and siltstone with scattered granules. Inner spire molds of fresh water snails of the Thiaridae family and undifferentiated bioturbation were observed in the lowermost bed of this facies.

Interpretation. Individual sheet-like deposits with lateral continuity and parallelism can develop in a wide variety of environments and are not conclusively diagnostic of any specific depositional setting. On the other hand, the failure of any of the beds in facies C to pinch out or show channeling is suggestive of sedimentation in an environment subject to persistent depositional conditions without preferential or concentrative erosive power.

Shallow meandering streams may develop sheet-like deposits similar to those in facies C but the absence of epsilon cross-stratification, the failure of beds to pinch out, and the predominant fine-grained nature of the rocks (despite the chaotic sorting), argue against this origin.

Sheetfloods and mudflows (both terms are used following Bull, 1972) may also form deposits similar to those observed in facies C but require conditions characteristic of desert environments (Bull, 1972; Davis, 1938; Laming, 1966; Mcgee,1896; Rich, 1935). Additionally, the thickness of individual events, unless of catastrophic nature, tend to be thinner than those observed in this facies, thus arguing against these depositional mechanisms.

Figure 16. Basal part of the thickest bed in facies C. Arrows point out to bone fragments. See text for description.

In contrast, an overbank flooding (Coleman, 1969; Elliott, 1974) or overbank splay (Coleman, 1988) origin provides a depositional mechanism that operates during flood events and involves suspended and bedload sediments spilling over channel banks, with no breaches or crevasse channels into adjacent lower lying areas; these areas can be flood plains of fluvial settings or interdistributary bays in deltaic environments. The presence of fresh water mollusks at the base of this facies is suggestive of a fluvial floodplain or fresh water lacustrine environment. Additionally, an excellent preservation potential for these deposits is suggested by the presence of debris flow deposits underneath, since they are usually associated with tectonic activity and subsidence.

FACIES D

Description. A 5.8 m thick deposit of altered and compacted pumice overlies facies C. Poorly-bedded, horizontal, normally-graded intervals are the only sedimentary structures present throughout the bed (figure 17). Distinguishable individual fragments range from coarse ash to lapilli; the biggest fragment observed was about 8 cm across. The coarser fragments are very soft and tend to be oblong in shape, with the longer axis in a preferential bedding-parallel position but not aligned. In hand specimens, the typical appearance of pumice is obvious but in thin section the expected glass cells and shards are collapsed and totally replaced by clay. Accessory minerals are biotite and quartz; small feldspar crystals are visible in thin section. The base of this deposit has a sharp contact with the top of facies C, where pedogenic features are well preserved (figure 18).

Figure 17. Slab of pumice deposit (facies D). Stratigraphic top is to the left.

Figure 18. Contact between the top of facies C and the bottom of facies D. Carbonaceous debris, silicified twigs, roots, and leaflets are well preserved. Bar scale is about 25 cm long.

Interpretation. The lack of flow-associated structures, and the presence of horizontal normally-graded intervals without alignment of the longer axis in the fragments suggest an air fall-type pyroclastic deposit. The oblong shape of some of the larger clasts may be due to compaction of clay-replaced glass cells and rounding produced during aerial transport.

In subaqueous falls, the dispersal and delayed sinking of pumice may result in beds with pumice-rich tops (Huang, 1980). This characteristic is totally absent from facies C where the base and top show similar sorting and bedding, thus implying a subaerial fall deposit.

A good preservation of fine details, other than standing vegetation, is usually present in beds underlying non-reworked pyroclastic fall deposits. In the present case, pedogenic features such as rootlets, carbonaceous debris, silicified twigs, leaflets, and a marked darker color are well preserved in the underlying bed; the density of rooting features suggests a sparsely vegetated area. A silicified interval, about 30 cm thick, is present below the horizon interpreted as a paleosol, and is also suggestive of soil forming processes but may as well represent solution and redeposition of silica from the pumice bed.

Interestingly, the overlying facies does not contain significant amounts of pumice, suggesting that the volcanic center, source for facies D, was likely located downstream. The source of tephra still remains to be identified; as indicated before, the Cerro San Gil or Montaña del Mico could be the source to some of the volcaniclastic rocks but the Motagua Valley region, due to its closeness, could as well be the source.

FACIES E

Description. This facies has a total measured thickness of 22.4 m. The lower part, about 9 m thick, is composed at the contact with facies F of trough cross-stratified coarse sand and granule conglomerate cosets with abundant bone fragments overlain by massive mudstone and siltstone. Small isolated channels cut into these strata; the observed width of the channels does not exceed 4 m; thickness varied from 0.5 to 1 m. The fill in one channel-set is composed of trough cross-stratified clay rip-ups, carbonized wood fragments and mud supported conglomerate (figure 19); in other channels the fill is normally-graded, oxidized, trough cross-stratified coarse sandstone with pebbly intervals and abundant bone fragments (figure 20). In all cases, infill appears to have been active and rapid.

The middle part of this facies, 11.4 m thick, has been deeply weathered and could not be observed directly; in the river bed it appears to be composed of mudstone similar to facies observed in the lower part.

The upper part is composed of a 2 m thick set of trough cross-stratified mud supported conglomerate with partly-dissolved spires of fresh water snails of the Thiaridae family.

Interpretation. A river flowing through alluvium forms deposits within the channel at ordinary river stages and on the floodplain in addition to within the channel at high flood stages (Allen, 1964). In areas adjacent to channels, bank and levee deposits are formed by vertical accretion through overbank flooding. Under certain conditions, flood waters may incise simple or composite channels over the bank and levee surfaces
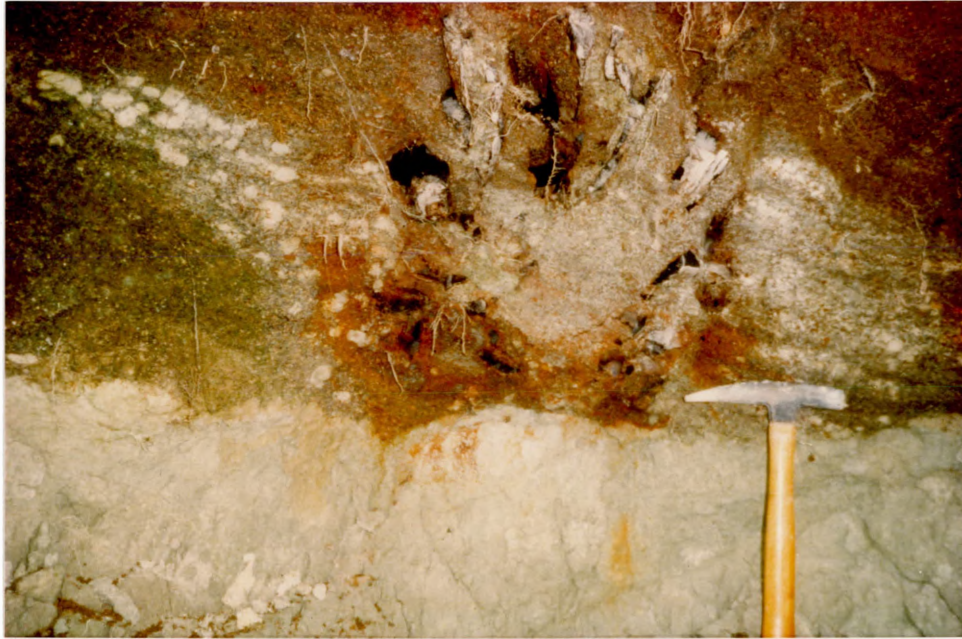
Figure 19.   Central part of small channel cut into massive mudstone filled with rip-
ups, carbonized wood fragments, and mud-supported conglomerate.

Figure 20.   Detail of channel cut into massive mudstone filled with oxidized trough
cross-stratified coarse sandstone with pebbly intervals.

forming crevasses and crevasse splay deposits that shoal away from the river. Continual aggradation without river avulsion into the now exposed area may lead to vertically stacked bank, levee, and crevasse-splay deposits traversed by crevasses. Grain sizes and unit thicknesses depend on rate of flood plain aggradation, magnitude of flooding, effectiveness of the confining levees, and water depths in the flood basin (Galloway and Hobday, 1983).

The presence of fresh water mollusks, trough cross-stratified cosets, and massive siltstone and sandstone cut by predominantly small channels is suggestive of a succession similar to the one outlined above, thus facies E is interpreted as a series of superimposed fluvial crevasse-splay and vertical accretion deposits. The absence of reworked pumice fragments, despite the abundance in the underlying bed, further supports the interpreted depositional mechanism.

FACIES F

Description. this facies has a total measured thickness of 13.55 m and is composed of sets of small-scale, planar, tabular cross-stratified fine to very fine white sandstone (figure 21). Set thicknesses vary from 10 to 60 cm; in contrast to the previous facies, some laminations less than one half millimeter thick can be easily distinguished from each other. Three erosion surfaces were identified and are marked by inclined boundings with coarse sandstone and granule-sized clasts conglomerate. Circular, branching burrowings filled with organic-rich debris are present in the upper part, below the uppermost 3.75 m where most of the primary attributes are deeply masked by silicification, fracturing, and weathering. Plant debris, scattered granules and concave bedding contacts are the only identifiable original constituents.

Figure 21.   Cosets of very fine white sandstone of facies F. Pike for scale is about 1 m
            long.

Interpretation. In modern sandy braided streams, planar cross-stratification forms by foreset deposition at the margins of transverse bars and similar large scale solitary or repetitive bedforms (Smith, 1972). Cross channel, linguoid and alternate bars produce tabular sets of cross-stratification as a result of the downstream advance of their slip faces (Collinson, 1986, page 27). The depth of flow must exceed the maximum thickness of a set; in a conventional setting, a train of sandwaves suggests average flow depths that are at least twice the height of the waves (SEPM, 1975).

Different types of transverse bars have been identified in isolated channels, stable areas, and in sheltered parts of active tracts in fluvial environments of diverse magnitudes; thus, a unique association between bar type and stream features cannot be established. The most common modern fluvial environments where this type of deposits are formed are anastomosing (Smith and Smith, 1980), low sinuosity, and straight braided streams (Cant and Walker, 1976).

Considering the above information, this facies is interpreted as vertically stacked braided stream active channel deposits. The presence of organic debris and absence of identifiable sedimentary structures in the upper part of this facies is suggestive of an active channel deposit that was thoroughly bioturbated and silicified under conditions similar to those of facies G.

FACIES G.

Description. Between the top of facies F and facies G there is a 12.71 m thick covered interval that could not be described. In facies G, four intervals with a total thickness of 47.83 m could not be measured because old and recent mining activities and a small fault-controlled ravine have destabilized the faces of the outcrops. Nonetheless, observations previous to current mining activities and generalized stratigraphic

sections made by Centram (1970) indicate that these covered intervals contain a lithologic association similar to those described below. The total measured thickness is 78.46 m. Facies G is composed of five different interbedded rock types; these rock types are:

(1) Gastropod and pelecypod shell-rich beds. The shells in this lithology show different degrees of reworking and transport but, generally, the spires of the gastropods and the beaks of the pelecypods are intact and uneroded; in some cases, bivalves are articulated and resemble living positions. Three gastropod and two pelecypod species were identified; all of them fresh-water non-marine taxa (table 1). Some intervals contain predominantly one or two shell species, but no zonations with exclusive occurrence of species are present.

(2) Marl. These beds are composed of shell fragments, silt, and clay mixed with calcium carbonate. Shaly partings with abundant finely-laminated organic matter are common (figure 22). Four samples processed for calcareous microfossils contained the same fresh-water non-marine ostracode assemblage. Fish teeth and bones, bird bones, and abundant well preserved gastropod shells are also present in the marl beds (Richard Forester, written communication, 1989; see table 1). One of the thickest marl beds also contains remains of charophyte plants, along with the above listed fossil assemblage (figure 23).

(3) Massive bioturbated muddy sandstone. Lithic fragments are deeply altered and clay-replaced. Gastropod and pelecypod shells are common in most beds. Abundant megafossil bone-fragments are present in the lowermost portion of this lithology; the proboscidean molars described on page 28 were collected at a small fault-controlled ravine that marks the base of this facies.

This and the following lithology have a typical bluish color when not weathered

Figure 22.   Marl bed with shaly interval and abundant gastropod shells.

Figure 23.   Thickest marl bed in facies G, it has been used as roof for test shafts. Charophyte plant remains, fish teeth and bones, and bird bones are present in this bed.

Table 1. Fossil assemblage in facies G.

_____

PELECYPODS:
        Unionidae, Cf. genus _Nephronaias_ Fischer & Crosse 1893
        Corbiculidae, cf. genus _Batissa_ gray, 1853

GASTROPODS:
        Thiaridae, cf. "_melania_" _inquinata_ DeFrance
        Pleuroceridae, cf. genus _Elimia_ H. & A. Adams, 1854
        Littoridinidae,   cf. _Tryonia clathrata_ Stimpson, 1856

OSTRACODES:
        Limnocythere n. sp.
        Metacypris n. sp.
        Darwinula stevensoni Brady & Roberson, 1870
        Darwinula n. sp.
        Pelocypris n. sp.
        Pseudocandona ? n. sp.
        Cyprid gen & sp indet A

CHAROPHYTES:
        Nitellopsis ? sp.
        Chara sp.

PROBOSCIDEANS:
        Zygolophodon tapiroides
        Gomphoterium angustidens

_____

Fossils identified by Barry Roth (Mollusks); Cary Madden (Proboscideans) and Richard

Forester (Ostracodes and Charophytes).

(figure 24). Oxidation of pyrite and other reduced minerals causes strong alterations with formation of small sulfur and gypsum crystals, and limonitic halos that give the outcrops a dark to light brown coloration, especially when heavily weathered.

(4) massive siltstone and mudstone. The beds in this lithology show varying degrees of bioturbation. Shells are also common; in some beds, most gastropod shells are articulated, remarkably well preserved, and in some cases, are in living positions. Small carbonized plant-debris are present in varying amounts.

(5) Lignite and carbonaceous shale. Carbonaceus beds are present throughout facies G. The thickness of individual strata generally does not exceed 30 cm but collectively the strata have a total thickness of more than 15 m (figure 25); the thickest lignite bed observed measures 1.5 m. The lignite and carbonaceous shale are generally well exposed where they have not been mined and seem to be little affected by weathering processes, especially if the outcrops are covered by caliche crusts. Shale and shell-rich partings are present in most lignite beds; shell-rich horizons also are present in the carbonaceous shales. When the lignite is allowed to dry, it becomes friable and desiccation cracks are formed; in that state, the lignite can be easily split along the stratification planes. This phenomenon is attributed to the high amount of moisture and mineral matter (see tables 3 and 4, appendix B).

Macroscopically, the lignite beds consist of monotonous thin laminations of dull black layers with a few intercalations of semi-bright laminae. Small flat fragments resembling coalified grass stalks can be identified in hand specimens when viewed along the stratification planes. Limonitic concretions up to 2.5 cm long and scattered bone fragments, especially of crocodilians, are present in some beds.

Figure 24. Massive muddy sandstone. Weathering progressing along fracture planes causes the alternance of bluish and brown coloration.

Figure 25. Outcrop where thin coal seams intercalated with sandstone, siltstone, and marl are predominant.

Interpretation. The fossil assemblage in facies G is entirely non-marine. Several of these species are known to be living or have very similar modern analogues. Although a fresh water paleoenvironment is indicated by the invertebrate fossils, it was large enough to have the complexities needed to account for the peculiar habitats of some of the taxa.

The ostracodes were likely limited to environments with temperatures permanently above 20° C annually; the flow was rarely reduced to create daily or seasonal changes in temperature and chemistry of the waters. The total dissolved solid content of the water was probably very low. The darwinulids are usually associated with ground water and are typically found in springs, gaining streams, and the margins of lakes (Richard M. Forester, written communication, 1989).

Recent Elimia species occupy a variety of substrata; unionid and curbiculid bivalves are known to burrow shallowly in uncompacted sediments. They tend to live in moving rather than standing water and tend to be intolerant of high turbidity. Mollusk shells in modern Central American streams are typically eroded by ambient acidity and perhaps through the action of micro-algae on the shell surface. The good condition of the fossils suggests that they inhabited buffered waters, probably Ca-enriched from flowing over carbonate terrane (Barry Roth, written communication, 1989).

The abundance of organisms with calcareous shells and marl beds is indicative of Ca-enriched waters. The modern Lake Izabal belongs to the calcium-hydrogen-carbonate type (Serruya and Pollingher, 1983, page 115) and a similar composition may have prevailed during the deposition of these strata. Waters shedding from the calcareous mountains could have provided additional sources of calcium and magnesium. The marl deposits probably were deposited in large open pools (or river-lakes) within a swamp that received the input of turbid and/or ground water. A water table increase or

a subsidence rate faster than required for peat accumulation would eventually deepen and extend the pools over the surrounding swamps and drown the vegetation. Sediment fill or water table fall would eventually reduce the water depth in the pools and peat formation and accumulation would occur again, creating an alternation of peat and marl beds. The contribution of Charophytes to calcium carbonate precipitation was probably very low, since remains of these plants were identified in only one marl bed.

The shell-rich beds, muddy bioturbated sandstone, and massive siltstone and mudstone are interpreted as deposits caused by flooding events of diverse magnitude. The different degrees of bioturbation and the presence of articulated gastropod shells in living positions are suggestive of floods long enough to allow colonization by mollusks, especially gastropods. The shell-rich beds represent lag deposits.

The monotonous thin laminations and the carbonized grass-like fragments that characterize the lignite beds are suggestive of a deposit formed in reed swamps with grasses and probably ferns, with absence of forest vegetation. This is supported by the absence of rootlets or large roots, even in the thinnest seams, as to indicate *in situ* growth of trees. This type of deposit requires a higher water table than forest swamps do; washed-in minerals are more abundant than in forest swamp coals (Stach et al., 1982, page 23). The high ash content (see table 5, appendix B) and the presence of shell-rich partings and carbonaceous shales, along with the above listed characteristics, are also suggestive of a hypautochthonous origin, that is, a deposit where rearrangements of plant remains or peat take place repeatedly during flooding events (Stach et al., 1982, page 19).

The invertebrate fossil assemblage found throughout this facies together with the interbedding of the different rock types is suggestive of a swamp environment with large open pools, subject to repeated flooding events of diverse magnitude and duration. No

evidence is available to determine whether the swamps were associated to an alluvial plain or lacustrine-marginal swamps receiving the input of streams and springs, like those that are formed in the modern lake Izabal during seasonal floods.

FACIES H

Description. Between the top of facies G and the bottom of facies H, a 110 m thick interval could not be described because it has been eroded by the river (see appendix C). Through isolated, discontinuous observations in the river bed along the covered interval, it was determined that this interval is composed of fine-grained strata with pebbly intervals; its lithologic characteristics resemble those of facies E. Despite the covered interval between facies G and H, the strata in facies H basically show the same attitude of the previous facies, suggesting that the tilting and folding of the Carboneras formation occurred after facies H was deposited.

Facies H corresponds to the uppermost part of the measured section. No further measurements were made because of poor exposure upsection. The total measured thickness of this facies is 80.22 m.

This facies is composed of upward-coarsening conglomeratic deposits. The lowest part, about 10 m thick, consists primarily of intercalated tabular beds of sand-supported conglomerate and sandstone (figure 26). The upper part comprises crudely bedded upward-coarsening conglomerate alternating with thin sets of sandstone and siltstone. A few carbonaceous shale is also present in thick laminated sets.

The conglomerate strata range from clast-to matrix-supported; coarse-grained sand is the most common matrix. Elongated clasts tend to be aligned in a horizontal to subhorizontal position with the intermediate axes inclined. Coarse clasts are sub-

Figure 26. Intercalation of tabular sand-supported conglomerate and sandstone at base of facies H.

rounded to rounded fragments of milky quartz, chalcedony, limestone, serpentinite, and rip-ups of muddy sandstone and mudstone with a lithologic composition similar to those in facies C (figure 27). Among the coarse clasts, rip-ups are predominant; the other clast types are concentrated at the upper part, where rip-ups are less abundant. Some of the rip-up clasts are partly replaced by calcite.

Interpretation. Thick sequences of pebbly alluvium are generated and preserved where there is topographic relief; this commonly implies tectonic activity during or immediately prior to deposition (Collinson, 1986, page 44). The preferential concentration of rip-up clasts at the base, and the predominance of the other clast types at the upper part of this facies is indicative of a "reversed stratigraphy" (Miall, 1970), i. e. the conglomerates mainly consist of intraformational clasts in which the proportion of reworked older deposits increases upsection.

The upward coarsening nature of these strata, which is concurrent with a loss of bedding definition, suggests that they were deposited from streams with high sediment concentration and increasingly high current velocities; this is likely in an actively prograding alluvial fan setting.

The partial replacement by calcite in some of the rip-up clasts is suggestive of weathering or soil forming processes which are common in alluvial fan sediments (Collison, 1986, page 34). Carbonate buffered waters shedding from the surrounding calcareous mountains would provide good sources of calcium and magnesium for carbonate replacement and deposition of carbonaceous mudstones in ephemeral ponds.

Figure 27. Rip-up clasts in the upper part of facies H. Individual clasts are sometimes difficult to identify due to similar coloration.

COAL PETROLOGY AND ECONOMIC POTENTIAL

Previous studies, e. g. Centram (1970), and Horcalsa (1987), have demonstrated that the lignite beds have an economic potential but do not provide conclusive information concerning their composition and coalification stage. In order to determine these properties, a suite of 5 representative samples of lignite were mounted in polyester resin and polished for microscopic evaluation following the procedure described in appendix B. A petrographic microscope equipped with normal and blue light was used to identify the different macerals. All the evaluated samples were collected from outcrops and showed, especially under the microscope, different degrees of weathering. In general, the lignites have extensive microfissures, characteristic of weathered coals (Chandra, 1962), suggesting that, although the exposed lignite beds seem to be little altered, significant physical and chemical changes have occurred.

Chandra (1962) studied the changes of reflectance between fresh unoxidized samples and the corresponding samples of naturally weathered outcrop and found that the reflectances are not significantly different. Chemically, however, the weathered and fresh unoxidized samples were very different. Considering this, and to determine the stage of coalification, vitrinite reflectance measurements were made on all five samples (See Davis, 1978, pages 27-81; Stach et al., 1982, pages 319-329 for discussions on measurement of reflectance on vitrinites) following the method described in appendix B. The corresponding data show that the Carboneras lignites have a mean vitrinite reflectance (R_m) that ranges from 0.34 to 0.37 %.

The lignites in incident light under oil immersion appear to be predominantly composed of structureless vitrinite (collinite); only a few vitrinite macerals resembling telinite are present. Other secondary constituents include the liptinite-

group macerals cutinite and sporinite. Fusinite, semifusinite, and abundant fungal spores (sclerotinite) are the observed inertinite-group macerals. Figures 28 to 33 are photomicrographs of the observed macerals. Mineral matter is abundant; undetermined clay minerals and pyrite are predominant and are present in all the samples without exclusive association to specific maceral types.

Appendix B shows the results of proximate, ultimate, and ash analyses for selected lignite samples. The results of proximate analysis for the selected samples are similar to those obtained by Centram, 1970. Figure 34 is a Van Krevelen diagram presenting results of the ultimate analysis. The field that the samples occupy is indicative of a humic coal, mainly derived from terrestrial plants, with no contribution of algae.

The microscopic features, macroscopic features, chemical composition, and vitrinite reflectance values of the samples, correspond to the rank of lignite (Stach et al., 1982, page 45; Tissot and Welte, 1978, page 208).

The regional precipitation in excess of 3,000 mm/yr (Serruya and Pollingher, 1983, page 115), the dip of the coal beds which may vary from 22 to 45°, and the poor induration of the lignite-associated strata suggest that open pit mining is the most feasible, long-scale mining method. Diverssion of the Carboneras River is not likely to be viable; mining below the river level may be technically difficult and hazardous (Centram, 1970). Centram also estimated that approximately three million cubic meters of lignite could be mined considering these limitations.

The high ash and sulfur content of the lignite, and its relatively low calorific value and rank (see tables 3 to 5, appendix B) constrain its potential applications. High-scale burning of lignite without reducing its sulfur and ash content or may create environmental hazards and technical complications (such as corrosion, slagging, and

fouling) with intervening equipment. Preliminary tests on coal-washing methods have yield encouraging results (Lee Mosheim, 1989, personal communication).

The argillaceous strata, some of which are interbedded with the lignite beds, are an additional economic resource. Their exploitation in conjunction with the lignite may increase the economic potential of any future operation. Their possible uses include floor, roof, and decorative tiles among many other ceramic applications. A face-brick industry may reduce the strong shortage of good quality building brick in the country. The properties of the different clay types should be thoroughly evaluated; the potential reserves, specially for simple ceramic applications, are relatively high.
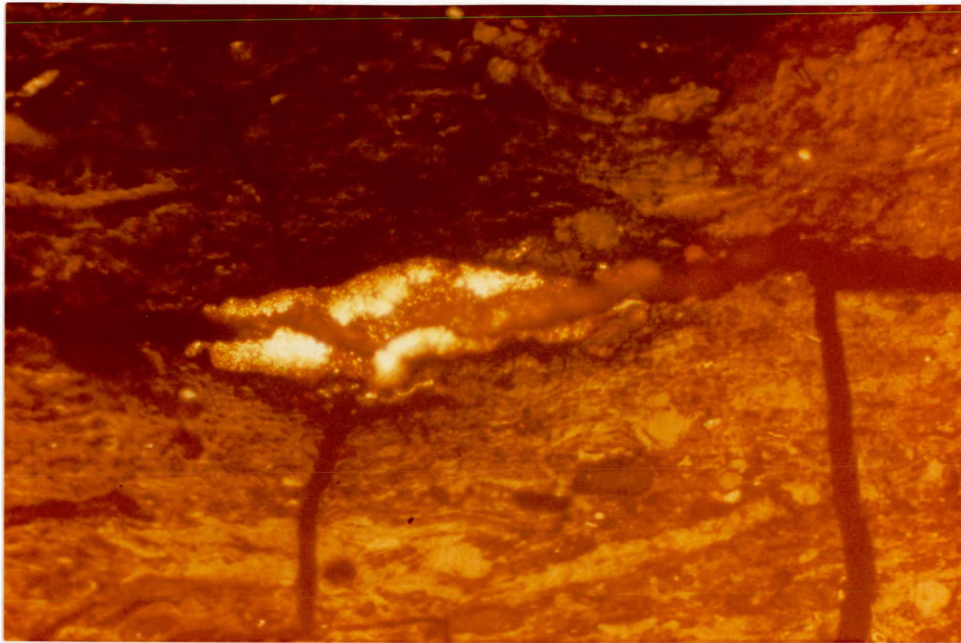
Figure 28. Pyrite along microfissure in vitrinite. White light, 200X.
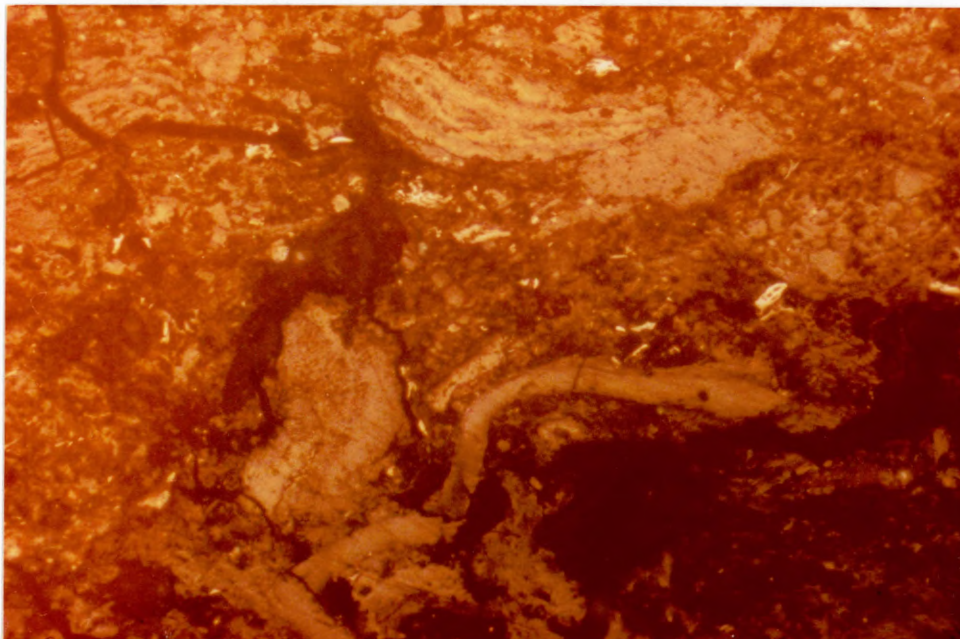
Figure 29. Typical appearance of vitrinite macerals. White light, 200X.
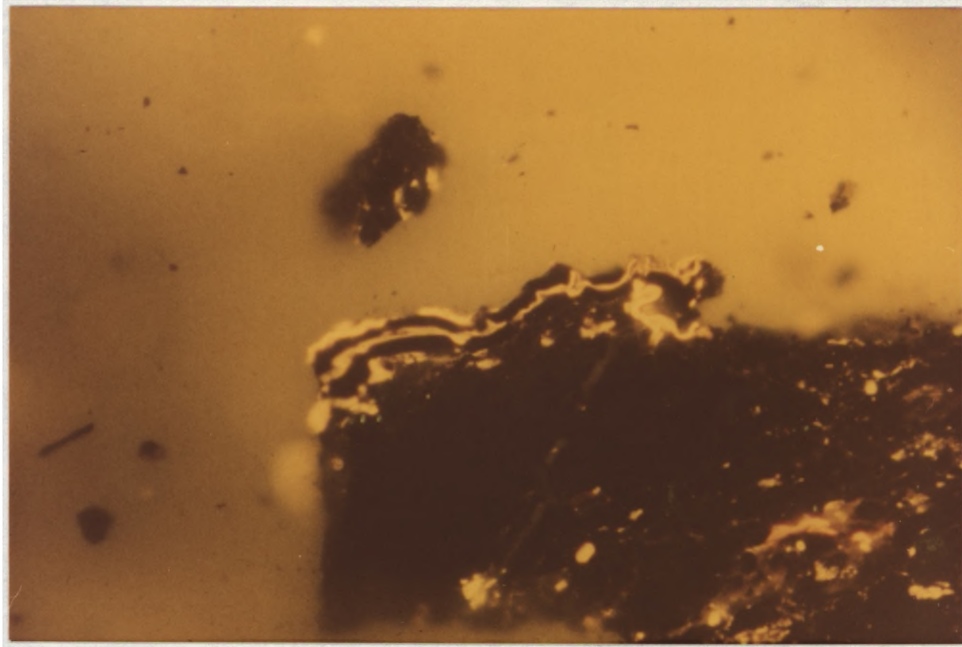
Figure 30. Fluorescing bright yellow liptinite, probably cutinite (curved bands), and liptodetrinite (yellow spots), in vitrinite (dark area). Greenish-yellow is polyester resin. Blue light, 200X.
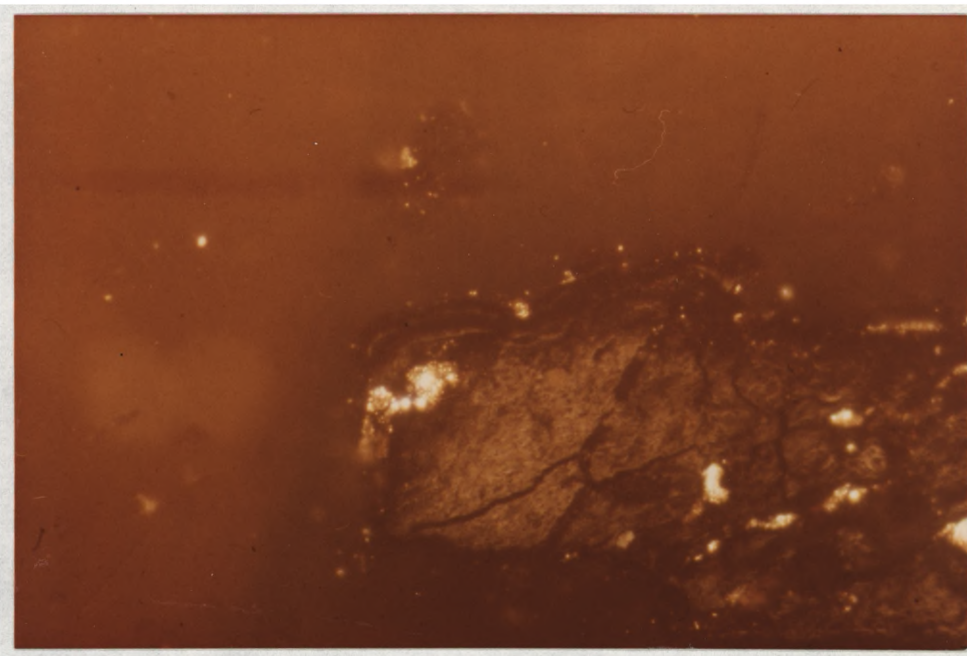
Figure 31. Same as above, white light. Bright spots are pyrite. 200X.
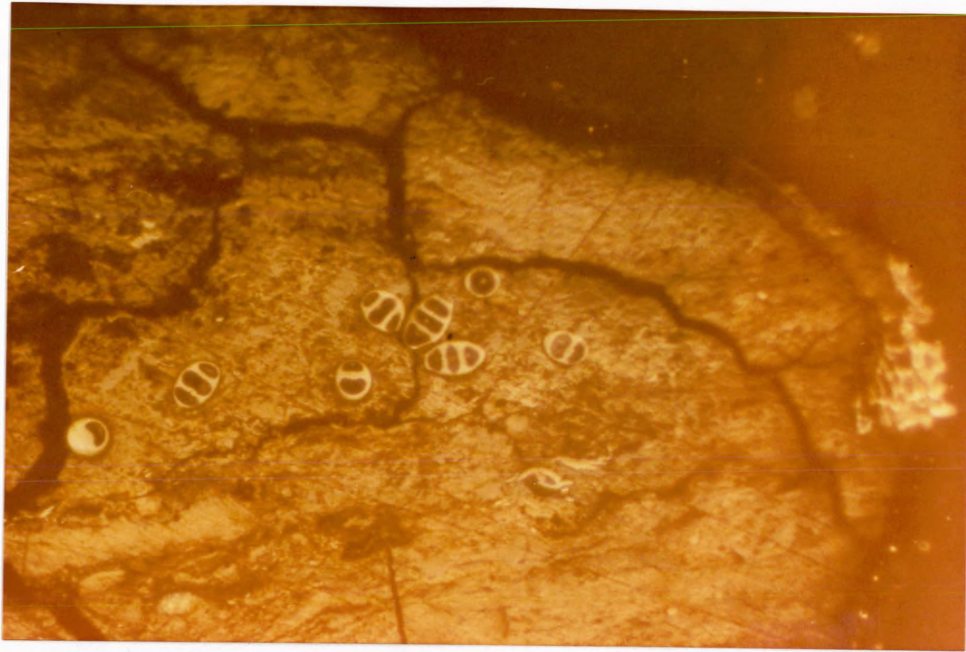
Figure 32. Fungal sclerotinite in vitrinite; microfissures are associated with weathering. White light, 200X.
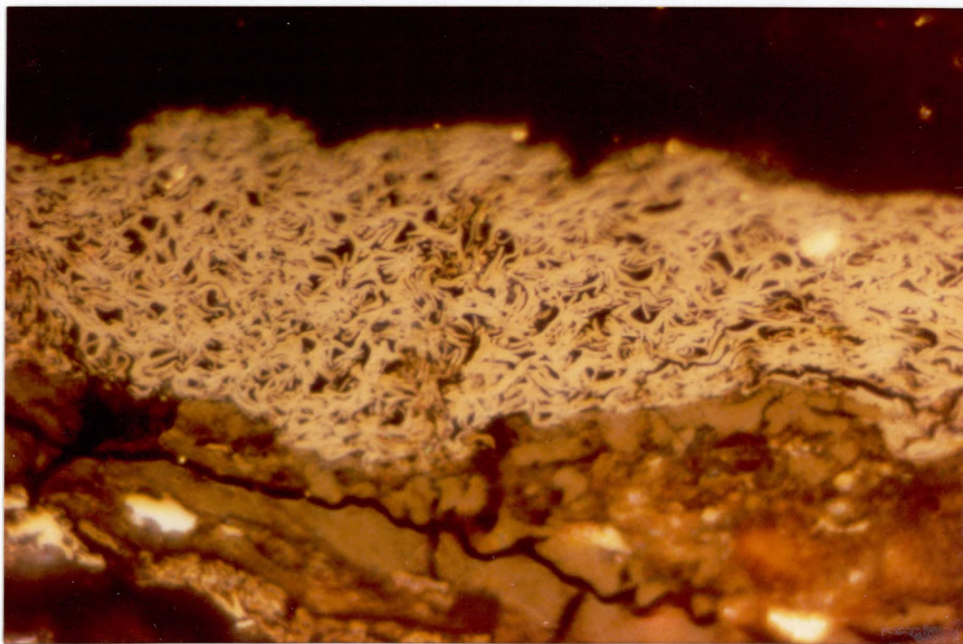
Figure 33. Fusinite showing partly fractured and collapsed cell walls (upper part). White light, 200X.
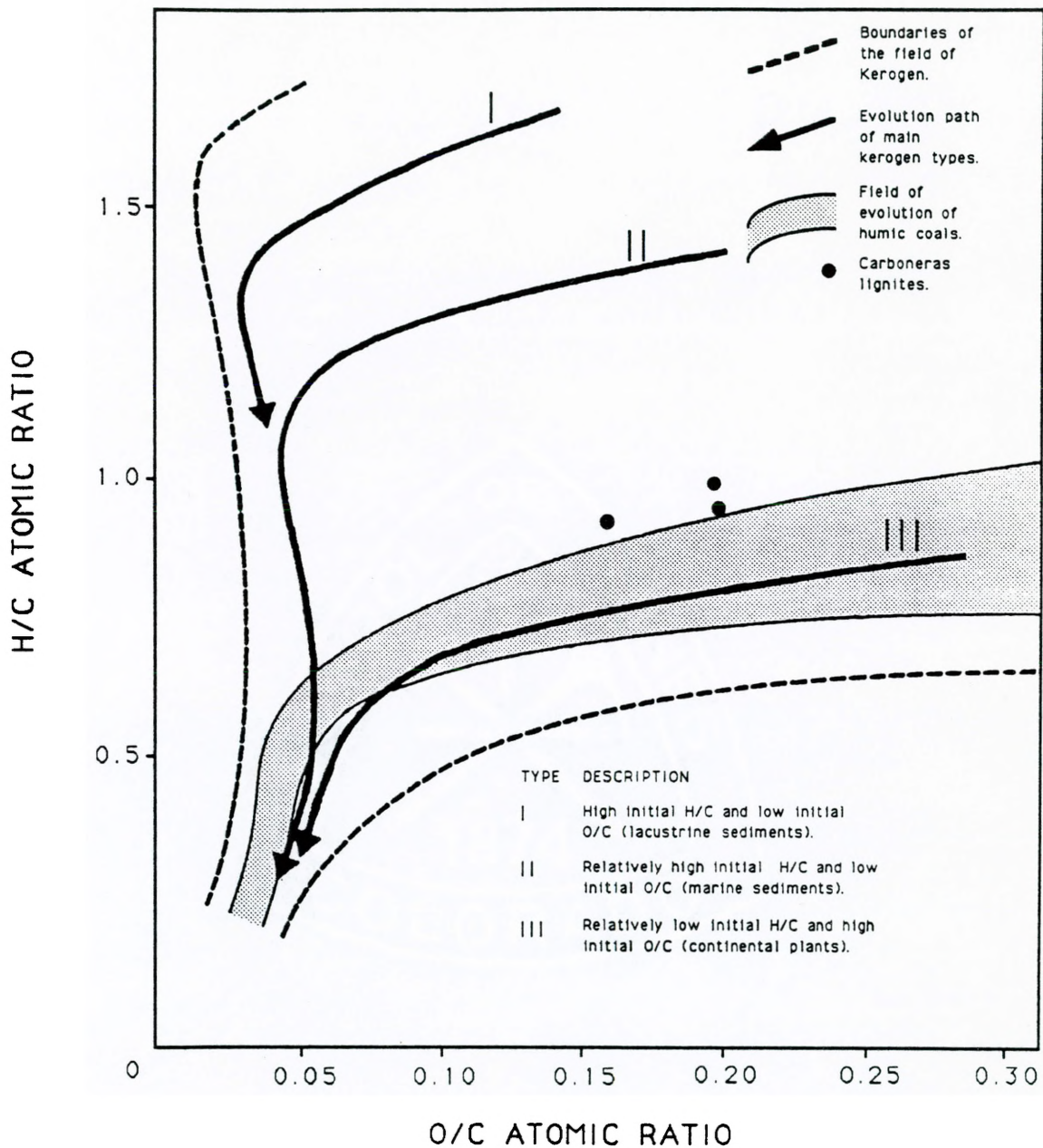
Figure 34.   Van Krevelen diagram showing the kerogen type in selected lignite samples
(see appendix B, table 4).

DEPOSITIONAL MODEL

The interpreted facies comprising the measured section can be divided into three main categories: fluvial, volcanic, and gravity flow deposits. Table 2 summarizes the facies, their thickness, interpretation, and category.

Table 2. Facies summary.

- -

FACIES	THICKNESS (m)	INTERPRETATION	CATEGORY
A	11.50	well drained swamps subject to flooding	fluvial (lacustrine?)
B	8.75	debris flow	gravity
C	32.28	overbank flooding	fluvial
D	5.80	pyroclastic fall	volcanic
E	22.40	crevasse-splay, vertical accretion	fluvial
F	13.55	active channel fill	fluvial
G	80.22	well to poorly drained swamps subject to flooding	fluvial (lacustrine?)
covered	110.00	-	-
H	82.46	alluvial fan	fluvial
TOTAL	366.96		

- -

Rivers tend to run either perpendicular or parallel to structural strike in non-marine basins within or adjacent to uplifted fold belts (Miall, 1981, page 4). In intermontane basins, like the LIB, whose length is much longer than its width, both drainages must coexist; the perpendicular drainages shedding from the surrounding mountains are tributary to either a lake or a main longitudinal trunk river that serves as drainage to the basin, or in turn are tributary to a lake in a deeper part of the basin.

The Motagua and CCP fault systems and their related features, although not conclusively dated, are older than Miocene. Considering this, it is expected that during the deposition of the Carboneras formation, the Sierra de las Minas, Cerro San Gil, and Montaña del Mico were already bounded to the north and south by these fault systems Furthermore, because the sedimentary rocks in the LIB and Motagua Valley have a few lithologic similarities but cannot be considered lateral equivalent facies within a same basin, these mountains were already structural highs and formed the southern edge to the LIB in a fashion similar to the present.

The clastic facies in the measured section (excluding facies D) are predominantly composed of rudaceous or sandy-argillaceous rocks. In the case of the rudaceous deposits (facies B and H), the gravity flow origin of facies B, the predominance of intraformational clasts in facies H, and the observed normal faults at the edge of the basin, suggest a provenance perpendicular to the structural strike of the basin probably associated with alluvial fans building from the south-bordering mountains into the center of the basin.

On the other hand, those facies comprising predominantly sandy-argillaceous strata (facies A, C, E, F, and the massive siltstone and mudstone in facies G), require a river whose size and area of influence cannot be accounted for only with the runoff of the surrounding mountains. Either by the physical requirements of their interpreted

depositional environment, or the extraordinary magnitude of individual events, these facies are interpreted as associated to a main longitudinal trunk river. For example, the thickness of individual flood events in facies C and the vertical persistence of the same type of deposits for more than 32 m can be better understood if associated to a main longitudinal trunk river various orders-of-magnitude bigger than the above mentioned perpendicular streams.

Among those facies interpreted as associated to a longitudinal trunk river, there is a predominance of flood plain deposits. Theoretical models on alluvial stratigraphy (Alexander and Leeder, 1987, pages 243-252; Allen, 1978, 1974; Bridge and Leeder, 1979; Leeder, 1978) suggest that if a rapid subsidence prevails, fluvial sandstone bodies tend to be isolated in flood plain deposits, as in the present case, where only a small part of the measured section (facies F) corresponds to active channel fill. The rudaceous deposits are supportive of strong syndepositional subsidence in the basin, and are additionally indicative of basement faulting with development of large topographic relief.

In a basin associated with a major fault system, a strong tectonic control on sedimentation is expected. The predominant left-lateral displacement that has been documented along the CCP fault in western Guatemala, and the geomorphologic features of the basin, suggest that the LIB is a pull-apart environment. Although a strong tectonic control on sedimentation is evident, the major characteristic of a strike-slip basin, i. e. sedimentation accompanied by significant strike-slip (Mann et al., 1983), cannot be proved, nor rejected, relying only on the current available information.

No strike-slip is needed to match the conglomeratic deposits to their likely source; in fact, according to the regional geologic map of the area, their most probable source is the Cerro San Gil-Montaña del Mico. However, the lack of additional outcrops or

subsurface information to study the lateral variability of the facies, causes difficulty in establishing the specific tectonic controls on sedimentation. The lack of detail in the regional geologic map, the presence of similar rock types throughout the mountains along the southern edge of the basin, and the predominance of volcaniclastic rocks in facies B further impede establishing definitive conclusions regarding the nature of strike-slip displacements. At any given time, strike-slip basins are hybrids associated with regional extension or shortening; most are composite basins influenced by varying tectonic controls during their evolution (Cristie-Blick and Biddle, 1985). Thus, even if strike-slip cannot be documented in the specific area of this study, no definitive conclusions can be made without studying the sedimentary features of other parts of the basin.

Figure 35 is a generalized block diagram of the depositional environments based on the integration of field data and interpretations. The morphology of the mountains, river and pond features, and the location of the high-angle normal faults at the edge of the basin are hypothetical.
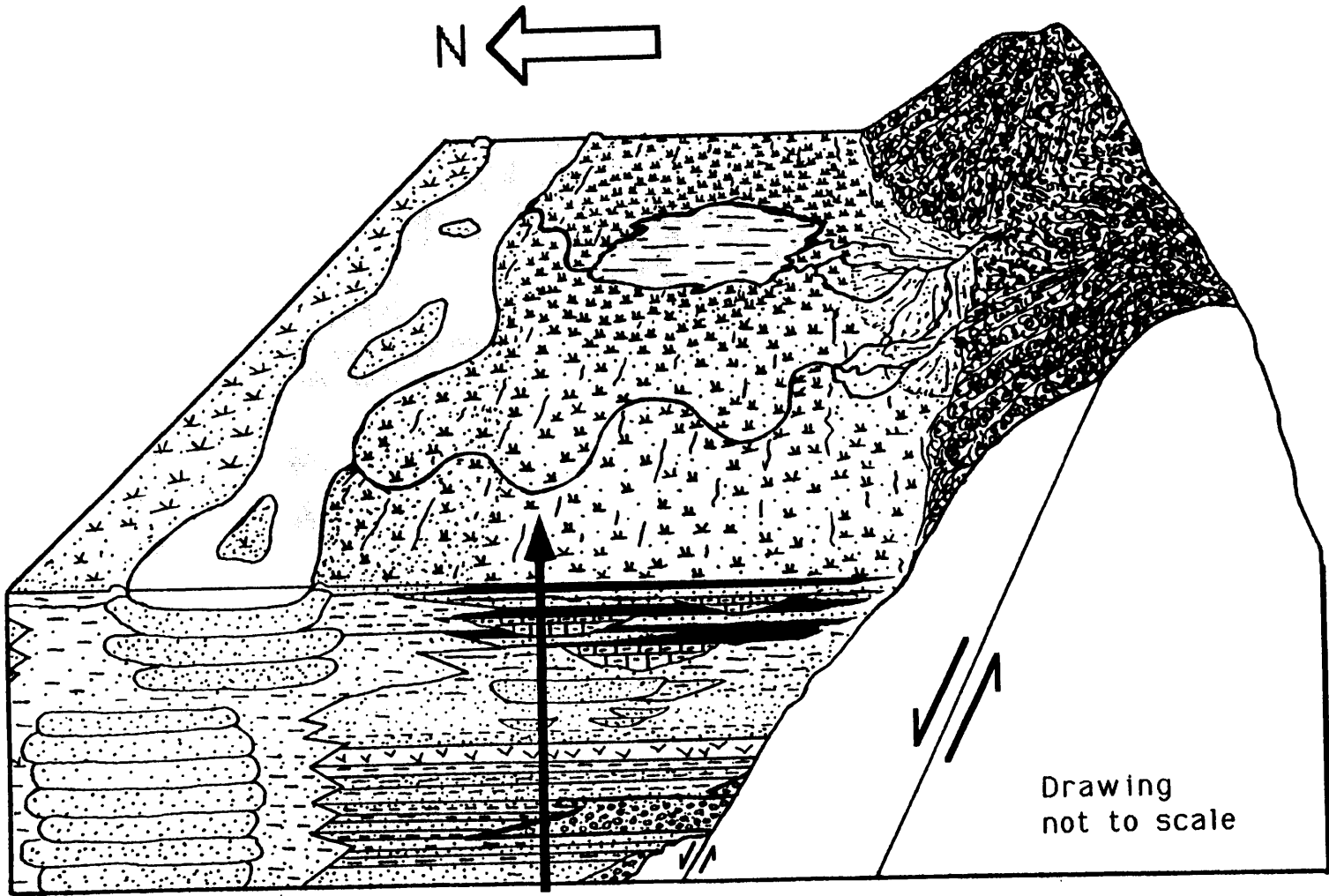
Figure 35. Hypothetical reconstruction of depositional environments of facies A through G. Deposition of facies H occurred after the previous facies were faulted, along the mountains, with development of topographic relief. Vertical arrow indicates approximate location of measured section.

CONCLUSIONS

Detailed measurements of the coal-bearing and associated strata cropping out along a portion of the Carboneras River were interpreted. A generalized model for the development of the southern margin of the LIB was formulated based on the stratigraphic interpretations and main structural features of the area.

The Paleogene formations present in the LIB and its surroundings were deposited in a complex depositional setting; only the Río Dulce and Herrería formations, and the studied coal-bearing strata appear to be areally limited to the LIB.

The measured section accumulated in a complex intermontane basin associated with the eastern portion of the CCP fault locally characterized by the abundance of detrital rocks, organic matter, and absence of marine influence. The sediment input was supplied through various sources: a main longitudinal river, an isolated volcanic event, and perpendicular gravity flows and alluvial fans emanating from the surrounding mountains.

An environment characterized by rapid subsidence with generation of topographic relief is suggested by the presence of intraformational clasts, gravity flow deposits, and the predominance of flood plain over active channel deposits in those rocks associated with a longitudinal river. The strike-slip environment suggested by the morphology and geologic and tectonic setting of the basin cannot be proved, nor rejected, relying only on the current available information.

The studied coal-bearing strata likely accumulated in swamps within a rapidly aggrading alluvial plain. Peat formation and accumulation was often interrupted by the development of sizeable open pools (or river-lakes) within the swamps and the

accumulation of flood-borne debris, resulting in the observed interbedding of peat, pond and flood deposits.

West-plunging folds with a rather constant plunge along the fold axes characterize the studied area. High angle normal faults perpendicular to the fold axes are present at the base of the Cerro San Gil, giving it a down-stepping configuration. All the strata in the measured section show tectonically-induced deformation; this is especially notable in the lignite and associated beds where small-displacement normal faults and slickenslides are present throughout, in addition to the regional deformation. In case any mining operation is planned, special consideration must be given to the fact that the area is seismically active.

Coal beds with a total thickness in excess of 15 m are present in the measured section. Physical, chemical and petrographic analyses of selected samples indicate a maturity rank of lignite, high ash and sulfur content and an origin derived from terrestrial plants. The relatively low specific energy of the lignite and its high sulfur and ash content constrain its potential applications; environmental hazards and technical problems with intervening equipment may arise if high scale burning of lignite is performed without previously reducing its sulfur and ash content. The argillaceous strata are an additional economic resource; their potential reserves, especially for simple ceramic applications, are relatively high. Exploitation of the lignite in conjunction with the clay may increase the economic potential of any future operation.

Exploitation of these resources may decrease the dependence of Guatemala on imported fuels, create new sources of employment, and boost the economic development of the Departamento.

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APPENDIX A

Main features of Lake Izabal.

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Altitude	+0.9 m to a few meters
Area	717 km^2
Maximum depth	16.8 m
Mean depth	11.6 m
Maximum length	50 km; 70 km including El Golfete
Maximum width	20 km
Volume	8,300 million m^3
Watershed area	6,862 km^2
Watershed area: lake volume ratio	0.83 m^2/m^3
Drainage	Rio Dulce, 42 km long. The Rio Dulce broadens half way to the sea to form El Golfete, a shallow water body 7.5 m deep.
Main inlet	Polochic river (76% of the watershed).
discharge of main rivers	13,290 million m^3/year (measured for the 1971-1972 hydrological cycle).

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Modified from Serruya and Pollingher, 1983.

APPENDIX B

CHEMICAL ANALYSES OF LIGNITE

Lignite samples were submitted to a commercial testing laboratory for proximate, ultimate and ash analyses (tables 3 to 5, respectively). Due to the previously determined similarities between the different seams (Centram, 1970), only one sample was analyzed for elemental analysis and fusion temperatures of ash. The different analyses were carried according to ASTM standards for coal and coke (Willis Collins, personal communication, 1989). The ash viscosity calculations, and slagging and fouling types were computed following Sage and McIlroy, 1960; Duzy, 1965; Attig and Duzy, 1969; and Vecci et al., 1978.

PETROGRAPHIC ANALYSES OF COAL

Five lignite samples were prepared for petrographic study following procedures modified from Bostick and Alpern, 1976. The samples were crushed to 2-4 mm size using a mortar and pestle. The crushed lignite was sieved to eliminate the finer particles, mixed with polyester resin, and placed in a cylindrical mold; the lignite particles were concentrated on one face of the mold by centrifugation. A small amount of resin catalyzer was used to avoid excessive heating. The mounted samples were ground using successively finer carburundum papers; aluminum oxide was used for polishing. Care was taken to leave a flat final surface free of scratches, with as little relief as the lignite samples permitted.

The lignite samples were examined under reflected white and blue light using a coal petrography microscope. The macerals were identified at magnifications of 200

Table 3. Proximate analysis of lignite samples.

Sample Identification	AS RECEIVED			DRY			AIR DRY		
	OC0104	OC06	PT10	OC0104	OC06	PT10	OC0104	OC06	PT10
MOISTURE	29.43	24.71	31.30	00.00	00.00	00.00	9.85	13.77	10.64
ASH	20.60	13.62	12.85	29.18	18.09	18.70	26.31	15.60	16.71
VOLATILE	30.50	37.10	33.17	43.22	49.28	48.28	38.96	42.49	43.14
FIXED C	19.47	24.57	22.68	27.60	32.63	33.02	24.88	28.14	29.51
SULFUR	3.92	4.79	4.31	5.56	6.37	6.28	5.01	5.49	5.61
BTU/LB	5823	7444	6641	8252	9888	9667	7439	8526	8638
MMF BTU/LB	7443	8716	7672	12188	12434	12249			
MAF BTU/LB				11653	12071	11890			
AIR DRY LOSS (%)	21.72	12.69	23.12						

Table 4. Ultimate analysis of lignite samples.

Sample identification	AS RECEIVED			DRY			AIR DRY		
	OC0104	OC06	PT10	OC0104	OC06	PT10	OC0104	OC06	PT10
MOISTURE	29.43	24.71	31.30	00.00	00.00	00.00	9.85	13.77	10.64
CARBON	33.46	42.54	37.47	47.42	56.50	54.54	42.75	48.72	48.74
HYDROGEN	2.75	3.33	2.97	3.90	4.43	4.32	3.52	3.82	3.86
NITROGEN	0.82	1.13	0.97	1.16	1.50	1.41	1.05	1.29	1.26
SULFUR	3.92	4.79	4.31	5.56	6.37	6.28	5.01	5.49	5.61
ASH	20.60	13.62	12.85	29.18	18.09	18.70	26.31	15.60	16.71
OXYGEN*	9.02	9.88	10.13	12.78	13.11	14.75	11.51	11.31	13.18
LB. ASH/MM BTU	35.37	18.30	19.34						
LB. SO2/MM BTU	13.47	12.88	12.99						

* Oxygen by difference.

Table 5. Elemental analysis, fusion temperatures, and viscosity calculations for ash in sample OC0104.

ELEMENTAL ANALYSIS OF ASH (%) ASH FUSION TEMPERATURES (DEG F)   ASH VISCOSITY CALCULATIONS

			Oxidizing	Reducing	Base content (%)	40.21
SIO2	29.06		Atmosphere	Atmosphere	Acid content (%)	59.79
AL2O3	16.75				Dolomite ratio	64.68
TIO2	0.88				Base/acid ratio	0.67
FE2O3	4.84	Initial	2210	2130	Silica/alumina ratio	1.73
CAO	15.61	Softening	2224	2152	T(CV) (deg F)	2384
MGO	4.70	Hemispherical	2249	2184	T250 temperature (Deg F)	2067
NA2O	5.63	Fluid	2530	2401	Equiv silica content (%)	53.61
K2O	0.62				Viscosity from equiv	
P2O5	0.34				silica @ 2600 F (poise)	13.65
SO3	16.01				Ash type	lignite
Total	94.44				Slagging type	severe
					Fouling type	high

and 500 diameters; different oil-immersion objectives and fixed eyepieces were used for this purpose.

Vitrinite reflectance measurements were made using a photometer mounted on the microscope and interfaced to a computer. 50 point-values were measured for each sample and processed by the computer to calculate the mean value, standard deviation, class listing and histogram.

POWDER X-RAY DIFFRACTION METHODS

Qualitative identification of major mineral constituents was made using powder X-ray diffraction methods on fine-grained, silicified, and altered pumiceous rock samples. The samples were air dried, ground to very fine powder, and mounted on the specimen holder. A Rigaku Rotaflex diffractometer (model Ru 200, copper target $K\alpha$, rotating anode system) with a computer-interfaced controller was used to generate the diffraction patterns. Trial runs were made to determine the appropriate voltage and ampere settings as well as scan speeds.

The major minerals were identified comparing the obtained 2θ values or d spacings with those listed in Chen (1977), and Brindley and Brown (1980). Smectite-group clays, quartz, and in some cases calcite are the major identified minerals; palygorskite was found to be present only in two samples. No specific end members of the smectites were identified. Several samples were analyzed both air dried and after being dried for one hour at 90° C. The resulting patterns show a shift of the basal diffractions located between d = 14.42-15.35 Å (2θ = 6.125-5.75) to d = 12.71-13.49 Å (2θ = 6.95-6.55). This phenomenon is diagnostic of the dehydration of the interlayer, characteristic of the swelling nature of smectites (figure 36).
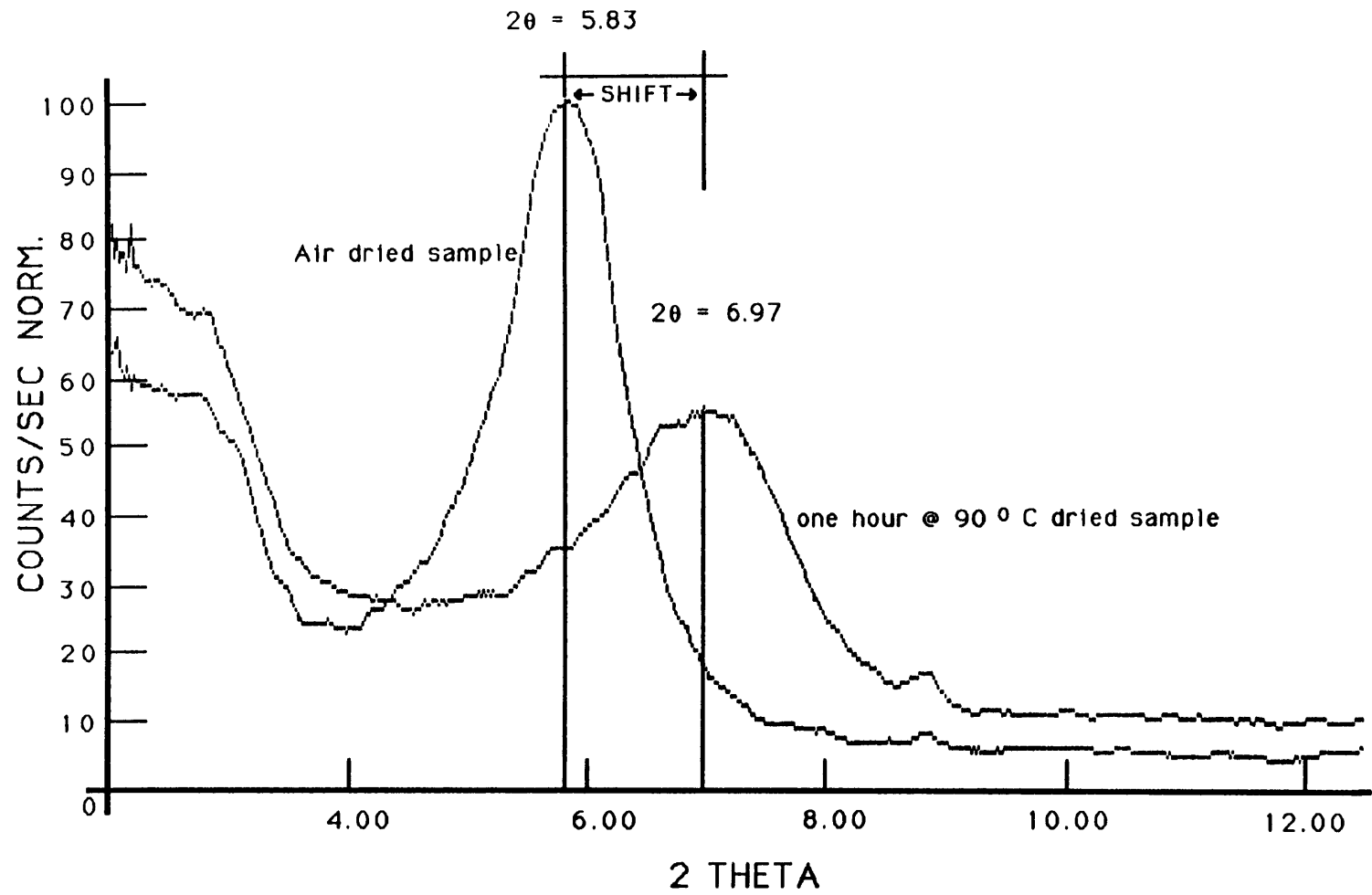
Figure 36. X ray diffraction pattern of argillaceous sample; air dried, and after drying at 90° C for one hour.

In general, the diffraction patterns may be affected by other minerals whose amount is beneath the detection limit; figure 37 is a representative pattern of the analyzed samples.
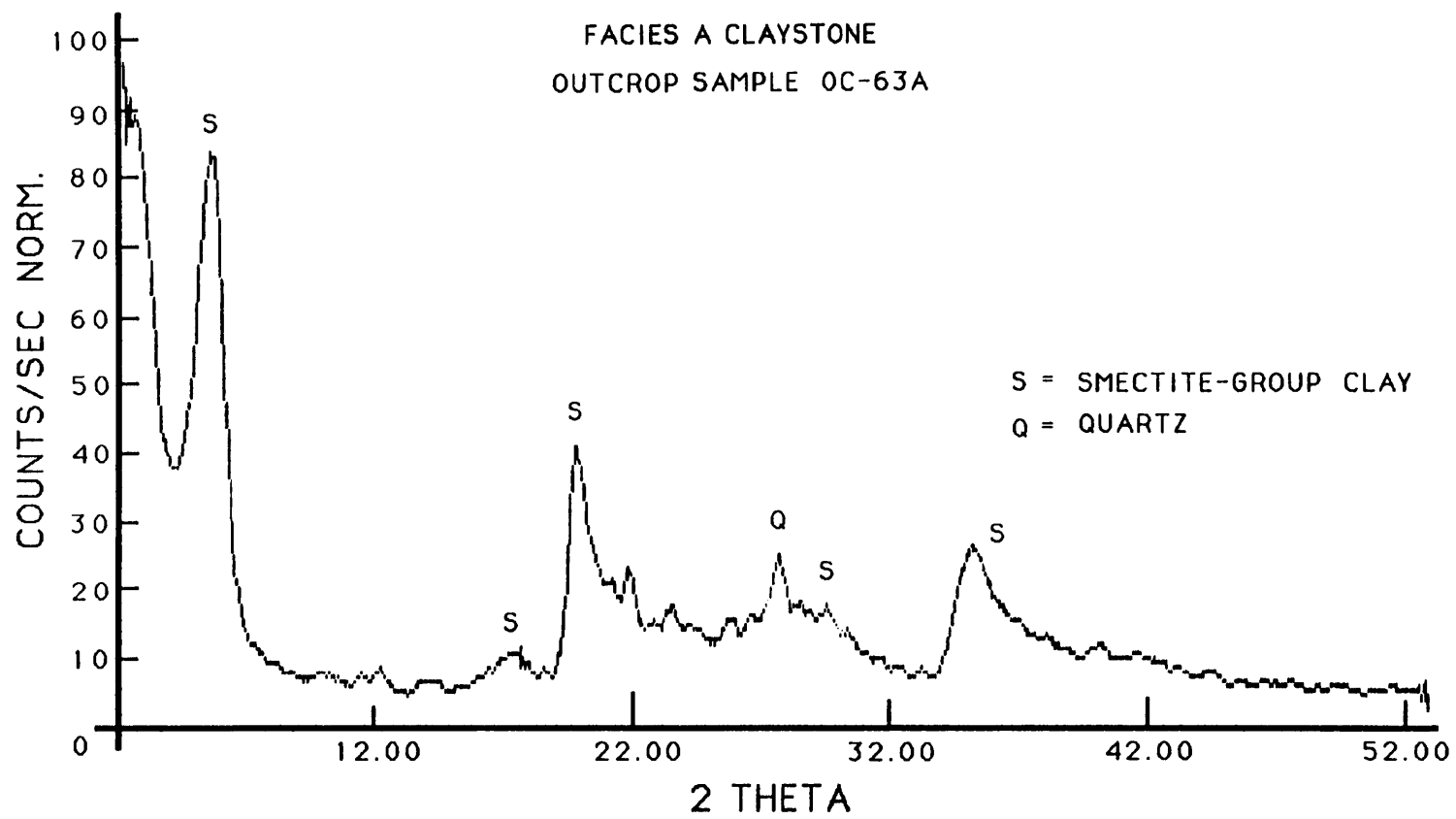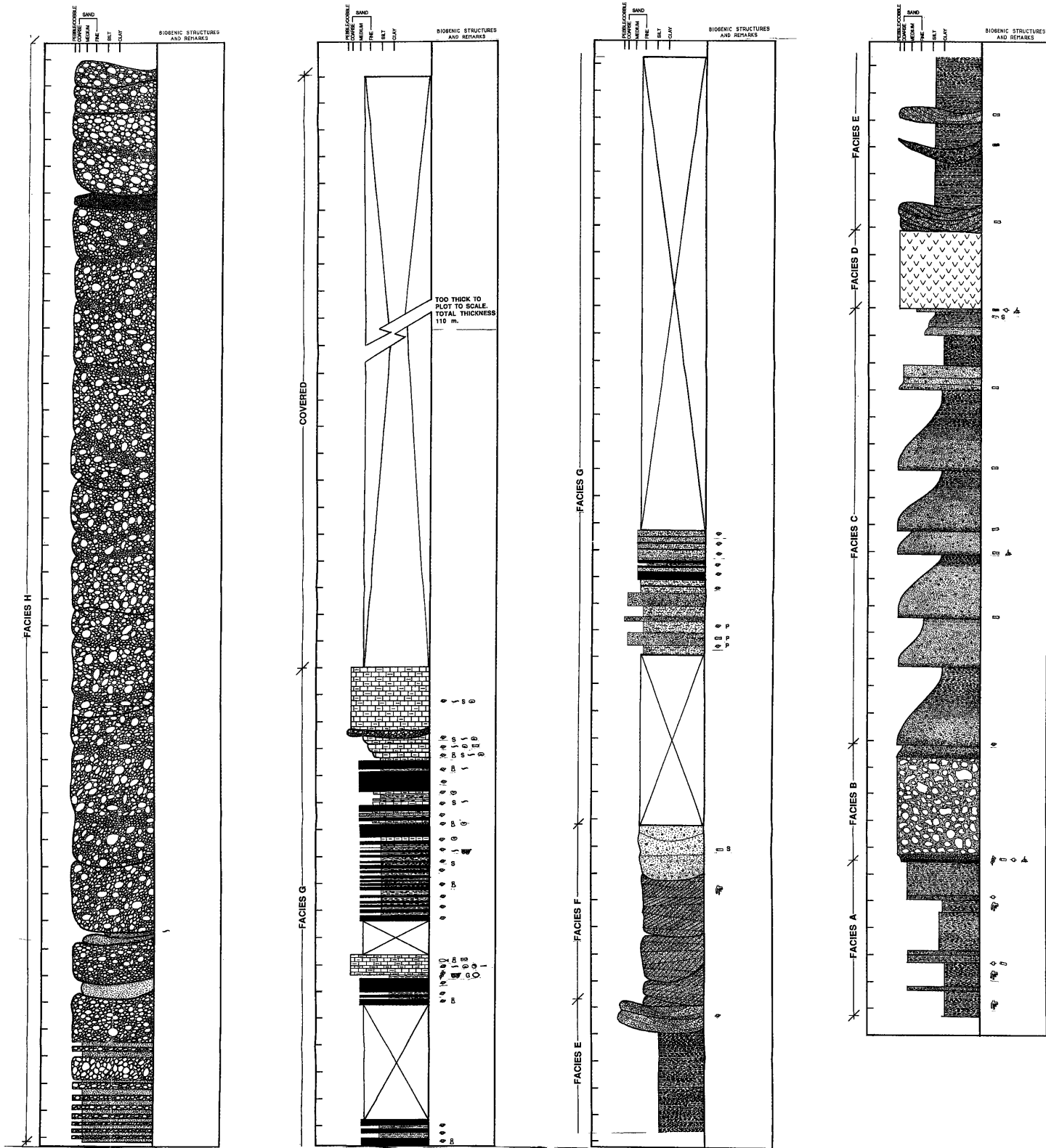
Figure 37. Representative X ray diffraction pattern of analyzed samples.

FACIES H

FACIES G

COVERED

TOO THICK TO
PLOT TO SCALE.
TOTAL THICKNESS
110 m.

FACIES G

FACIES F

FACIES E

FACIES G

FACIES E

FACIES D

FACIES C

FACIES B

FACIES A

LITHOLOGY AND SEDIMENTARY STRUCTURES

- Claystone / mudstone
- Siltstone
- Silty-pebbly mudstone
- Tabular planar cross-stratified very fine sand-stone
- Massive / tabular sandstone
- Massive sandstone, silicified.
- Lignite
- Marl

- Well sorted granule-pebble conglomerate
- Planar-bedded pumice and bone fragment conglomerate in muddy matrix
- Trough cross-stratified coarse sandstone and granule conglomerate
- Trough cross-stratified mud-supported conglomerate
- Trough cross-stratified rip-up conglomerate
- Conglomerate, predominantly coarse-sand supported
- Unsorted matrix-supported conglomerate
- Altered pumice

- Mica flakes
- Carbonaceous laminae
- S   Silicified
- G   Gypsum
- P   Pyrite

BIOGENIC STRUCTURES

- Silicified wood
- Coalified wood
- Roots
- Leaves
- Ferns

- Gastropods
- Ostracodes
- Pelecypods
- Chara
- Vertebrate bone fragments

- Fish teeth
- Fish bones
- Bioturbation (vertical, branching)
- Bioturbation (undiff.)

BIOGENIC STRUCTURES MODIFIED
FROM SWANSON, 1981

4
3
2
1   METERS
0

T-3682

PLATE 1

APPENDIX C

MEASURED SECTION

T-3682

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