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Preliminary Source Rock Evaluation of the Lower Cenozoic Toledo Formation, Belize Basin, Southern Belize

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ABSTRACT

A Paleogene sedimentary succession of the informally named Toledo formation crops out in the Toledo District of southern Belize along the newly cut Mile 14 highway. These outcropping strata in the southern Belize Basin have organic-rich beds that were analyzed for their hydrocarbon source potential. The Toledo formation is up to 3000 m thick in the basin and consists of submarine fan deposits composed of interbedded calcareous sandstones and mudstones with up to 45% calcite content, some pebbly conglomerates, and sparse detrital carbonate beds, but only a few hundred meters of this formation is exposed in the study area.

Thirteen outcrop samples of the Toledo formation with visible organic matter were analyzed using Leco carbon analysis and Rock-p Pyrolysis. Total organic carbon (TOC) values ranged from 0.26 to 1.86 wt% (avg. = 0.85 wt%) and hydrogen index values (HI) from 4 to 77 mg HC/g TOC. The TOC is mostly type IV kerogen from terrigenous woody plants and is gas prone. T_{max} values in the six samples where they could be measured at all ranged from 430 to 439°C, indicating they are immature to early mature for hydrocarbon generation. Unpublished geochemical results from cuttings in wells drilled in southern Belize reveal similar consistently low TOC values. Although our data set of selected samples is small and our results are preliminary, they contribute new information on the petroleum geochemistry of the Paleogene section in the Belize Basin.

INTRODUCTION

Oil and gas exploration in Belize began during the 1930s, and to date, more than 100 wells have been drilled. Most petroleum exploration efforts in Belize have focused on the Corozal Basin of northern Belize, where the Spanish Lookout and Never Delay fields were discovered during 2005 and 2009, respectively. The few exploration wells drilled in southern Belize have encountered minimal hydrocarbon shows, but there have been several oil seeps reported from within this area's Cretaceous limestones (Sanchez-Barreda, 1990; Petersen et al., 2012). The most recent well drilled during 2014 by US Capital Energy, Temash no. 2, is reported to have encountered some noteworthy oil shows, but was not declared a discovery.

Petersen et al. (2012) carried out source-rock evaluation and organic geochemistry on oils from both the Corozal and Belize basins. In the Belize Basin, their work was focused on oil seeps from Cretaceous carbonates. Their results identified organically lean source rocks (<0.5 wt% total organic carbon [TOC]) and very low S_2 pyrolysis yield, which suggested to them that most of the oil in Belize, both northern and southern, was derived from source areas in Guatemala (i.e., the Petén Basin). Presently, oil is produced from two declining fields in northern Belize, Spanish Lookout and Never Delay (Petersen et al., 2012), and no oil is produced from southern Belize. It is likely that southern Belize oil, if ever found in commercial quantities, will derive from a petroleum system that will include the Toledo formation, as both a reservoir and a seal, and underlying Cretaceous carbonates including the Coban formation (Petersen et al., 2012). Hence, it is important to understand more about this formation. Figure 1 shows the stratigraphy of the Belize Basin.

The hydrocarbon potential in the Lower Cenozoic Toledo formation was first suggested by Sanchez-Barreda (1990) based on a brief review of unpublished data from the offshore Palmetto Caye no. 1 well. In this well, he suggested that thin organic-rich lamina constitute a significant organic-rich component of the Toledo's stratigraphic sequence, which was approximately 3000 m thick in the well. Based on data in proprietary, unpublished reports on file with the Geology and Petroleum Department in Belmopan, there are petroleum shows in the Belize Basin's Punta Gorda no. 1 well, but they are below the Toledo formation. Results from unpublished geochemical reports on samples from the Palmetto Caye and Punta Gorda wells reportedly indicate overall very low organic matter (<0.5 wt% TOC), which is composed of oxidized terrestrial kerogen, within the Toledo.

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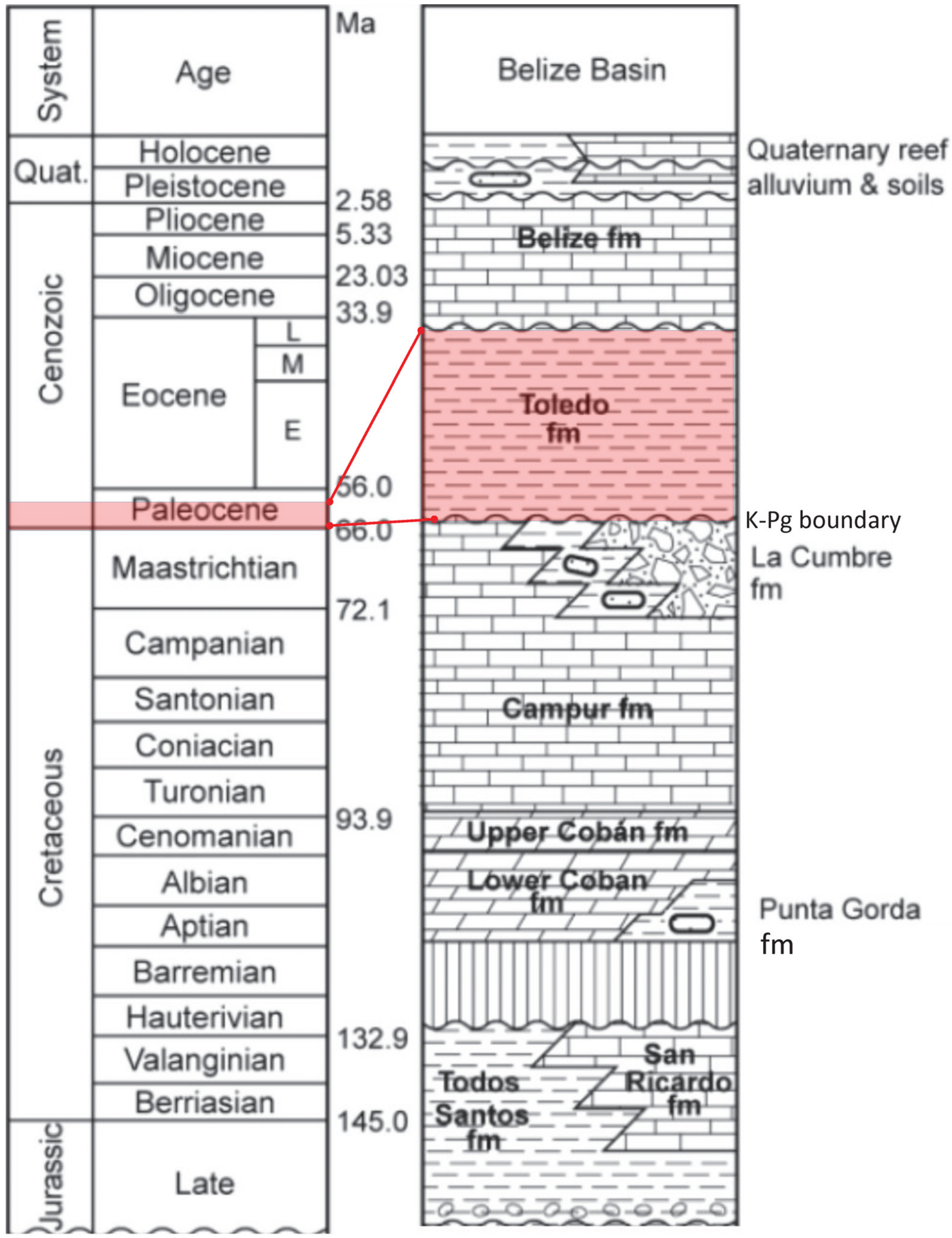
Figure 1. Lithostratigraphy of the Belize Basin (right), which has been updated from Purdy et al. (2003) and Petersen et al. (2012) by adding a new chronostratigraphy (left) from King and Petruny (2022). The age of the Toledo formation in the outcrop area has been determined to be middle Paleocene by Fisher et al. (2016) and Keller et al. (2003) have indicated that the Toledo conformably rests on the Cretaceous-Paleogene boundary (K–Pg). Those age relations are indicated by the red boxes and correlation lines shown in this figure.



This study provides a preliminary assessment of the hydrocarbon source potential of the Toledo formation based on outcrop sampling. Unfortunately, proprietary subsurface samples are presently unavailable for this purpose. In the present report, standard geochemical techniques were used to assess the quantity, quality, and thermal maturity of sedimentary organic matter from the perspective of hydrocarbon generation.

GEOLOGIC SETTING

The Belize Basin is a Late Jurassic to Paleogene feature located south of the Maya Mountains in southern Belize (Fig. 2). This basin is the eastward extension of the Chapayal Basin (or Southern Petén Basin) in Guatemala (Vinson, 1962; Bryson, 1975; Donnelly et al., 1990; Fourcade et al, 1999; Kim et al., 2011), and is both an onshore and offshore feature of southern Belize geology. Just south of the southern limit of the basin lies the Motagua-Polochic fault system, a left-lateral strike-slip fault system, related to the boundary between the North American and Caribbean plates (Pindell and Kennan, 2009) (Fig. 3).

The Cenozoic stratigraphic section of the Belize Basin crops out in several accessible locations within the Toledo District of southern Belize. Most notably along the northeast-trending section of the Southern highway (i.e., the highway follows approximately the depositional strike in the eastern part of the Belize Basin), Cenozoic strata of the Toledo formation crop out as far north as the village of Dump (Fig. 4). Also, on the newly built Mile 14 highway, westward from Dump toward the Guatemalan border, there is a well-exposed, approximate-strike section of the clastic Toledo formation. The Mile 14 highway section represents the middle part of the Belize Basin. In the Belize Basin, the Toledo attains maximum thicknesses of as much as 3000 m (as observed in exploratory wells; Purdy et al., 2003), however in outcrop a few hundred meters of section, mainly the upper part of the Toledo formation, is well exposed.

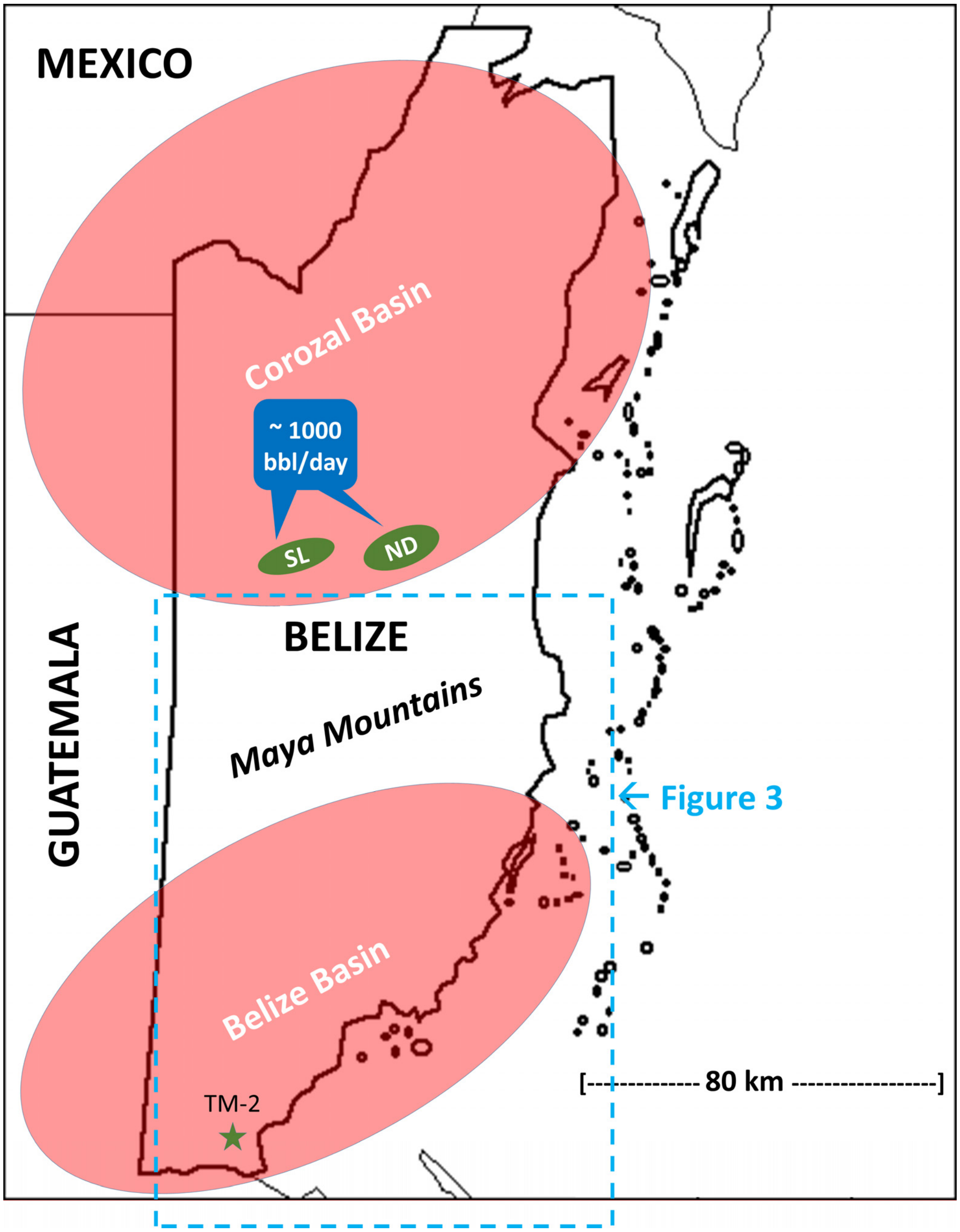


Figure 2. Belize's location with respect to adjoining countries. Also, the approximate locations of the Corozal Basin of northern Belize and the Belize Basin of southern Belize. The approximate location of the two northern Belize oil fields, Spanish Lookout (SP) and Never Delay (ND), are indicated as is the present level of combined production from those fields. The location of a recent exploration well with noteworthy oil shows, Temash–2 (TM–2), is indicated within the Belize Basin. The approximate area of Figure 3 is shown by the dashed box.

The Toledo's thick siliciclastic sequence both conformably and, in places, unconformably overlies Cretaceous Campur carbonates or the unnamed southern Belize Cretaceous-Paleogene ('KT') boundary ejecta deposits. Cretaceous and Paleogene sediments, particularly the informal Toledo formation, exhibit substantial downdip thickening over short lateral distances within the basin, thus indicating the presence of faults active since Cretaceous (Bryson, 1975; Whittaker, 1983). The Toledo formation's age (Paleogene; Keller et al., 2003) has been affirmed by recent nannofossil analyses (Fisher et al., 2016).

The Toledo formation is an informal unit in Belize stratigraphy; hence the name is written with a lower-case "f" (as per the International Stratigraphic Guide [Salvador, 1994] and the North American Stratigraphic Code [NACSN, 2005]). Formal stratigraphic units must be published in a recognized scientific medium and must include a statement of intent to designate that formal unit. On both of these points, the Toledo formation and nearly all other stratigraphic units in Belize fail to qualify as formal units. For a more detailed discussion on the informal status of the Toledo, the reader is referred to comments in Fisher and King (2015).

The siliciclastic sequence of the Toledo formation consists of interbedded calcareous sandstone and mudstone, sandstone, conglomerates, and carbonates (more common in the upper part of the Toledo) and is interpreted as a laterally extensive submarine fan deposit (Fisher and King, 2015). The schematic depositional setting for the Toledo formation's submarine fans is shown in Figure 5. Further analysis of Toledo lithofacies by Fisher and King (2016) caused them to subdivide the Toledo stratigraphic sequence into seven fan-related lithofacies (in accordance with lithofacies A–G of the submarine-fan model of Mutti and Ricci Lucchi [1975]).

Briefly summarizing these lithofacies (A to E) in relation to the Toledo depositional model (Fig. 5), lithofacies A is a polymict, cobble- and boulder-bearing conglomerate with a medium immature sandstone matrix, which likely occupied the

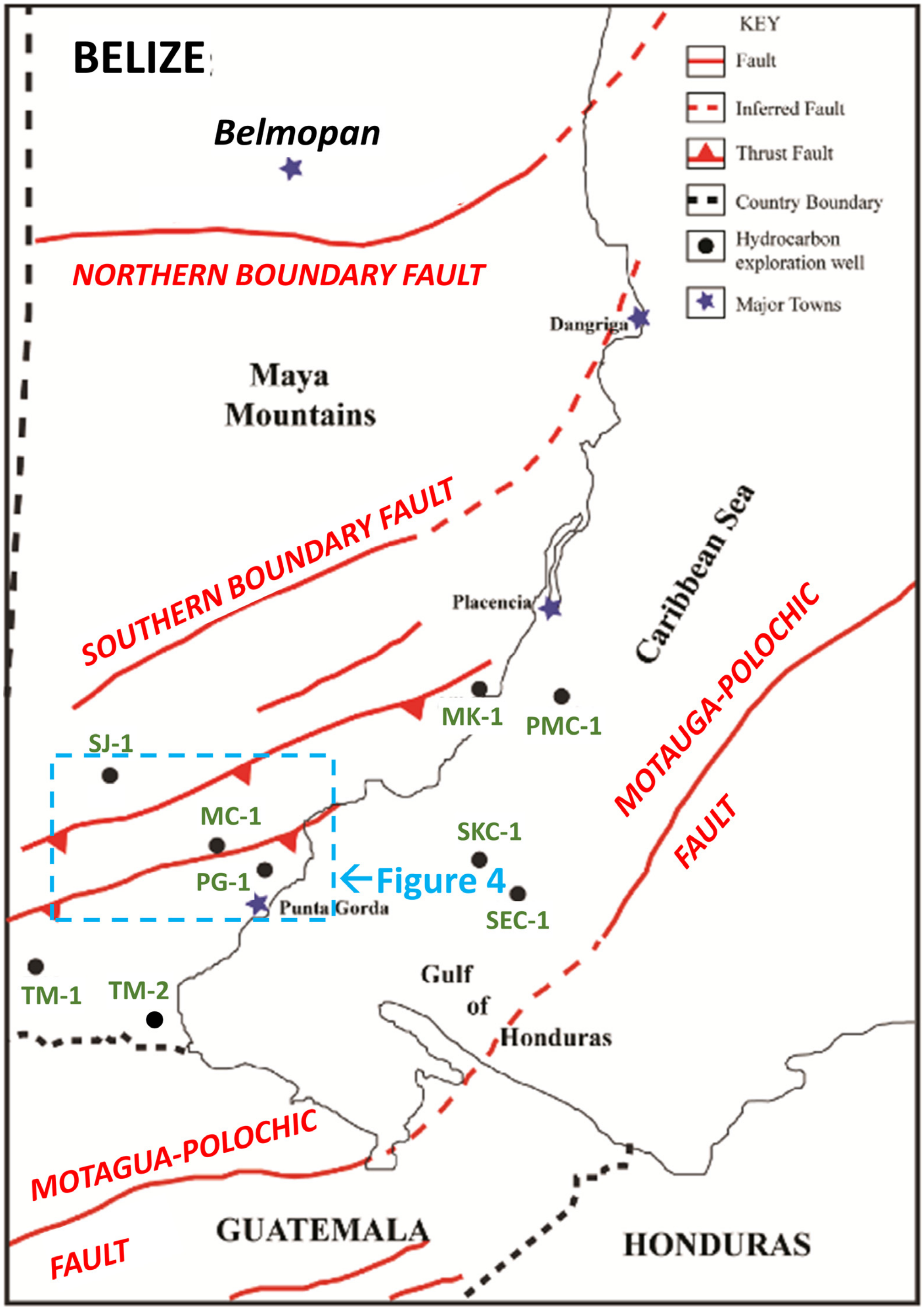


Figure 3. Simplified structural map of central and southern Belize showing key faults, major towns, and locations of exploratory wells drilled (modified after Purdy et al. [2003]). The Belize basin lies approximately between the Southern Boundary fault of southern Belize and the Motagua-Polochic fault of northern Guatemala. Wells drilled in the Belize basin are indicated: MC–1 (Machaca–1), MK–1 (Monkey River–1), PG–1 (Punta Gorda–1), PMC–1 (Palmetto Cay–1), SEC–1 (Seal Cay–1), SKC–1 (Snake Cay–1), SJ–1 (San Jose–1), TM–1 (Temash–1), and TM–2 (Temash–2). The approximate area of Figure 4 is shown by the dashed box.

proximal reaches of the main channel apex (Fisher and King, 2016). Lithofacies B is coarse to medium, immature sandstone, which occurs in massive, scour-based beds, and is interpreted as an upper channel-filling deposit (Fisher and King, 2016). Organic-rich deposits were not noted in lithofacies A or B, however noteworthy organic-rich beds were observed within lithofacies C, D, and E.

Lithofacies C is a fine to coarse, immature sandstone with organic-rich interbeds of silty mudstone and mudstone (Fig. 6A), which were likely deposited in extra-channel areas or areas directly adjacent to the channel, within the middle-fan setting (near the mid-fan "channel-levee complex" in Figure 5 [Fisher and King, 2016]). Sandstone beds of lithofacies C are commonly 0.25 to 2.5 m thick and grade upwards into thin mudstone layers. Sandstone-to-shale ratios are generally high. Beds show little or no channelization, and as a result, tops and bottoms of beds are parallel. Due to the presence of thin interbeds of mud, features such as sole marks and trace fossils are well preserved.

Lithofacies D (Fig. 6B) consists of interbedded thin, calcareous sandstone and silty mudstone. The sandstone is fine to medium-grained and contains organic matter in some outcrops. Beds are generally 0.05 to 0.40 m thick, parallel, and persist laterally for great distances. Sandstone-to-mudstone ratios are variable and are generally one or less. Thick strata sections of lithofacies D are gradational with thin intervals of lithofacies C, and the two

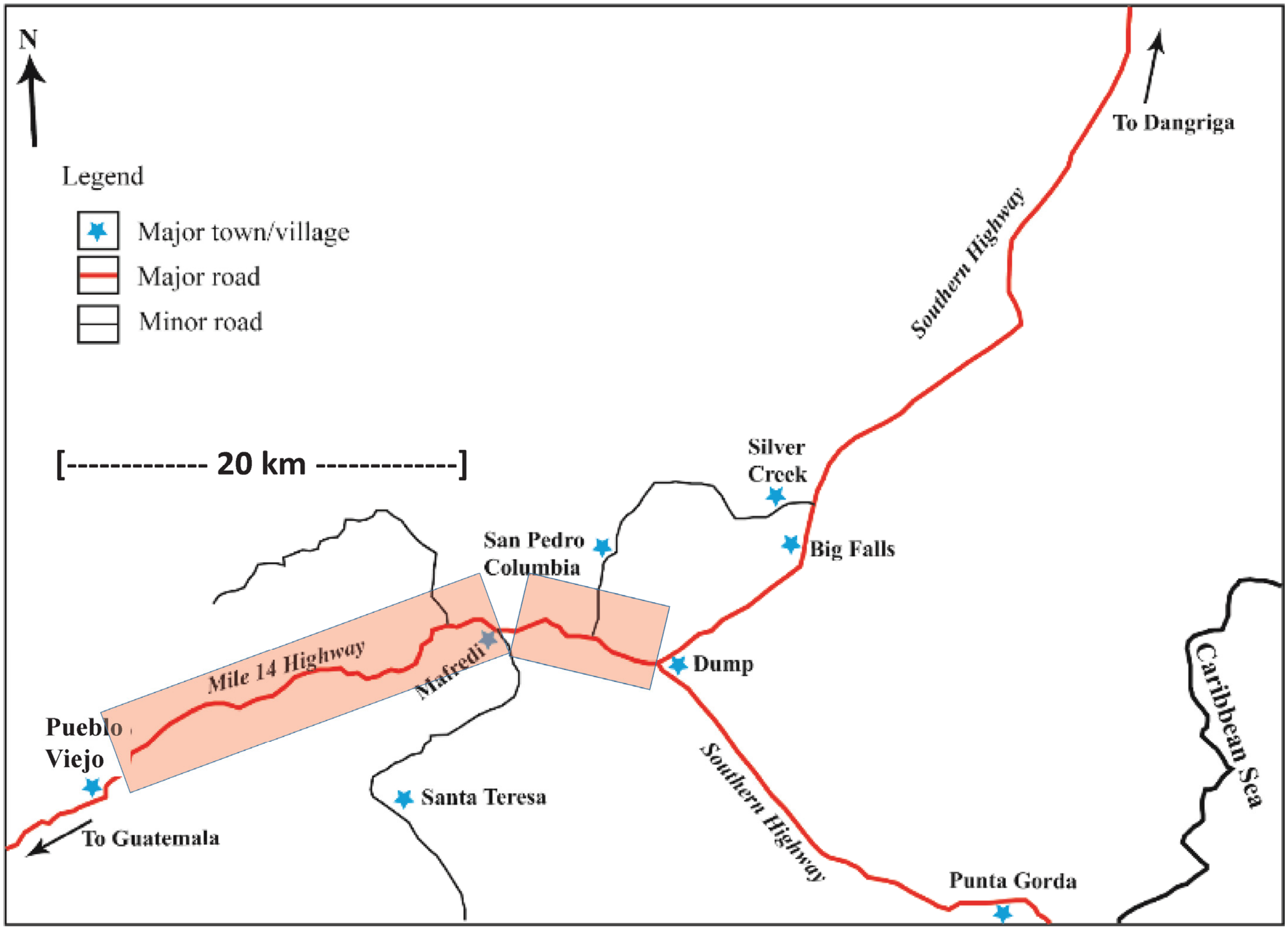


Figure 4. Highway map of southern Belize showing roads and key towns. The study area follows the southern highway from Dump to a few km east of Pueblo Viejo. The area for sample collection is highlighted with red boxes.

are commonly interbedded. Lithofacies D is interpreted as being similar in origin to lithofacies C but was deposited in a more distal setting in the submarine-fan complex (Fisher and King, 2016).

Lithofacies E (Fig. 6C) is similar to lithofacies D in that beds generally consist of interbedded sandstones and mudstones. However, lithofacies E differs from D by having the occurrence of wavy and discontinuous bedding in sandstones, and a relatively low ratio of sandstone to mudstone. Like lithofacies D, these deposits are likely of a distal origin in the submarine-fan complex (Fisher and King, 2016).

Organic matter throughout lithofacies C, D, and E is dispersed in a range of particle sizes (Figs. 7A–7D). Fine organic matter is concentrated inside trace fossil fillings, and within thin laminae, whereas coarser plant macerals occur in layers and as dispersed fragments in sandstones.

MATERIALS AND METHODS

Geochemical analyses were conducted on 13 samples of siltstones/fine sandstones, silty mudstones, and sandstones, all of which contained organic matter as described in the previous section. These were collected from outcrops along the Mile 14 highway in the Belize Basin during the summer 2016 field session. LECO TOC analysis and Rock-Eval II Pyrolysis were used to determine source-rock parameters, including type and amount of organic matter (OM), thermal maturity, and hydrocarbon generation potential. The carbonate content of each sample was also determined.

Approximately 15 g of each sample was ground and homogenized before analysis. For Leco TOC analysis, powdered aliquots of the samples were chemically treated using hydrochloric acid for 12 to 24 hr to remove carbonate minerals. Once dissolution of carbonate minerals was complete, samples were washed and analyzed for carbon content using a LECO carbon analyzer. Rock-Eval II pyrolysis was conducted on powdered aliquots of the samples. The samples were progressively heated from 300 to 550°C, in the absence of oxygen, thus leading to the release of gaseous hydrocarbons and carbon dioxide.

The quantity of organic matter, or (TOC, is measured in weight percent. Very poor source rocks have TOC values below 0.5 wt%; poor source rocks range from 0.5 to 1 wt%; fair source rocks have TOC values ranging from 1 to 2 wt%; good source rocks have TOC values ranging from 2 to 4 wt%; very good source rocks have TOC values ranging from 4 to 12 wt%; and excellent source rocks have TOC values of >12 wt% (McCarthy et al., 2011).

The quality and quantity of organic matter are assessed using S_1, S_2, and S_3, obtained from pyrolysis data. Parameter S_1 is the release of free hydrocarbons at about 300°C; S_2 is the percentage of the cracked hydrocarbons during pyrolysis at maxi-

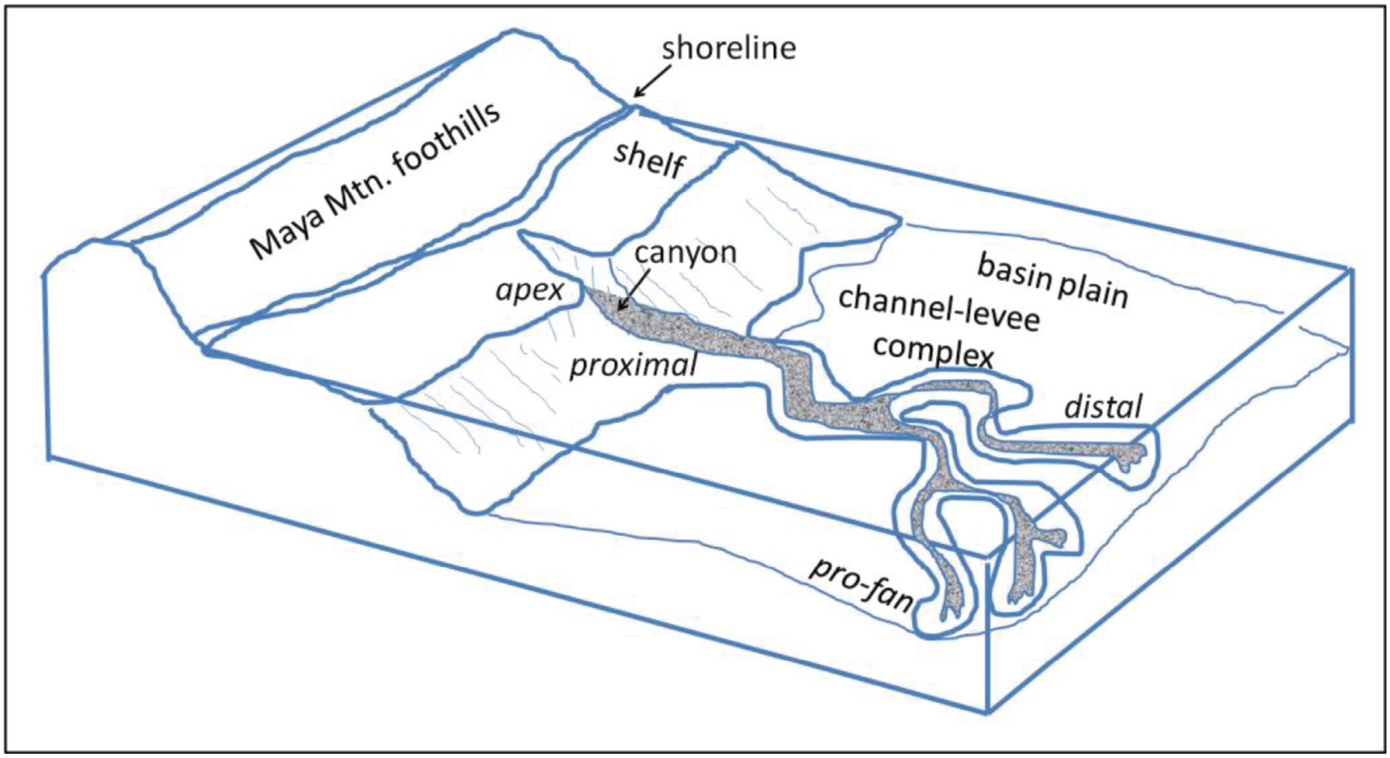


Figure 5. Sketch showing the schematic model of depositional environments of Toledo submarine fans as interpreted for the Belize Basin and likely southern source terrain (Dixon, 1956; Donnelly et al., 1990) (modified after Fisher and King [2015]). Grey shading indicates main area of conglomerate and sandstone distribution in a submarine channel complex. Lithofacies A corresponds to the proximal reaches of the main channel apex; whereas lithofacies B is a proximal channel-filling deposit. Lithofacies C was deposited in areas directly adjacent to the channel, within the middle-fan setting (i.e., the "channel-levee complex"), whereas lithofacies D was deposited in more distal areas of the submarine-fan complex. Lithofacies E was deposited in the most distal (including pro-fan) areas.

mum temperature T_{max}; whereas S_3 is the release of organically bound CO_2 at temperatures ranging from 300 to 550°C. Hydrogen and oxygen indices (HI and OI) are determined from TOC and Rock-Eval pyrolysis data, where HI and OI are equivalent to H/C and O/C ratios in the kerogen, respectively. The production index (PI) is equal to S_1 / (S_1 + S_2). The potential yield (PY) is equal to (S_1 + S_2) is an important parameter in assessing the source potential.

The thermal maturity of organic matter is typically assessed using vitrinite reflectance (R_o), but can be calculated by converting T_{max} values obtained from Rock-Eval pyrolysis to an R_o equivalent using any of several different equations (e.g., Jarvie et al., 2017). For this study only T_{max} values are reported.

RESULTS AND DISCUSSION

Quantity of Organic Matter

The organic richness of sedimentary rocks is important in the assessing those rocks as a source for hydrocarbons. Table 1 shows the results for all 13 analyzed samples and shows that TOC values ranged from 0.26 to 1.86 wt%, thus indicative of very poor to fair potential as source rocks. Alongside TOC, S_1 and S_2 are often utilized to determine organic richness (quantity). The S_1 values obtained are between 0–0.5 mg HC/g and S_2 values are between 0–2.5 mg HC/g. This suggests that the studied samples do not contain sufficient organic matter to generate hydrocarbons. Also, it should be noted that the organic matter in the samples tested causes a bias toward results indicating gas generation rather than oil.

Quality of Organic Matter

The initial type of organic matter within a source rock is essential for the prediction of the source rock's hydrocarbon potential. HI values and S_2 / S_3 have been used to differentiate various organic matter source types and the main hydrocarbon products generated (Peters and Cassa, 1994). Table 2 shows the geochemical parameters for kerogen types and expelled products at maturity. Results from the present analyses (see Table 1) show low HI values ranging from 4 to 77 mg HC/g TOC and low S_2 / S_3 values from 0.25 to 3.89. These parameters indicate that the samples contain type III/IV kerogen. Type III kerogen is gas prone and type IV kerogen is commonly referred to as 'dead carbon,' which tends not to generate any hydrocarbons (Peters and Cassa, 1994).

Our Toledo pyrolysis data was used to generate a van Krevelen plot, or kerogen classification diagram, which cross-plots HI and OI (Fig. 8). This figure shows that our Toledo samples contain type IV kerogen marginally grading to type III. This agrees with the classification scheme using HI and S_2 / S_3 described by Peters and Cassa (1994). Plots of HI versus T_{max} and S_2 versus TOC (Figs. 9 and 10) also agree with the HI and S_2 / S_3 classification and the modified van Kreleven plot.

Eighty-five percent of the Toledo samples studied are classified as a type IV kerogen, which may represent organic matter affected by weathering or oxidization during deposition or otherwise represent recycled organic matter. Toledo organic matter appears to be from a terrestrial source as confirmed by the kerogen type and woody organic fragments observed in outcrops. The hydrocarbon potential (S_1 + S_2) is generally very low. The

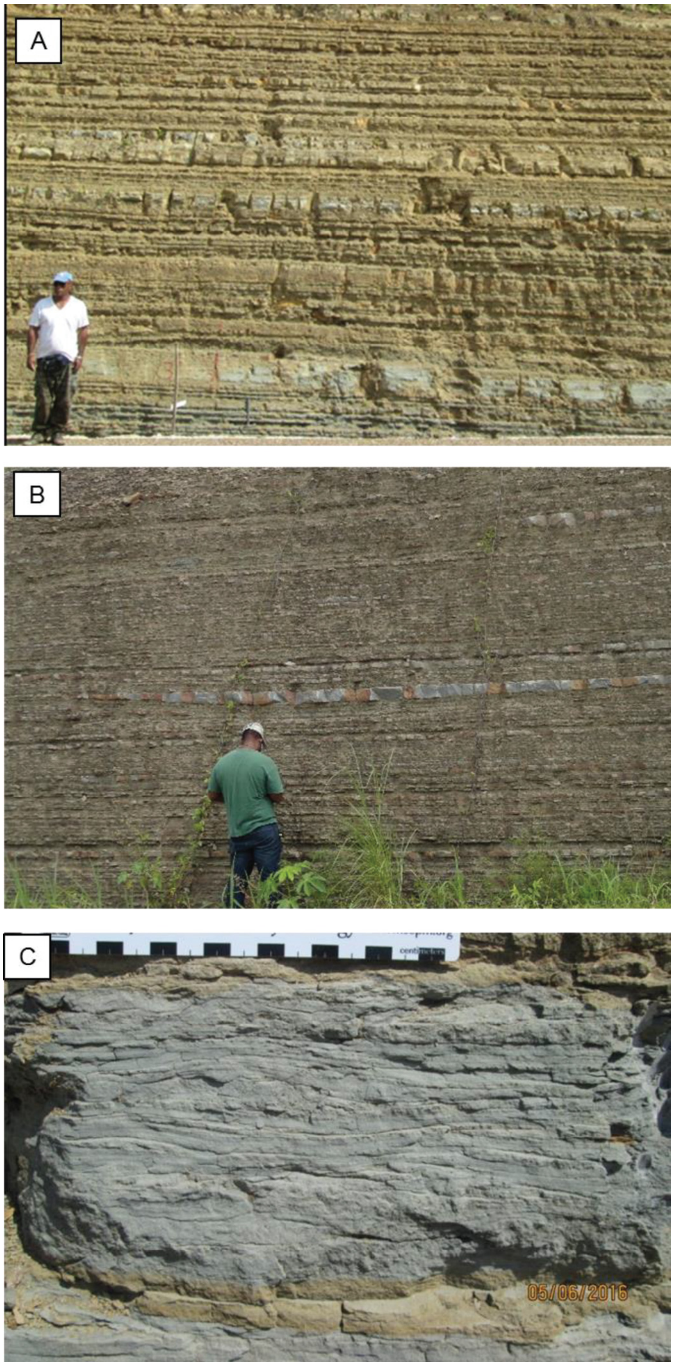


Figure 6. Example outcrops of Toledo lithofacies that contain significant organic matter. (A) Lithofacies C—Interbedded mudstone and thin to thick sandstone beds. (B) Lithofacies D—Thinly interbedded sandstone and silty mudstone, showing small channel-scour features. (C) Lithofacies E—Interbedded sandstones and mudstones in which sandstones display wavy and discontinuous bedding. Scales—Persons in (A) and (B); centimeter scale in (C).

presence of ichnofossils formed by boring bivalves, specifically *Teredolites* sp. (Fig. 11), within abraded, terrestrial wood fragments suggests transportation of terrestrial organics from a coeval, shoreline area, which was located updip from the Toledo submarine fan system (Fig. 5). Regarding this specific trace fossil, please see Savrda and King (1993).

Kerogen Maturity

The concentration and distribution of hydrocarbons within a source rock depend on the type of organic matter and its degree of thermal alteration or its maturity (Tissot and Welte, 1984). In this study, the pyrolysis T_{max} values generally are unreliable owing to the poor S_2 peak. Seven of the samples yielded low S_2 values (less than 0.16) and did not generate a T_{max} value. The remaining 6 samples provided results for T_{max}, with those yielded temperatures of 430 to 439°C. Based on the kerogen classification diagram constructed using HI versus T_{max} (Fig. 9), the results suggest that the Toledo samples of the present study are immature to mature.

SUMMARY AND CONCLUSIONS

In the present study, outcrop samples were collected from the upper part of the Lower Cenozoic Toledo formation of southern Belize in order to characterize the geochemistry of organic-rich submarine fan-related lithofacies. Rock-Eval parameters and TOC were determined in order to evaluate the various lithofacies within the informal Toledo formation's potential source rocks. The results presented here indicate that the investigated sections of the Toledo formation have very poor to fair source rock potential (TOC values ranging from 0.2 to 1.86 wt%), which possess kerogen of type IV (as inferred from low HI (4 to 77 mg HC/TOC), S_2 / S_3 values (<1 to 3.82), and an S_2 versus TOC plot). These outcrop-based samples tend to show that the investigated upper part of the Toledo formation has a generally low hydrocarbon potential, as suggested by Sanchez-Barreda (1990). The rocks sampled are immature to mature and are gas prone. Their status according to HI versus T_{max} plot indicates a low position in the oil window.

Presently, there are no openly published data, besides what is presented here, on the petroleum-related geochemistry of this formation in the Belize Basin. Thus, it remains to be determined if the balance of this formation has more hydrocarbon potential. To better assess the hydrocarbon potential of the whole of the Toledo formation, it is recommended that future petroleum geochemical studies are conducted upon proprietary subsurface samples from one or more of the several previously drilled exploration wells, and on samples from any new wells drilled in the area. This would help to increase our understanding of the Toledo formation's petroleum potential as a self-sourcing reservoir in southern Belize, perhaps akin to the offshore basin of Guyana and Suriname (Ballard, 2019, 2020).

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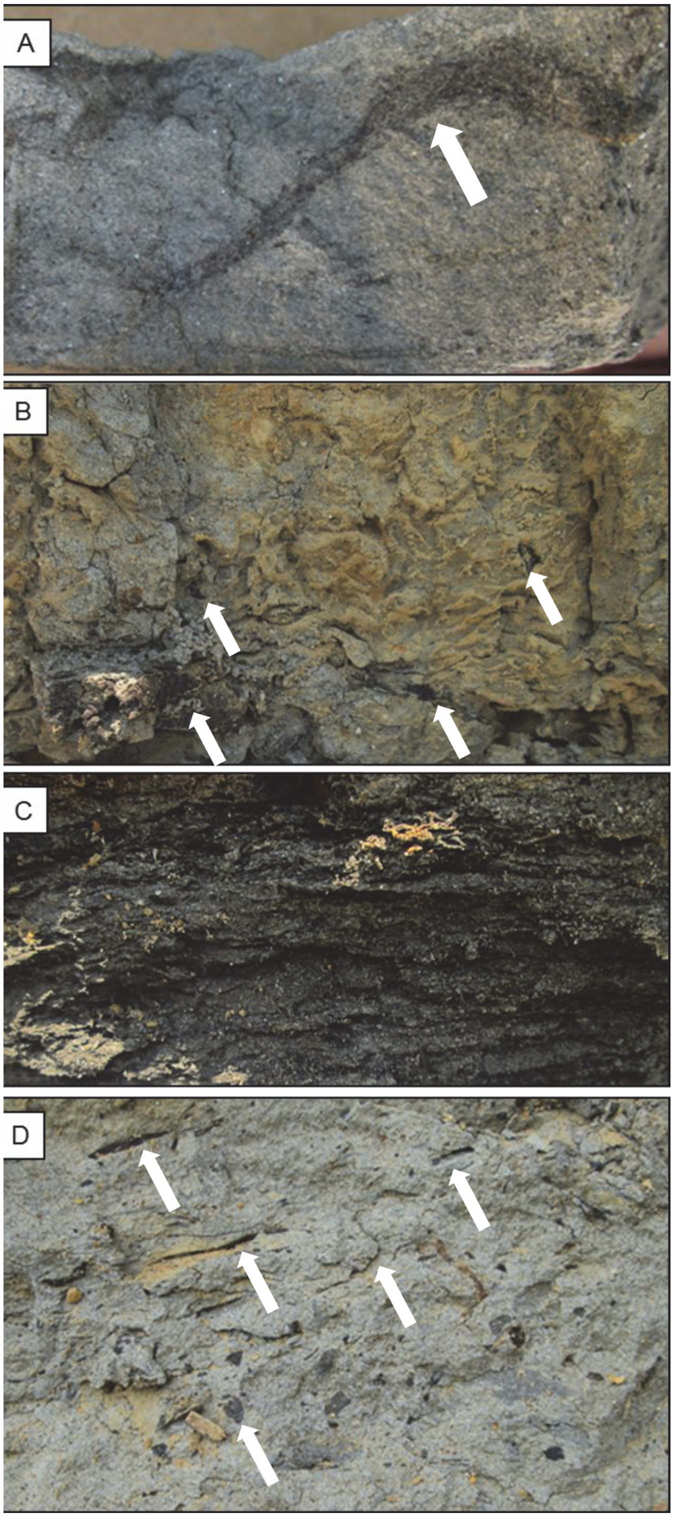

Figure 7. Close-up views of the granular occurrence of organic matter in Toledo lithofacies. (A) Organic matter, which is concentrated within a trace fossil (indicated by an arrow). (B) Bioturbated layer with coarse-grained plant macerals (selected macerals are marked with arrows). (C) Organic matter, which is concentrated in laminated silty mudstone. (D) Stratum containing dispersed, medium-grained plant macerals (selected macerals are marked with arrows).

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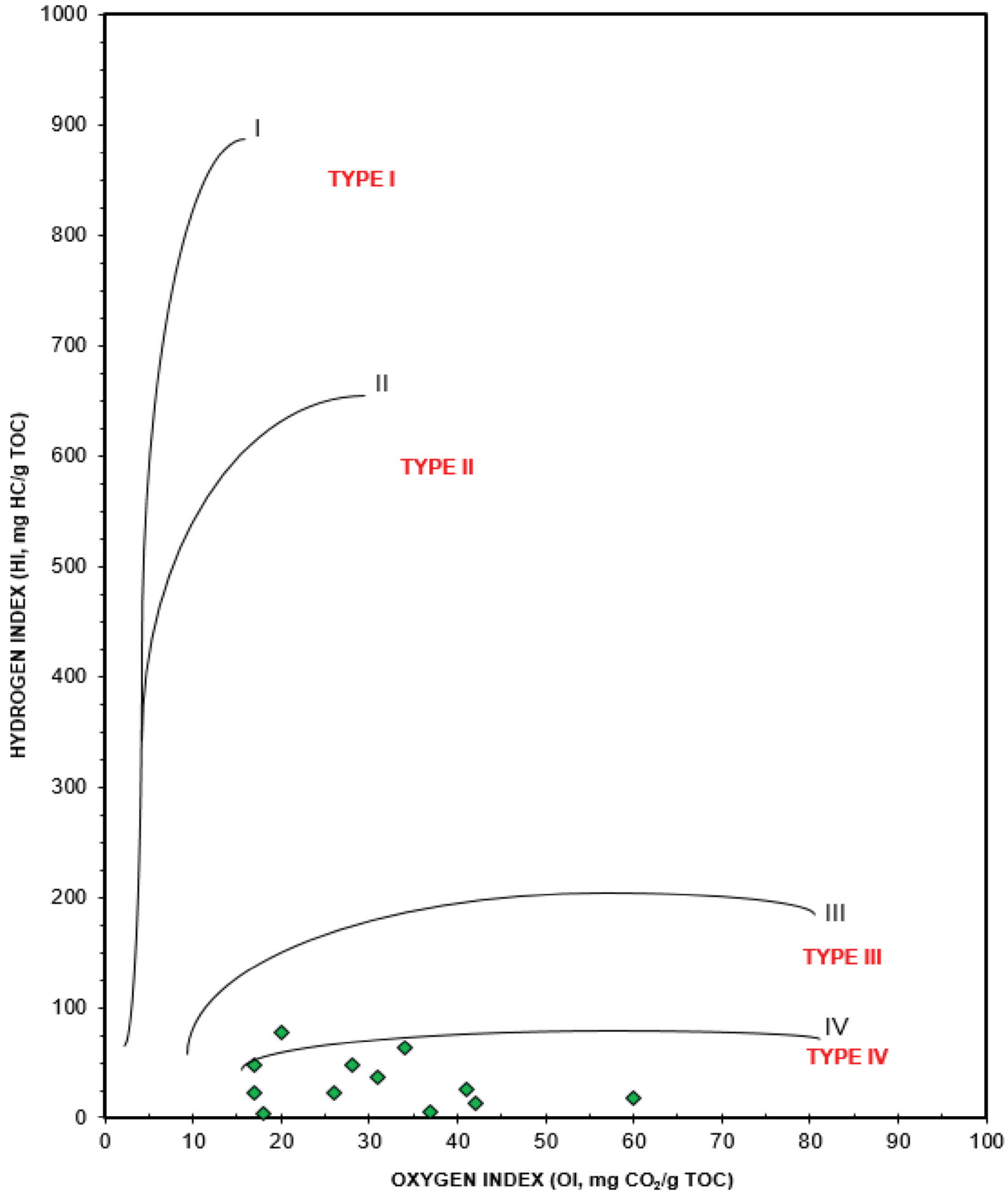
Table 1. Rock-Eval pyrolysis and LECO TOC data for samples of the Toledo formation of southern Belize. The letter (A–E) below the sample ID number identifies the lithofacies, as described by letter in the text above. Dashes (–) mean too low to have a value.

Sample ID / Lithofacies	Rock Type	Carbonate Content (wt%)	Source Quality and Thermal Maturity Parameters										Test
			TOC	S_1	S_2	S_3	$S_1 + S_2$	S_2 / S_3	HI	OI	PI	T_{max}	TOC, Rock-Eval II
FTD48 A	Siltstone	44.57	0.26	0.07	0.08	0.28	0.15	0.29	31	108	0.47	–	TOC, Rock-Eval II
FTD75 B	Siltstone	38.45	0.38	0.02	0.08	0.14	0.04	0.57	5	37	0.5	–	TOC, Rock-Eval II
FTD75 C	Siltstone/ fine sandstone	34.64	0.29	0.02	0.04	0.12	0.06	0.33	14	42	0.3	–	TOC, Rock-Eval II
FTD76 B	Mudstone/ siltstone	30.89	0.49	0.02	0.11	0.13	0.13	0.85	22	26	0.15	–	TOC, Rock-Eval II
FTD77 A	Siltstone	33.53	1.22	0.05	0.28	0.21	0.33	1.33	23	17	0.15	439	TOC, Rock-Eval II
FTD77 D	Siltstone	42.3	0.71	0.06	0.26	0.22	0.32	1.18	37	31	0.19	436	TOC, Rock-Eval II
FTD78 B	Siltstone	39.54	1.86	0.05	0.87	0.32	0.92	2.72	47	17	0.05	432	TOC, Rock-Eval II
FTD78 C	Siltstone	24.49	1.68	0.05	1.3	0.34	1.35	3.82	77	20	0.04	430	TOC, Rock-Eval II
FTD79 A	Siltstone/ fine sandstone	36.35	1.35	0.02	0.87	0.46	0.89	1.89	64	34	0.02	434	TOC, Rock-Eval II
FTD79 B	Siltstone	36.5	0.38	0.05	0.07	0.23	0.12	0.30	18	60	0.42	–	TOC, Rock-Eval II
FTD79 C	Siltstone/ fine sandstone	63.62	1.07	0.05	0.5	0.3	0.55	1.67	47	28	0.09	432	TOC, Rock-Eval II
FTD79 E	Siltstone/ fine sandstone	36.31	0.42	0.05	0.11	0.17	0.16	0.65	26	41	0.31	–	TOC, Rock-Eval II
FTD80 B	Sandstone	33.24	0.91	0.05	0.04	0.16	0.09	0.25	4	18	0.56	–	TOC, Rock-Eval II

Table 2. Geochemical parameters describing kerogen type (quality) and character of products (modified after Peters and Cassa [1994]).

Kerogen Type	HI (mg HC/g TOC)	S_2 / S_3	Expelled product at maturity
I	>600	>15	Oil
II	300–600	10–15	Oil
II/III	200–300	5–10	Mixed oil and gas
III	50–200	1–5	Gas
IV	<50	<1	None

Figure 8. Modified van Kreleven plot showing results of outcrop samples from the Toledo formation (diamond symbols) with almost all points falling below the type IV line indicative of 'dead' organic matter.



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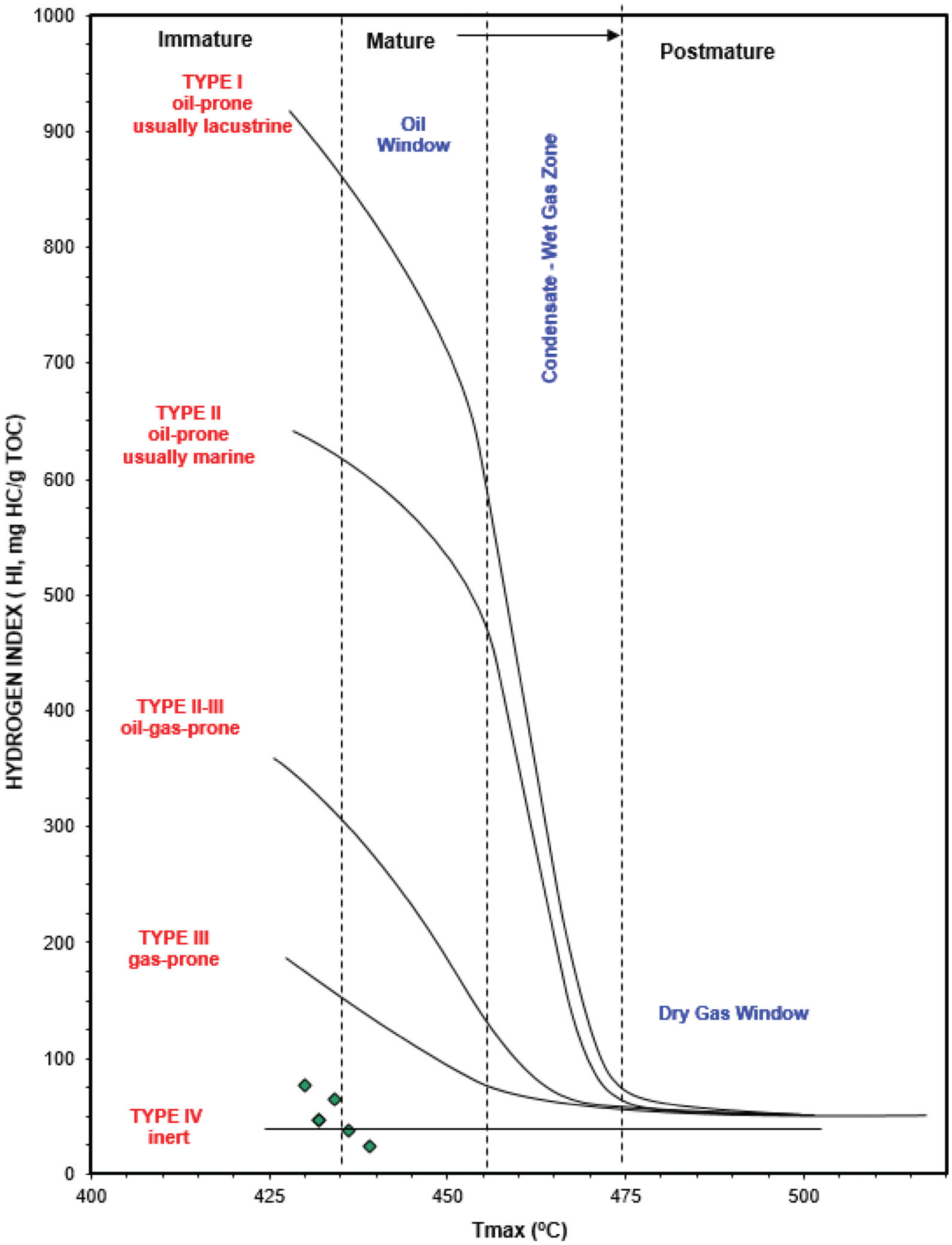

Figure 9. Kerogen type and maturation plot based on T_{max} and HI showing results of outcrop samples from the Toledo formation (diamond symbols) again showing that all samples are dominated by type IV organic matter.

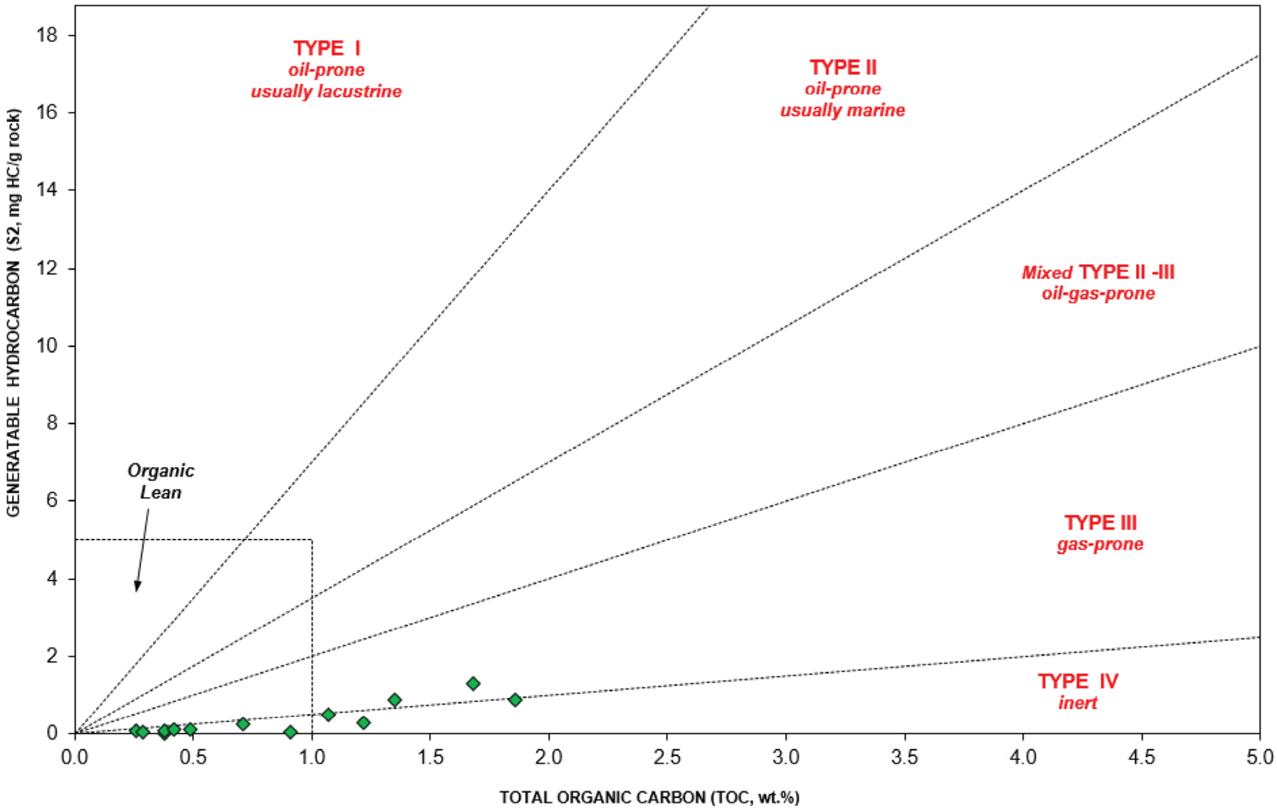

Figure 10. A plot of kerogen type based on TOC and S_2 values showing results for outcrop samples from the Toledo formation (diamond symbols) further confirming the abundance of type IV organic matter.

Figure 11. Terrestrial fossil wood (a black lignitic material) containing *Teredolites* sp. (a boring bivalve ichnofossil; marked by arrows) from the Toledo formation of southern Belize. The fossil wood fragment is about 2.5 cm thick.