



## Planning for the Lake Izabal Basin Research Endeavor (LIBRE) continental scientific drilling project in eastern Guatemala

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**Abstract.** As Earth's atmospheric temperatures and human populations increase, more people are becoming vulnerable to natural and human-induced disasters. This is particularly true in Central America, where the growing human population is experiencing climate extremes (droughts and floods), and the region is susceptible to geological hazards, such as earthquakes and volcanic eruptions, and environmental deterioration in many forms (soil erosion, lake eutrophication, heavy metal contamination, etc.). Instrumental and historical data from the region are insufficient to understand and document past hazards, a necessary first step for mitigating future risks. Long, continuous, well-resolved geological records can, however, provide a window into past climate and environmental changes that can be used to better predict future conditions in the region. The Lake Izabal Basin (LIB), in eastern Guatemala, contains the longest known continental records of tectonics, climate, and environmental change in the northern Neotropics. The basin is a pull-apart depression that developed along the North American and Caribbean plate boundary ~ 12 Myr ago and contains > 4 km of sediment. The sedimentological archive in the LIB records the interplay among several Earth System processes. Consequently, exploration of

sediments in the basin can provide key information concerning: (1) tectonic deformation and earthquake history along the plate boundary; (2) the timing and causes of volcanism from the Central American Volcanic Arc; and (3) hydroclimatic, ecologic, and geomicrobiological responses to different climate and environmental states. To evaluate the LIB as a potential site for scientific drilling, 65 scientists from 13 countries and 33 institutions met in Antigua, Guatemala, in August 2022 under the auspices of the International Continental Scientific Drilling Program (ICDP) and the US National Science Foundation (NSF). Several working groups developed scientific questions and overarching hypotheses that could be addressed by drilling the LIB and identified optimal coring sites and instrumentation needed to achieve the project goals. The group also discussed logistical challenges and outreach opportunities. The project is not only an outstanding opportunity to improve our scientific understanding of seismotectonic, volcanic, paleoclimatic, paleoecologic, and paleobiologic processes that operate in the tropics of Central America, but it is also an opportunity to improve understanding of multiple geological hazards and communicate that knowledge to help increase the resilience of at-risk Central American communities.

## 1 Introduction

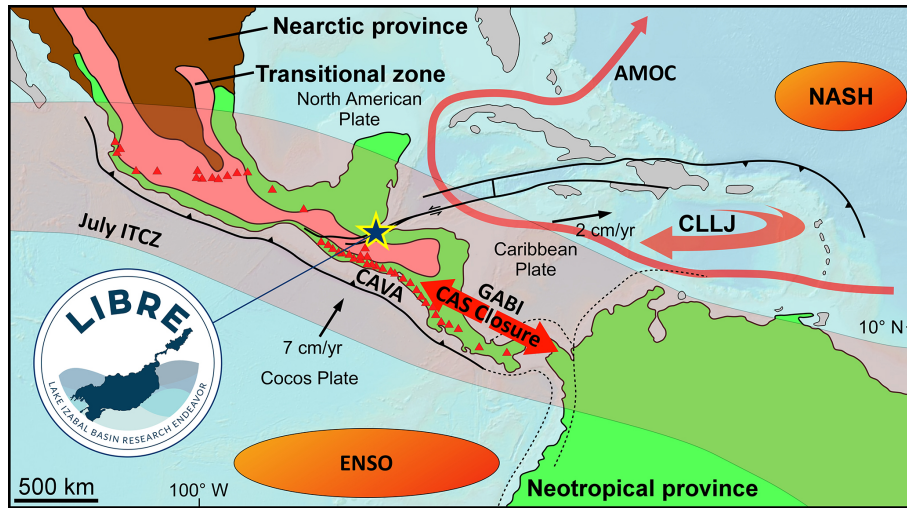
Drilling and coring in continental settings has provided answers to compelling scientific questions and has enabled us to better understand Earth and forecast how Earth Systems might behave in the future (Colman, 1996; Harms et al., 2007; NRC, 2011; Soreghan and Cohen, 2013; NASEM, 2020). Long sediment records have allowed us to infer tectonic, volcanic, climatic, environmental, and ecological processes on long temporal scales (Soreghan and Cohen, 2013). However, we still lack records from key regions around the world, including continental Central America. Despite being a relatively small region, Central America has played an outsized role in influencing several Earth System processes through geologic time (Fig. 1). For example, a major continental strike-slip fault system in Guatemala forms part of the North American–Caribbean plate boundary (Lyon-Caen et al., 2006; Authemayou et al., 2012; Ellis et al., 2019; Guzmán-Speziale and Molina, 2022) and has caused devastating earthquakes in the past (Plafker, 1976; White, 1984, 1985). The area also possesses one of the most active volcanic chains in the world along the Pacific coast (Kutterolf et al., 2008a) and hosts important biological hotspots (Graham, 2010; Correa-Metrio et al., 2011). Central American mountains influence easterly winds that affect the El Niño–Southern Oscillation and regional precipitation patterns (Baldwin et al., 2021). The closure of the Central American Isthmus that connects North and South America caused one of the most important biotic interchanges in recent geologic history (Bacon et al., 2015), modified global ocean circulation patterns (Sentman et al., 2018), and may have helped establish Northern Hemisphere glaciation (Haug et al., 2001; cf. Molnar, 2008). The many geological processes that affect the region expose a large proportion of the Central American population to multiple hazards, some of which are not well characterized and are poorly understood.

The Lake Izabal Basin (LIB) in eastern Guatemala is an active pull-apart basin along the North American and Caribbean plate boundary (Figs. 1, 2), with > 4 km of sed-

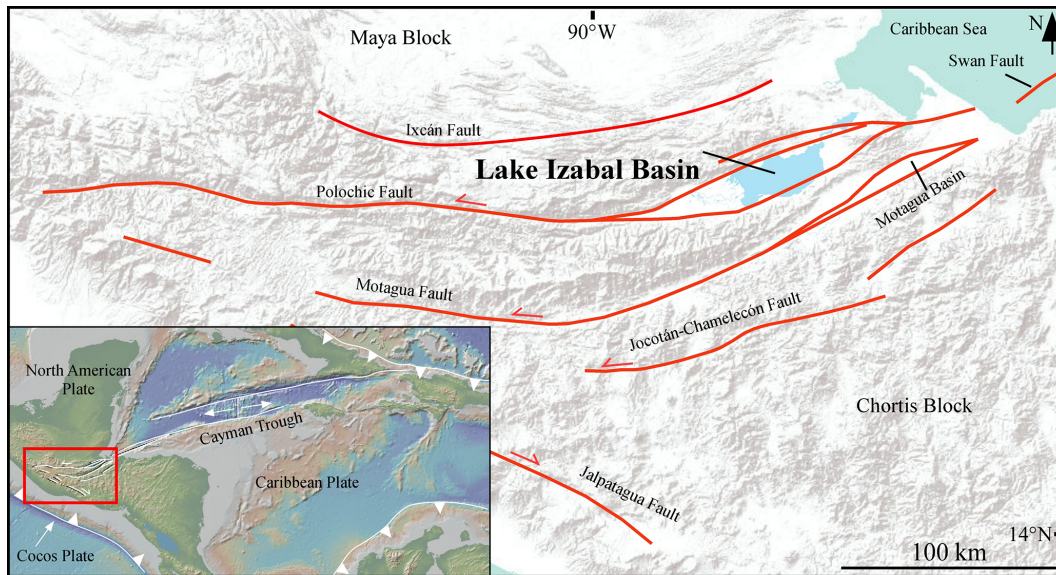
iment that likely began to accumulate during the Miocene (~ 12 Myr ago; Obrist-Farner et al., 2020). Seismic stratigraphic investigations indicate that the basin is deep and asymmetric: it is the result of a complex interplay between tectonics and sedimentation (Bartole et al., 2019). The accumulated deposits preserve potentially unrivalled continental paleoclimatic, volcanic, paleoseismic, and paleoecologic records of the region. The location of the basin along a major tectonic plate boundary, the thick and asymmetric sediment record, and frequent eruption of tephras for chronology make the LIB an ideal location for a project within the International Continental Scientific Drilling Program (ICDP). Drilling in the LIB will enable better quantification of seismic hazards and coring the basin's asymmetric infill will provide a continuous Miocene-to-recent sediment record. Recovery of such a long record will provide opportunities to investigate the following: (1) the seismo-tectonic evolution of the basin and of the North American and Caribbean plate boundary; (2) neotropical hydroclimate from the late Miocene to present, providing constraints on terrestrial hydroclimate responses to tectonic, greenhouse gas, and orbital variations; (3) biological and ecological dynamics related to the period during which the land bridge developed between North and South America and related to glacial–interglacial cycles that were established in the Quaternary; (4) the history of explosive volcanism from the northern Central American Volcanic Arc (CAVA); and (5) the diversity and abundance of life in the terrestrial deep biosphere, as well as feedback dynamics on nutrient cycles (e.g., carbon and nitrogen) through geomicrobiological processes.

## 2 The Lake Izabal Basin Research Endeavor (LIBRE) project

In August 2022, we organized and held a workshop in the city of Antigua, Guatemala, with 65 scientists from 13 countries and 33 institutions. Workshop discussions focused on the rationale for the project and drafting of scientific questions and hypotheses that can be addressed using instru-



**Figure 1.** Tectonic map of Central America and northern South America (modified from Mann, 2007) showing the diverse Earth System processes that interact in the vicinity of the Lake Izabal Basin (yellow star). The basin is located at the boundary between the North American and Caribbean tectonic plates, where devastating earthquakes have occurred in the past. The basin is also located at the transitional zone between Nearctic and Neotropical provinces (Holt et al., 2013). Several ocean–atmosphere processes influence regional hydroclimate, such as the position of the Intertropical Convergence Zone (ITCZ), the El Niño–Southern Oscillation (ENSO), the North Atlantic Subtropical High (NASH), and the Caribbean Low-Level Jet (CLLJ). Closure of the Central American Seaway (CAS closure) resulted in the Great American Biotic Interchange (GABI) and in changes in the Atlantic Meridional Overturning Circulation (AMOC). Finally, the basin is located north of one of the most active volcanic chains in the world, the Central American Volcanic Arc (CAVA).



**Figure 2.** Topographic and tectonic map of southern Guatemala showing the main fault traces of the Polochic–Motagua Fault System and the location of the Lake Izabal Basin. Inset map shows the tectonic and topographic map of the Caribbean region, highlighting the location of the study area and the North American and Caribbean plate boundary. Modified from Obrist-Farner et al. (2020).

mented boreholes and drill cores from the basin, and chronological tools and outreach activities. With that in mind, the group identified drilling targets and discussed logistics associated with a drilling campaign. Key government and industry collaborators in Guatemala donated data sets that were discussed during the workshop. For instance, the Guatemalan

government provided seismic data from the LIB that was acquired by the Arco oil company in 1978 (Fig. 3), of which 332 km was acquired in Lake Izabal and 127 km in the alluvial plain to the east. The Shell Oil Company reprocessed all Arco lines in 1991 and acquired an additional 69 km of seismic lines on land and 431 km in Lake Izabal. In addition,

the Guatemalan government made available all data from the Colorado-1 well, which was drilled in 1993 on the eastern side of the LIB (Fig. 3) and provides information related to lithologies, seismic velocities, and age of the basin fill. The data sets are key to our understanding of the LIB and helped us formulate hypotheses based on the potential geological time intervals we expect to recover from the basin.

### 3 Current knowledge of the Lake Izabal Basin

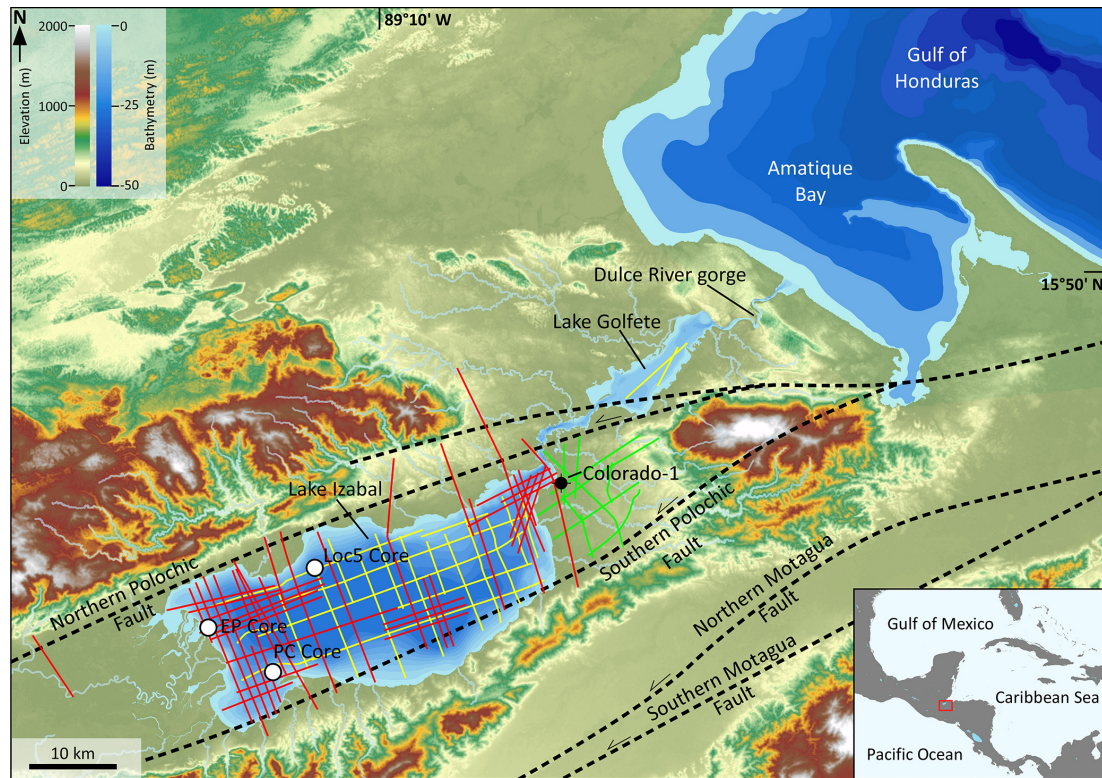
During the workshop, participants discussed available data from the LIB. The LIB is 80 km long and 20 km wide (Fig. 2). The eastern side of the basin is occupied by Lake Izabal (15°30' N, 89°10' W), whereas the western side contains a wetland of international importance, the Ramsar site Bocas del Polochic (Ramsar site no. 813). Lake Izabal is shallow ( $z_{\max} = 15$  m) and polymictic, with a temperature difference between surface and bottom waters of only  $\sim 2$  °C (Brinson and Nordlie, 1975). Mean annual precipitation in the region is  $\sim 3300$  mm (Duarte et al., 2021), and the climate is characterized by a rainy season that extends from May through December and a dry season from January to April (Duarte et al., 2021). The basin is confined to the north by the Santa Cruz Mountain Range, to the south by the Minas Mountain Range, and to the east by the Mico Mountains (Fig. 3).

Outcrop studies, seismic stratigraphic analysis, and syntheses of industry well data provide constraints on the timing of basin formation and the basin's stratigraphic architecture. Three formations make up the Tertiary stratigraphy of the Izabal region (Fig. 4; Powers, 1918; Vinson, 1962; Mota-Vidaure, 1989; Obrist-Farner et al., 2020). The oldest formation is the Upper Oligocene to Lower Miocene Rio Dulce Formation, which rests unconformably on top of marine Permian limestones (Vinson, 1962). The Rio Dulce Formation consists of marine limestones that are light buff, tan, and cream-colored, with abundant coral and mollusk fragments (Powers, 1918; Vaughan, 1919; Vinson, 1962). The formation is overlain unconformably by the informally defined terrigenous mid-Miocene Carboneras formation (Mota-Vidaure, 1989). The lower part of the Carboneras formation is constrained to the Serravallian by zircon weighted-mean  $^{206}\text{Pb}/^{238}\text{U}$  ages of  $12.060 \pm 0.008$  Ma from a volcanic tuff  $\sim 30$  m above the Rio Dulce–Carboneras unconformity (Obrist-Farner et al., 2020). The Carboneras formation is composed of claystone, siltstone, marl, sandstone, conglomerate, and lignite beds (Mota-Vidaure, 1989; Obrist-Farner et al., 2020). The uppermost formation is the Herrería Formation, constrained to the Pliocene–Pleistocene based on freshwater gastropod shells (Powers, 1918). The formation is composed of claystone, siltstone, marl, sandstone, conglomerate, and lignite beds (Powers, 1918; Vinson, 1962). Correlation between outcrop information and seismic profiles by Obrist-Farner et al. (2020) indicates that the Carboneras for-

mation forms part of the initial infill of the LIB, constraining basin initiation to the mid-Miocene.

Seismic stratigraphic studies revealed that the basin is asymmetric in both a north–south and an east–west direction. In a north–south direction, the basin geometry resembles that of a half-graben, resulting from transform-normal extension along the Polochic Fault (Ben-Avraham and Zoback, 1992), with the thickest sedimentary package occurring parallel to the principal deformation zone (Bartole et al., 2019; Fig. 5). In an east–west direction, basin asymmetry resulted from a migrating depocenter similar in form to extant (Crowell, 2003) and young (Beeson et al., 2017) pull-apart basins along the San Andreas Fault, California (USA). The LIB depocenter has migrated  $\sim 70$  km during Polochic Fault displacement (Bartole et al., 2019), with a basin infill that thickens on the western side (Fig. 5). Constraints on the basin stratigraphy are based on the Colorado-1 industry well (Shell Oil Company, Exploradora y Productora de Guatemala: Informe final de exploración, unpublished report, 1993). Located on the eastern side of the basin (Fig. 3), the well was drilled through 1400 m of sediment before it was plugged and abandoned. Cuttings from the well indicate that the lowermost strata (1400–500 m) are composed of mudstone with thin sandstone beds, with the appearance of coal from 1000 to 800 m and conglomerate from 600 to 500 m. Conglomerate and sandstone content become more dominant from 500 to  $\sim 200$  m, with an increase in mudstone and limestone from 200 m to the surface (Obrist-Farner et al., 2020). Correlation among outcrops, seismic profiles, and the Colorado-1 well indicate that the 1400 m drilled by the well is younger than 12 Ma (Obrist-Farner et al., 2020), and preliminary palynological results support this interpretation based on Tortonian-age pollen ( $\sim 8$  Ma) found in cutting samples at  $\sim 1200$  m.

Short sediment cores from Lake Izabal further constrain the stratigraphy of the basin and reveal climate and environmental change during the Holocene. Variations in elemental abundances in a 7.6 m radiocarbon-dated sediment core obtained from the northwest side of the basin (Loc5 in Fig. 3) suggest a hydroclimate shift from drier to wetter conditions from the early to the mid-Holocene and stable hydroclimatic conditions thereafter until  $\sim 1000$  years ago when drier conditions returned (Duarte et al., 2021). Superimposed on this long-term trend is a marine incursion during the 8.2 ka event (Obrist-Farner et al., 2022), highlighting the sensitivity of this low-lying lake to sea-level variations. This marine incursion resulted in an ecosystem shift, modifying the low-lying lake for  $\sim 4500$  years. A shorter sediment core from the southern side of the basin (PC in Fig. 3) spans the last 1400 years, revealing interesting hydroclimate changes during the Little Ice Age (LIA). In contrast to many records from Central America that suggest a drier hydroclimate during the LIA, evidence from Izabal suggests increased runoff (Obrist-Farner et al., 2023) and increased tropical forest cover after substantial human-mediated deforestation during ancient Maya times, which ended ca. 1000 years ago (Mongol et al.,



**Figure 3.** Topographic and bathymetric map of the Izabal region. White circles show existing coring locations discussed in the text. Yellow and green lines show the location of the 1978 Arco seismic lines, and red lines show the location of the 1991–1992 Shell seismic lines. Major faults are shown with thick dashed black lines. Inset shows a map of Central America and part of the Caribbean, with the location of the Izabal region in eastern Guatemala indicated by the red box.

2023). In addition, a shorter sediment core obtained near the Polochic Delta (EP core in Fig. 3) revealed several geochemical variations that indicate human disturbance of Lake Izabal during the last 100 years, including an increase in the lake's trophic status (Obrist-Farner et al., 2019) and metal contamination caused by mining activities in the catchment (Hernández et al., 2020). Together, these data sets indicate that the sedimentary archive of the LIB contains records of paleoseismic, paleoclimatic, and paleoenvironmental changes across various timescales.

#### 4 The Lake Izabal Basin – a world-class scientific drilling site

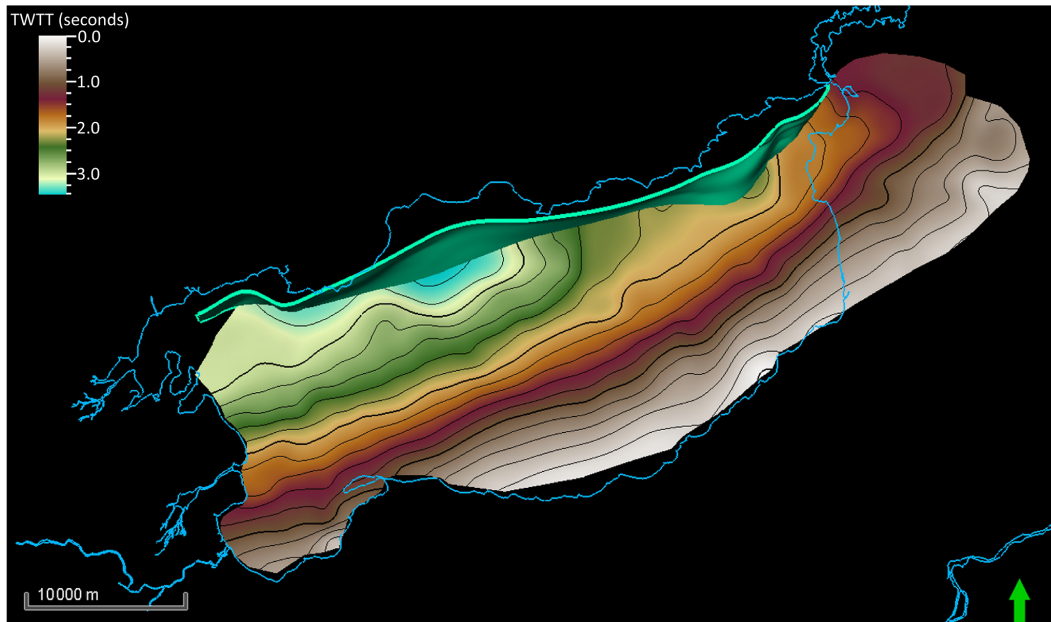
The LIBRE project is well positioned to address two science priorities identified by ICDP (Anselmetti et al., 2020), using an integrated scientific approach, as follows: (1) understanding the full chain from geologic hazard to risk (Theme 02: geohazards), and (2) exploring sedimentary archives to understand Earth's evolution (Theme 04; environmental change). Expanding on these two themes, the LIBRE workshop focused on defining scientific priorities and questions, logistics, drilling targets, and education and outreach

plans. The resulting discussions were synthesized into five scientific motivations and an outreach and education plan.

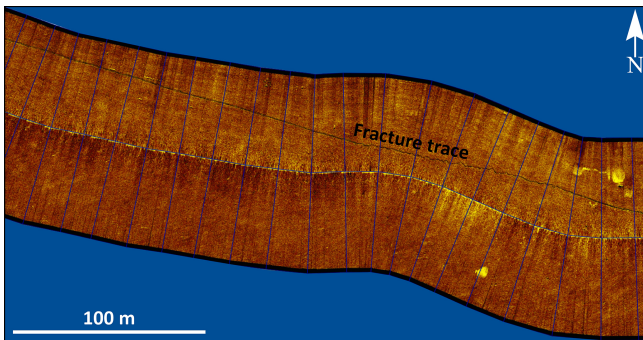
##### 4.1 Tectonic processes and seismic risk (ICDP Theme 02)

The LIB is an ideal scientific drilling site because it is a pull-apart basin that developed along the Polochic–Motagua Fault System (PMFS; Lodolo et al., 2009), a system comprised of four sub-parallel faults that separate the North American and Caribbean plates in Guatemala (Figs. 1, 2; Lyon-Caen et al., 2006). Through geologic time, basin depocenter migration and continued subsidence played a large role in the morphology of the basin. For example, the depocenter migrated  $\sim 70$  km at the speed of the transform (Bartole et al., 2019), recording the complex interplay between tectonic deformation and sedimentation. The area is also subject to intense seismic activity, as evidenced by the 1976 Motagua earthquake (Plafker, 1976) and by estimates of destruction and shaking during the estimated  $M_w$  7.6 Polochic earthquake in 1816 (White, 1985). In addition, high-resolution geophysical surveys of Lake Izabal's floor revealed contemporary surface fractures (Fig. 6). Despite evidence of contemporary deformation and potential for catastrophic earthquakes,





**Figure 5.** Basement contour map in two-way travel time (TWTT) of the Lake Izabal Basin (LIB). Green fault is the main principal deformation zone of the LIB. On the eastern side of the basin, the basement has been uplifted and is closer to the surface than it is on the western side, an area where more than 4 km of sediment has accumulated.



**Figure 6.** Side-scan sonar profile from the southwestern side of Lake Izabal showing a contemporary fracture trace. For location of the profile, see the blue square in Fig. 7.

through time and possible external controls on CAVA activity – information needed to better understand volcanic hazards in the region.

#### 4.3 Paleoclimatic reorganizations and analogs for modern climate change (ICDP Theme 04)

The sediments of the LIB record the response of terrestrial climate to tectonic, greenhouse gas, and orbital variations over the last  $\sim 12$  Myr, providing a unique opportunity to investigate a hydroclimate record from the Neotropics that extends back to the late Miocene. A continental drilling project in the LIB will enable the study of climate evolution during the late Miocene, Pliocene, and through the Quaternary.

Expansion of  $C_4$  plants in regions such as North America, tropical Africa, and Indo-Asia during the late Miocene and Pliocene points to major ecosystem shifts (Strömberg and McInerney, 2011; Uno et al., 2011; Feakins et al., 2020). However, the expansion appears to have been region-specific (Strömberg, 2011) and likely the result of increased overall aridity and changes in the seasonality of precipitation (Pagani et al., 1999; Strömberg and McInerney, 2011). However, only sparse late Miocene to Pliocene paleoclimate data exist from the Neotropics to determine the regional expression of these changes. In addition, the paucity of long Central American paleoclimate records makes it difficult to resolve debates about the drivers of tropical climate change during the mid-Pliocene, a time of higher atmospheric  $CO_2$  and global warmth, and a prospective analog for present-day climate change (Burke et al., 2018).

Superimposed on long-term cooling, closure of the Central American Seaway (CAS) spanned  $\sim 7$  to 4 Myr, with the last near-surface ocean connection closing by ca. 2.5 Ma (O’Dea et al., 2016; McGirr et al., 2020). CAS closure caused profound changes in the Atlantic Ocean, with a strengthening of the Atlantic Meridional Overturning Circulation (AMOC; Haug and Tiedemann, 1998; Auderset et al., 2019). Impacts of CAS closure on global climate are debated (Utescher et al., 2017 vs. Molnar, 2008) and model simulations suggest that southern Central America and northern South America became generally drier and colder (Fedorov et al., 2013, 2015; Brierley and Fedorov, 2016). On glacial and orbital timescales, the LIB offers an opportunity to extend paleoclimate records through the entire Quaternary; i.e.,

the past  $\sim 2.6$  Myr. The current lack of continuous Quaternary records precludes the evaluation of climate drivers during key time intervals, such as before and after the Mid-Pleistocene Transition (MPT)  $\sim 1.25$ – $0.70$  Ma, when global ice age cycles intensified and moved from 41 to 100 ka pacing (Chalk et al., 2017). Therefore, a long, continuous, and high-resolution record from the LIB will provide an unrivalled opportunity to reconstruct neotropical climate from the late Miocene to the present, enabling testing of hypotheses related to precipitation changes as a result of CAS closure, potential drying caused by reduced convection during the mid-Pliocene, and changes in hydroclimate as a result of the establishment of Northern Hemisphere glaciation.

#### 4.4 Paleoeological evolution and the American biotic exchange (ICDP Theme 04)

The LIBRE project offers the opportunity to explore the composition and structure of neotropical biological communities from the Miocene to present. Closure of the CAS marked one of the most important events in terms of the biogeography of the Neotropics (Jaramillo, 2018). Although species interchange between the Nearctic and Neotropical biogeographic realms started before the Miocene (Bacon et al., 2015), closure of the CAS accelerated migration rates, triggering ecological dynamics of community rearrangement. Before the complete emergence of the CAS, northern South America and southern Central America were mostly occupied by rainforests and mangroves, under a warm and wet climate regime (Graham, 1998; Salzmann et al., 2008; Jaramillo et al., 2020). A long sediment record from the LIB could help constrain how climate change after CAS closure modified the availability of environmental niches in the Neotropics, leading to the synthesis of novel ecosystems in the region (Correa-Metrio et al., 2012; Pérez et al., 2021).

Furthermore, a Quaternary record from the LIB can contribute to our understanding of how regional vegetation changed in response to glacial–interglacial dynamics. Paleontological data suggest that during the Quaternary, vegetation changes in the northern Neotropics were characterized by relatively sparse forest cover, dominated by Nearctic elements during glacials and dense Neotropical forests during interglacials (Correa-Metrio et al., 2012). Thus, after the establishment of Northern Hemisphere glaciation, vegetation changes were likely associated with the formation/disappearance of corridors that promoted/impeded migration (Bacon et al., 2016). Differing migration patterns, together with climate variability, probably resulted in the synthesis of novel and “no-modern-analog” ecosystems in the region (Correa-Metrio et al., 2012; Perez et al., 2021). Long Quaternary records from the Izabal Basin will also enable us to understand vegetation changes in what is one of the currently wettest areas of Central America, and one that is influenced by climate drivers different from those that affect sites in the drier northeast lowlands of Central America and Mexico. For

instance, the Lake Izabal region is thought to have provided a haven for biodiversity (refugia) during past periods of climate change (Prance, 1982), and long sediment cores from the Quaternary will allow us to investigate the role of the region in maintaining regional ecosystems and biomes during times of climatic turmoil. Furthermore, we will be able to investigate relationships between the structure of aquatic and terrestrial ecosystems and sea-level variability (Obrist-Farner et al., 2022).

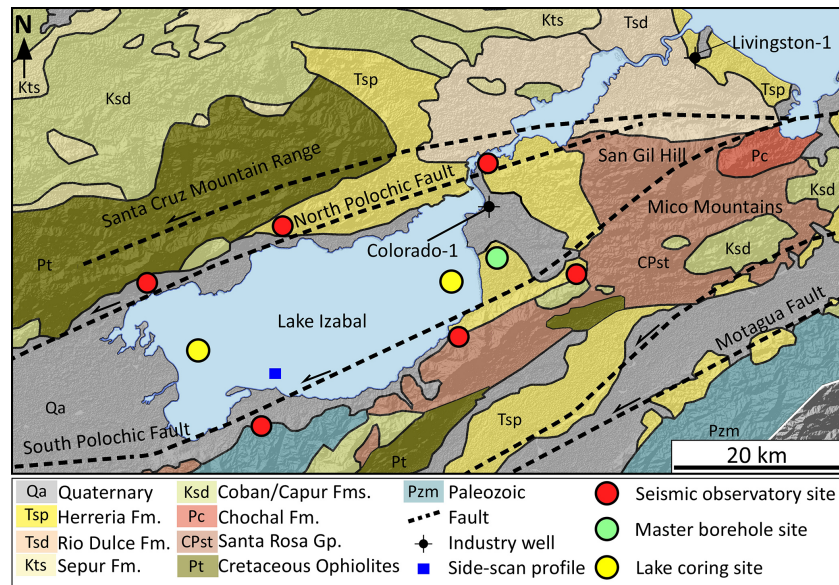
#### 4.5 Life in the deep biosphere: a continental lacustrine view (ICDP Theme 04)

The deep biosphere, microbial life that thrives in sediments down to several kilometers of depth, plays a major role in global biogeochemical cycles of carbon, nitrogen, and sulfur. Our knowledge of the community composition and abundance of the deep biosphere relies largely on studies carried out within the framework of the Integrated Ocean Discovery Program (IODP) and its predecessors over the past 3 decades (Parkes et al., 1994; D’Hondt et al., 2004). Such studies have provided a wealth of information on the nature and abundance of microbial life, showing that life can exist to  $\sim 10$  km below the surface and at temperatures that may reach  $> 120^\circ\text{C}$  (Inagaki et al., 2015; Heuer et al., 2020). They have also demonstrated that the genetic diversity of the deep biosphere and its abundance rivals that found in the overlying ocean waters (Kallmeyer et al., 2012), but data from continental settings are largely missing. In general, our understanding of the composition, abundance, and evolution of life in deeply buried lacustrine archives is sparse, hindering an understanding of the role of the continental deep biosphere in global biogeochemical cycles. With a Miocene-to-recent sediment record, Lake Izabal offers a unique opportunity to study the community composition of the continental deep biosphere at an unprecedented scale and resolution. It will also provide key insights into the vertical zonation and abundance of microbial cells. Given the generally higher productivity and organic matter preservation of lake systems compared to the marine realm, we expect that deeply buried lacustrine sediment sequences are oases of life and hot spots of microbial activity on the continents, but such deposits remain terra incognita. Furthermore, the sensitivity of Lake Izabal to sea-level variability (Obrist-Farner et al., 2022) offers an opportunity to understand how repeated marine incursions into Lake Izabal may have influenced the development of hot spots of microbial life in the deeply buried sediments.

#### 4.6 Increasing public engagement with geology in Guatemala

An important component of the LIBRE project is its education and outreach plan. During the workshop, participants focused on several ideas to build public interest in the drilling project. These include: (1) involvement of Guatemalan sci-





**Figure 7.** Geological map of the study area showing the proposed drilling and coring locations for the LIBRE project. Map modified from Bonis et al. (1970).

entists who have been working in Lake Izabal and on seismic hazard assessment in the country; (2) participation of Guatemalan geoscience undergraduate and graduate students; (3) collaboration with the Authority for the Sustainable Management of Lake Izabal (AMASURLI), the NGO Defensores de la Naturaleza, which is in charge of protecting the Izabal wetland, and the Guatemalan Institute for Seismology, Volcanology, Meteorology, and Hydrology (INSIVUMEH); (4) development of Earth Science stations at museums in Guatemala City and in the offices of AMASURLI and Defensores de la Naturaleza, near Lake Izabal; and (5) production of a book targeted to 10–13-year-old children that highlights the spectacular geology and environments of Guatemala, with the main focus related to the ICDP drilling project.

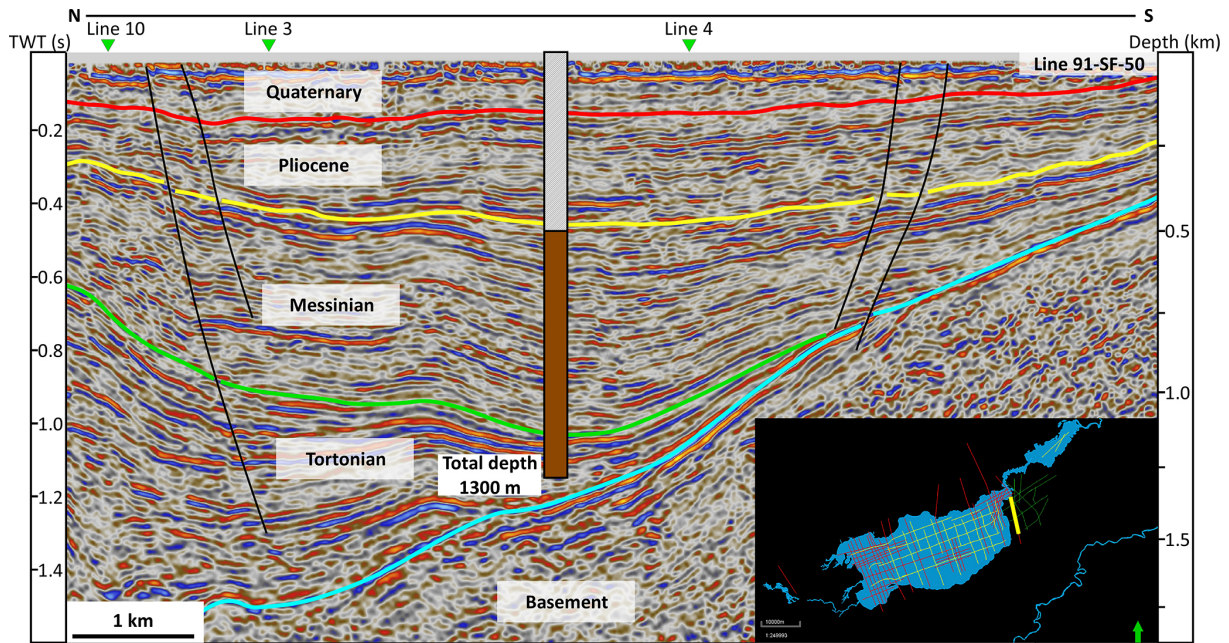
## 5 The LIBRE scientific drilling plan and site selection

The LIBRE workshop participants discussed drilling locations and operations within the framework of the scientific questions and generated specific drilling targets and borehole instrumentation plans. A consensus was reached on establishing a comprehensive three-component drilling plan that involves a network of instrumented boreholes and collection of long sediment cores, both on land and in Lake Izabal. These include a deep master borehole cored and instrumented onshore on the eastern side of the LIB, six instrumented seismic observatory onshore boreholes in the vicinity of Lake Izabal, and two coring sites offshore in Lake Izabal (Fig. 7). All drilling locations were selected and identified based on: (1) seismic data from the LIB; (2) stratigraphic cor-

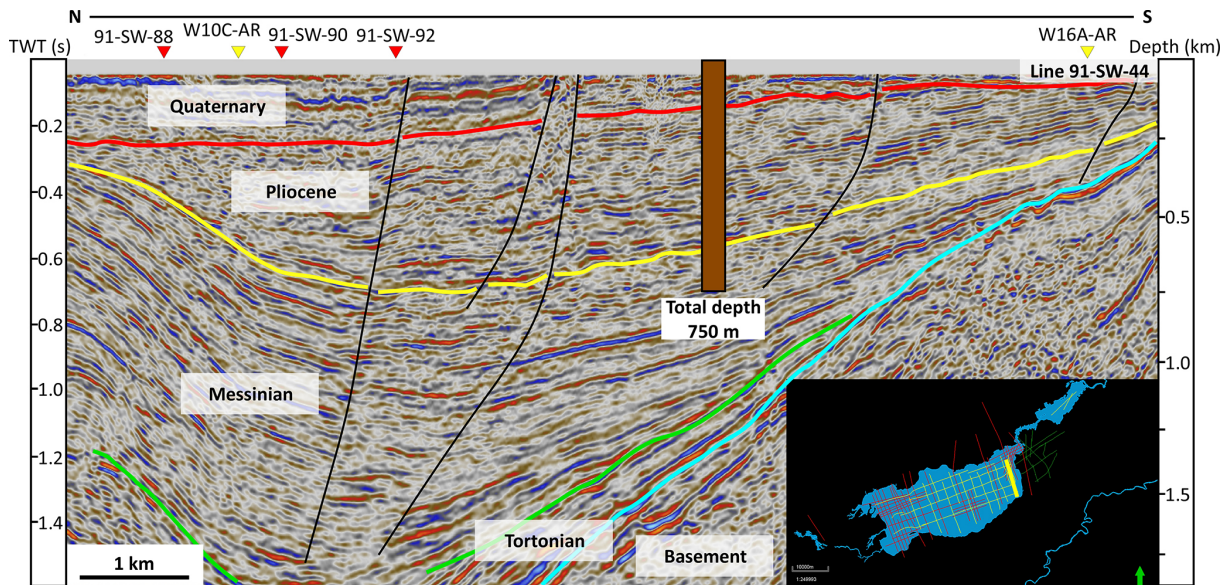
relations between seismic lines and the reconstructed progradational infill of the basin (Bartole et al., 2019), ensuring stratigraphic overlap between coring sites and complete recovery of the sediment record to 8 Ma; (3) the velocity model and preliminary palynological work for the Colorado-1 well; and (4) the geologic map (Bonis et al., 1970) and revised stratigraphy for the Izabal region (Obrist-Farner et al., 2020; Fig. 4).

We discussed the drilling and coring of a master borehole on the alluvial plain along the eastern side of the LIB. The area is along seismic line 91-SF-50, 4 km from the location of the Colorado-1 well (Fig. 8) and near two crossing lines (lines 3 and 4; Figs. 7, 8). The master borehole will drill through 500 m of sediment without core recovery because this interval is most likely composed of sandstone and conglomerate, based on information from the Colorado-1 well. We discussed the possibility of then collecting a core from 500 to 1300 m, avoiding drilling deeper because of logistical challenges, available technology, and associated costs. Seismic interpretation (Fig. 8), in combination with the velocity model from the Colorado-1 well and preliminary palynological results, indicates that the 800 m core will contain thick mudstone intervals with minimal sandstone and will at least contain sediment from the Tortonian (~8 Ma) to the Messinian and Pliocene (~5 Ma). The borehole will then be used as a seismic observatory, with the installation of seismometers and strainmeters at multiple depths.

We identified two coring locations within Lake Izabal. The first site is in the eastern side of the lake, located along inline 91-SW-44 and near crossing line 91-SW-92 (Figs. 7, 9). The location is ~5 km from the master borehole site and is in an area where the lake is 15 m deep. A core will be collected to



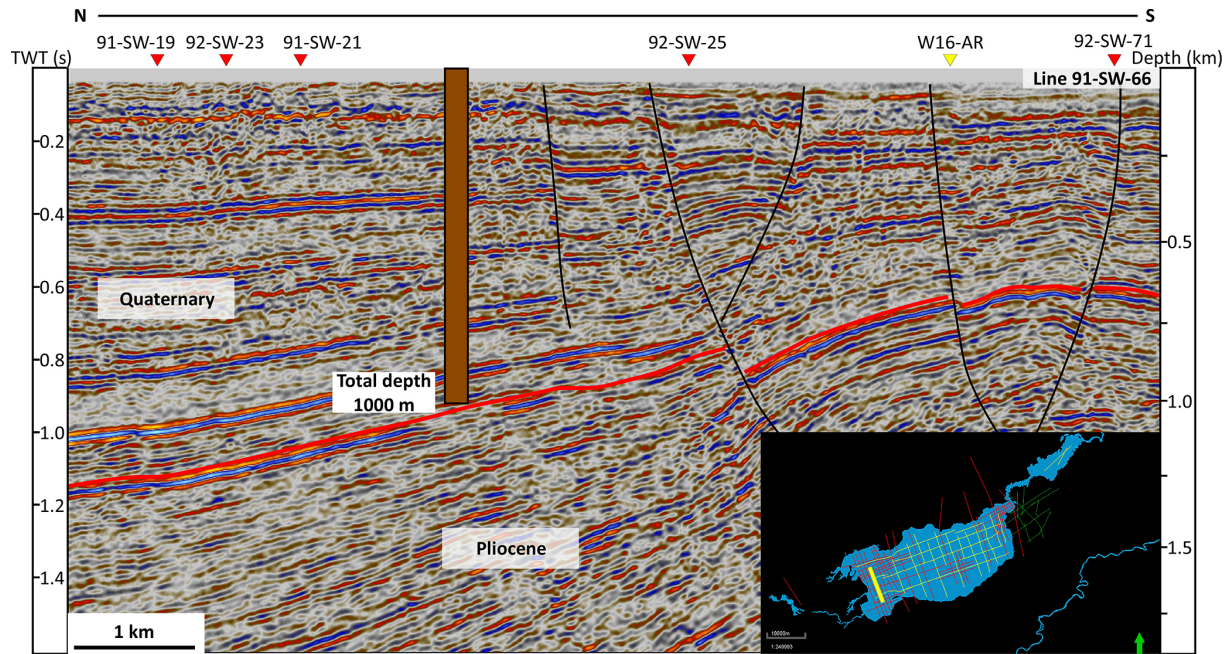
**Figure 8.** Interpreted seismic line 91-SF-50 showing the location and total depth of the master borehole (brown) and the proposed age of the sediment package. The inset map shows the location of profile 91-SF-50 on the eastern side of the Lake Izabal Basin.



**Figure 9.** Interpreted seismic line 91-SW-44 showing the location and total depth of the eastern lake core (brown) and the proposed age of the sediment package. The inset map shows the location of profile 91-SW-44 on the eastern side of the Lake Izabal Basin.

a depth of ~ 750 m and based on seismic interpretation will contain sediments deposited from the Messinian (~ 6 Ma) to the present. The second site is on the western side of Lake Izabal, located along inline 91-SW-66 and crossline 91-SW-21 (Figs. 7, 10). We plan to collect a 1000 m core from this site. Seismic interpretation indicates that the 1000 m core will contain a record from ~ 2.5 Ma to the present, providing a highly resolved Quaternary record from the LIB.

Key to investigating the long record preserved in the LIB, obtained by drilling at three sites, is establishment of stratigraphic correlations and a robust chronology. Availability of industry seismic data provides the key to correlate the three planned long sediment cores. Furthermore, workshop participants discussed several suitable chronometric techniques and correlation strategies. We agreed that the LIBRE chronology will combine multiple well-developed techniques. For exam-



**Figure 10.** Interpreted seismic line 91-SW-66 showing the location and total depth of the eastern lake core (brown) and the proposed age of the sediment package. The inset map shows the location of profile 91-SW-66 on the western side of the Lake Izabal Basin.

ple, presence of CAVA tephra in outcrops surrounding Lake Izabal (Obrist-Farner et al., 2020) and in the broader region (Kutterolf et al., 2016) suggests that the recovered cores will contain sufficient tephra to establish anchor points for correlations. We will also utilize radiocarbon, optically stimulated luminescence, magnetic stratigraphy, U-series dating,  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology, and cosmogenic nuclide dating to establish correlations between core sites and a robust chronology for the LIB records.

Finally, workshop participants discussed the possibility of creating a set of fault observatory boreholes in the vicinity of Lake Izabal (Fig. 7). To establish a borehole-based observatory, drilling in bedrock is necessary to achieve coupling between the cemented borehole and the host rock. Discussions focused on drilling all boreholes in locations where bedrock is exposed at the surface (Fig. 3). All boreholes will be drilled to a depth of 200 m, cased, and instrumented with seismometers and strainmeters. Establishing a borehole-based observatory provides an excellent opportunity to monitor and record earthquake processes in close proximity to active faults. In particular, the borehole observatory will provide rich information for investigating and monitoring microseismicity and strain rates across the system (e.g., Prevedel et al., 2015) and be used to determine fault activity and geometries, which are essential input parameters for subsequent modeling studies that aim to assess the long-term hazards of the plate boundary.

**Data availability.** No data sets were used in this article.

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