International Ocean Discovery Program
Expedition 387 Scientific Prospectus

Amazon Margin

Deep drilling of the Amazon continental margin: the evolution of Cenozoic neotropical biodiversity, climate, and oceanography

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Abstract

International Ocean Discovery Program (IODP) Expedition 387 aims to recover sediments at two sites located in shallow water (~350 to 450 m) on the uppermost continental slope west of the Amazon Fan, northwest of the mouth of the Amazon River. These sediments were deposited in the upper part of the long-lived Foz do Amazonas Basin of the equatorial margin of Brazil. These two sites will recover a sedimentary sequence that spans much of the Cenozoic but with variable provenance and highly variable sedimentation rates. By virtue of their location, the Quaternary sediments will recover an abundance of terrigenous materials including pollen, organic matter, zircon grains, and clay minerals, allowing detailed reconstruction of the biodiversity, climate, and hydrology of the adjacent tropical South American continent. At the same time, an abundance of well-preserved marine microfossils and organic matter will allow accurate determination of the age and oceanographic conditions of the western equatorial Atlantic that partly forced the climate of the adjacent continent.

However, our reconstructions of the spatial patterns of biodiversity and climate through time must be interpreted with the knowledge that the geometry of the watersheds that contributed water and sediment to the coastal Atlantic was itself rearranged through time. For example, a transcontinental proto-Amazon river did not likely reach the Atlantic until somewhere between 11 and 2 Ma, a date that we expect to more accurately determine from these new cores. Prior to that event, terrigenous sediments at our sites would have been derived from smaller coastal rivers draining watersheds limited to the eastern tropics of northeastern South America.

The planned drill sites of Expedition 387 will be the marine complement to a transect of continental drill sites. Together, the marine and continental sites form the Trans-Amazon Drilling Project (TADP), a project that is partly funded by the International Continental Drilling Program (ICDP). The TADP addresses fundamental questions about the Cenozoic climatic evolution of the Amazon region, the origins and evolution of the neotropical rain forest and its biodiversity, and the origins and rearrangements of the transcontinental Amazon River. Together, we expect that these IODP and ICDP projects will transform our understanding of Amazonian geological, climatic, biological, and paleoceanographic history.

Schedule for Expedition 387

International Ocean Discovery Program (IODP) Expedition 387 is based on IODP drilling proposal Number 859-Full2 and 859-Add2 (**http://iodp.tamu.edu/scienceops/expeditions/amazon_margin.html**). Following evaluation by the IODP Scientific Advisory Structure, the expedition was scheduled for the R/V *JOIDES Resolution*, operating under contract with the *JOIDES Resolution* Science Operator (JRSO).

At the time of publication of this *Scientific Prospectus*, the expedition is scheduled to start in Georgetown, Barbados, on 26 April 2020 and end in Fortaleza, Brazil, on 26 June 2020. A total of 61 days will be available for the initial port call, transit, drilling, coring, and downhole measurements described in this report. For the current detailed schedule, see **http://iodp.tamu.edu/scienceops**. Further details about the facilities on board *JOIDES Resolution* can be found at **http://iodp.tamu.edu/publicinfo/drillship.html**.

Introduction

We plan two primary drill sites located between 4° and 6°N, northwest of the modern Amazon Canyon, on the upper continental slope of the equatorial margin of Brazil. Although the targeted sedimentary sequence spans the entire Cenozoic, drilling limitations dictate that we will likely reach no more than the 59 Ma horizon at total depths as great as 2200 meters below seafloor (mbsf). The recovered sequences will allow high-resolution reconstruction of terrestrial biodiversity and climate, as well as the oceanographic conditions that, in part, forced the climate of the adjacent continent. This IODP expedition constitutes the marine complement to a transect of continental drill sites that is separately funded by the International Continental Drilling Program (ICDP) (as well as the US National Science Foundation [NSF], São Paulo Research Foundation [FAPESP] of Brazil, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior [CAPES] of Brazil, and private funding). The full ICDP/IODP transect (Figure **F1**), known as the Trans-Amazon Drilling Project (TADP), described by Baker et al. (2015), will span 50° to 73°W, most of the width of continental South America and its Atlantic margin and nearly 7% of the Earth's equatorial circumference. This undertaking has far-reaching scientific significance, addressing fundamental questions about Cenozoic climatic evolution of the entire Amazon region, the origins of the neotropical rain forest, the origins of the transcontinental Amazon River, and the paleoceanographic history of the western equatorial Atlantic. These topics directly relate to two of the four major themes described in the IODP Science Plan 2013–2023: (1) climate and ocean change: reading the past, informing the future and (2) biosphere frontiers: deep life and environmental forcing of evolution.

The IODP drilling is considered to be an essential component of the TADP transect because it will (1) likely generate a more continuous stratigraphic record than any of the continental drill sites; (2) record the entire Quaternary glacial–interglacial history of Amazon climate and flora; (3) record the oceanographic conditions that, in part, force the South American summer monsoon, the nearly continental-scale circulation that is responsible for much of the precipitation of tropical South America; (4) provide a continuous record of the early (premodern Amazon) history of the forests and savannahs of the eastern Amazon and their diversity; (5) as the depocenter for modern Amazon outflow, record the onset of transcontinental drainage into the Atlantic and changing rates of Amazon outflow, postonset; and (6) provide critical marine biostratigraphic control for correlation with the continental TADP sites.

Expedition 387 will build on knowledge acquired on two previous scientific ocean drilling expeditions on the Amazon margin (Figure **F2**). Ocean Drilling Program (ODP) Leg 155 (Flood, Piper, Klaus, et al., 1995) drilled 17 sites on the deepwater Amazon Fan in water depths >2750 m. However, the deepest penetration during that expedition reached 433 mbsf, and the oldest recovered sediments likely date to Marine Isotope Stage (MIS) 7, ca. 250 ka. The major goal of Leg 155 was to determine the facies architecture of the fan, but some important paleoclimate and paleoceanographic results were achieved. On the basis of Nd and Pb isotopic analyses, McDaniel et al. (1997) concluded that "muds of the Amazon Fan are derived dominantly from the Andean highlands." Their conclusion was validated using U/Pb analyses of sedimentary zircons in the sand fraction from the Leg 155 cores (Mason et al., 2019). Hoorn (1997) concluded that "palynological data give no indication of major vegetational changes in the drainage basin" during the late Pleistocene and "Amazon Basin forests were not extensively replaced by savannah vegetation during the glacial period." However, a more recent paper by Hoorn et al. (2017) concludes that there were major changes in the Amazon flora during earlier parts of the Pleistocene and the Neogene.

ODP Leg 154 (Curry, Shackleton, Richter, et al., 1995) drilled five sites in a depth transect from the top (3041 m water depth) to the deep flank (4356 m water depth) of the Ceará Rise, a carbonate sediment–draped aseismic ridge located at ~5°N, ~300 km beyond the offshore edge of the Amazon Fan. Leg 154 recovered sediments from late Paleocene to Holocene age, and these sediments have proven to be of enduring interest in paleoceanography (e.g., Stewart et al., 2016; Wilkens et al., 2017) and paleoclimatology (e.g., Rühlemann et al., 2001; Dobson et al., 2001; Harris and Mix, 2002; van Soelen et al., 2017). The Ceará Rise presently receives a minor input of terrigenous sediment, dominantly from an Amazon source. All of this terrigenous sediment arrives at the Ceará Rise as suspended load only after entrainment on the continental shelf by the northwestward-flowing North Brazil Current (NBC) and subsequent retroflection at ~8°N during the boreal summer into the eastward-flowing North Equatorial Countercurrent with unknown influence from subsurface currents. As a result of this long and circuitous advective pathway from the Amazon mouth to the Ceará Rise, the terrigenous mass accumulation rate (TAR) on the rise averages only about 1 $g/cm^2/ky$, whereas TAR on the upper Amazon Fan (e.g., Core CDH5; Nace et al., 2014) was more than 100 times higher during the Pleistocene. Despite many studies undertaken on the Ceará Rise that purport to reconstruct Amazon outflow and paleoclimate, the modern physical oceanography and its unknown past variation limit the fidelity of these studies. These results from previous drilling expeditions help to motivate our proposal to recover sediments from the upper continental slope from sites that are both proximal to the continental margin and deposited more equitably during periods of sea level lowstand and highstand. However, such sites do present the inherent operational challenges we describe below.

Long sedimentary sections have previously been drilled on the Amazon slope and shelf in industry wells. In fact, more than 40 exploration wells have been drilled in the region; a few of these were dated using marine microfossils and have limited geochemical and paleobiotic data (Figueiredo et al., 2009; Gorini et al., 2014; Hoorn et al., 2017). Although stratigraphic columns and logs are publicly available for most wells, only cuttings were collected. The use of synthetic and natural drilling muds of undocumented composition largely precludes organic geochemical analyses and may introduce significant pollen contamination, whereas sediment samples are generally difficult to access. Furthermore, industry drill sites were not chosen for the stratigraphic continuity of the Cenozoic section, and many are replete with stratal disturbance by canyons, slumps, and faulting.

Our drilling goal is recovery of long and nearly continuous stratigraphic sequences that span almost the entire Cenozoic and that contain abundant terrigenous input. However, the stratal architecture and complex deformation of this margin result in a scarcity of appropriate drilling targets, requiring drilling in shallow water to great depth. Operational conditions are challenging because of fast surface currents and extremely deep drilling targets. The anticipated result is a two-site, multiple-hole, composite sequence containing a sedimentary record of variable resolution (very high resolution in the Quaternary and lower resolution during most other intervals), reaching the 59 Ma horizon (thus spanning most of the Cenozoic), containing abundant terrestrial markers (especially during the Quaternary), and well dated by marine microfossils (predominantly calcareous nannofossils and planktonic foraminifers).

Background

Geological and paleoceanographic setting

Cenozoic climatic evolution of tropical South America

To date, there are few studies of Cenozoic continental climate in tropical South America. By early Albian time, tropical South America had begun its westward drift away from Africa, always remaining at nearly the same latitude. Both the increasing expanse of the Atlantic Ocean moisture source to the east and plate convergence with development of the high Andes to the west tended to enhance the South American monsoonal circulation and increase the intensity of tropical South American precipitation (e.g., Lenters and Cook, 1995; Insel et al., 2010; Poulsen et al., 2010; Garreaud et al., 2010; Liu et al., submitted). Likewise, increased Pacific Walker circulation, proposed to have taken place in the Pliocene (Wara et al., 2005; Ford et al., 2015), may have been associated with increased precipitation in the Amazon center of convection (Garreaud et al., 2010). All three posited controls work in the same direction to increase precipitation, perhaps fitfully, through the Cenozoic. These tendencies toward increased precipitation through the course of the Cenozoic were opposed by the effects of decreasing atmospheric CO_2 and cooling during the Cenozoic that favor decreased precipitation. However, because we have no long-term record of precipitation or runoff for Cenozoic Amazonia, it is unclear which tendency won out and what were the climatic conditions faced during the evolution of the Amazon rain forest.

Prior to the late Quaternary, nothing is known about higher frequency, millennial-to-orbital scale climate variation in the Amazon Basin. The longest published archives of continental climate in tropical South America are found in speleothems, dating to 0.25 Ma (Cheng et al., 2013), and long-lived lakes, including the 0.4 Ma record from Lake Titicaca (Fritz et al., 2007) and a low-resolution 3.0 Ma record from Sabana de Bogota (Torres et al., 2005). Therefore, the drill core records that we will retrieve from the Amazon margin will be far older than any other continuous paleoclimate records in tropical South America. In these older sediments, we anticipate observing some of the same climate forcings and teleconnections reconstructed for the late Quaternary (e.g., orbital variation and/or influence of North Atlantic and Pacific sea-surface temperature on climate dynamics and precipitation; Baker and Fritz, 2015).

Cenozoic biotic evolution of the Amazon forest

The origin of the great biodiversity in tropical South America has spurred debate since the foundational work of Darwin (1859), Agassiz and Agassiz (1868), and Wallace (1878), yet it remains one of the fundamental problems of modern science. Wallace (1878) proposed that low extinction rates, resulting from a relatively stable and equitable tropical climate throughout the Cenozoic, enabled the progressive accumulation of species over time, a hypothesis that has been termed the "museum" model. In contrast, the "cradle" model (Stebbins, 1974) posits that most tropical diversity is relatively recent and arose episodically in response to climatic and geological drivers (Richardson et al., 2001). For example, Hoorn et al. (2010) proposed that most modern species originated prior to the Pleistocene and that species origination rates were shaped primarily by geological agents including Andean uplift, tectonic arches, marine incursions, and riverine barriers. Others argue for nearly constant diversification throughout the Neogene and Quaternary, influenced by the temporal and spatial dynamism of regional landscapes and climate (Rull, 2011). One pathway to resolution of these different interpretations of the rates and drivers of change, the timing or origins and extinctions of taxa, is recovery of the Cenozoic record of plant diversity across the Amazon region and placing these biotic data into a well-resolved geologic, climatic, phylogenetic, and biogeographic framework.

The South American tropical rain forest likely originated and attained its modern structure in the early Cenozoic. In the Cretaceous, the South American continent occupied nearly the same latitude as today, but its tropical forests were dominated by gymnosperms and ferns and hence were very different from modern forests (Morley, 2000; Graham, 2011; Jaramillo, 2012). The rise of angiosperms in the early Cretaceous initiated major changes in the structure, function, and composition of the forest, changes that were influenced by the nearby Chicxulub impact event at the Cretaceous/Paleogene boundary. Although some authors suggest that an Amazon-type lowland forest did not exist prior to the Eocene (Burnham and Johnson, 2004; Morley, 2000), this conclusion may arise from a lack of fossil evidence; phylogenetic studies indicate that many rain forest plant taxa extend into the Cretaceous, making plausible the existence of a modern-type rain forest (in terms of diversity and structure) in the Late Cretaceous or early Cenozoic (Davis et al., 2005).

The expansion of megathermal angiosperm-dominated forests has been linked to greenhouse climates (Morley, 2000; Fine and Ree, 2006). Palynofloral data from Colombia and Venezuela that span the Paleocene through early Miocene suggest maximum diversity at the Paleocene/Eocene Thermal Maximum (PETM) (Jaramillo et al., 2006, 2010; Jaramillo and Cárdenas, 2013), followed by a subsequent decline, a pattern that mirrors global temperature reconstructions (Zachos et al., 2001). At least on the face of it, given scant data, it appears that the early mid-Cenozoic climatic "optimum" was an evolutionary optimum, inviting the suggestion that rain forest plant taxa may survive and thrive in future global warming scenarios (Willis et al., 2010; Dick et al., 2013).

All existing palynological studies of diversity through time have been undertaken outside the margins of the modern Amazon Basin (Morley, 2000; Jaramillo et al., 2006; Graham, 2011). In fact, almost no Paleogene sediment has been recovered and described from the Brazilian Amazon. Although a recent palynological study of cuttings from a well on the Amazon continental slope documents vegetation history from the Miocene onward (Hoorn et al., 2017), its stratigraphic resolution is very low, and the interpretations regarding the presence of Andean taxa are complicated by contamination with palynomorphs from the drilling mud and the fact that many so-called Andean floral elements occur in other regional vegetation types. Thus, no complete Cenozoic pollen record is currently available, and patterns of vegetation change, the evolution of plant diversity, and the correlated environmental drivers all remain to be established by the integration of the Expedition 387 marine sedimentary record with the continental (TADP) drill sites.

Cenozoic geologic evolution of the Amazon River

The Amazon River is the greatest river by discharge on Earth, yet many aspects of its history remain unknown. Widely varying estimates for the timing of transcontinental Amazon drainage have been proposed, and processes leading to development of the modern integrated Amazon drainage system are contentious. In several studies, the transcontinental drainage of the Amazon from the Andes to the Atlantic has been assigned to the late Miocene (Tortonian), deduced from ages of supposed Andean-derived sediments on the Amazon continental margin (~11.5 Ma, Figueiredo et al., 2009; revised to 10.5 Ma, Figueiredo et al., 2010). Gorini et al. (2014) suggested that a significant Amazon delta, perhaps with non-Andean provenance, may have existed in the early Miocene (~18–15 Ma) (Figure **F3B**). Gorini et al. (2014) dated the transition from carbonate to terrigenous sedimentation at the base of the Amazon Fan as 9.5 to 8.3 Ma and suggested a younger age for the first appearance of Andean sediments on the Amazon margin. Hoorn et al. (2017) presented new Nd isotopic data and proposed a slightly later (9.4 to 9.0 Ma) date for establishment of transcontinental drainage. However, the major, order-of-magnitude increase of sedimentation rate did not initiate until ~2.0 Ma, a pattern that is observed in multiple interpreted seismic sections along the Amazon margin (Cruz, 2013), thus seemingly largely independent of sea level control.

If Andean sediments first appear offshore ca. 9 Ma, it is unclear why the great increase of sedimentation rate was delayed for 7 My. An alternative hypothesis is that the Nd signal at 9 Ma indicates establishment of hydraulic connectivity between the Atlantic and the Solimões and Acre Basins (Figure **F3C**) but not the Andes in a region where the Amazon craton has average $\varepsilon_{Nd(0)} = -6.7$ ($N = 13$) (Sato, 1998), values similar to those typically associated with Andean provenance. Other researchers have proposed more recent ages (Figure **F3D**). For example, Latrubesse et al. (2010) concluded that trans-Amazon drainage initiated between 6.5 and 5 Ma, soon after deposition of the Solimões Formation ceased in the western Amazon. Ribas et al. (2012) constrained the age of the Amazon River to ~3 Ma using molecular genetic data for the timing of originations of bird species that occupied opposite banks of the trunk river, coinciding more closely with the major increase of sedimentation on the margin.

The significance of these points for our recovered record includes the following: (1) prior to the middle Miocene or later, terrigenous sediments on the Amazon margin were derived from small rivers sourced only in the easternmost region of tropical South America (Figure **F3A**), therefore pollen and other terrigenous proxies recovered offshore from pre-middle Miocene sediments will only record the environments of this eastern region; (2) it is possible that westward headward erosion (of the Gurupá and Purus Arches) progressively broadened the proto-Amazon drainage basin and source region through the course of the Cenozoic; (3) with breaching of the final divide (possibly the Iquitos Arch) somewhere between 10 and ~2 Ma, Andean sediments reached the Atlantic and transcontinental drainage was achieved. This is one of many plausible yet greatly disparate paleogeographic histories (Hoorn et al., 2010 and 2017; Latrubesse et al., 2007, 2010; van Soelen et al., 2017), none of which are sufficiently constrained by the sparse available data. Identifying the timing of these events will be elucidated by our recovery of complete sequences of Late Miocene and younger age, more precise determination of ages, and multiproxy records of provenance.

Geologic history of the Foz do Amazonas Basin

The Foz ("mouth") do Amazonas Basin is the largest offshore basin on the Brazilian equatorial Atlantic margin. The Amazon Fan is the main sedimentary feature of the deep part of the Foz do Amazonas Basin, built out as a prominent and thick (as thick as 10 km) sedimentary prism (Brandão and Feijó, 1994; de Figueiredo et al., 2007). This marginal basin evolved as the western passive margin of the opening Atlantic, but it was also kinematically related to ancient transform movements, especially along the Saint Paul fracture zone (Darros de Matos, 2000; Moulin et al., 2010).

In the central Foz do Amazonas Basin, south of our proposed drill sites, the Upper Cretaceous to Quaternary stratigraphic sequence has failed along three main décollement surfaces in a linked extensional-compressional system (Cobbold et al., 2004; Reis et al., 2010), forming an upslope set of extensional faults and huge downslope fold-and-thrust belts. The base of the stratigraphic succession of the Foz do Amazonas Basin is composed of Neocomian to Albian fluvio-deltaic, lacustrine, and marine strata, infilling pull-apart half-grabens (Brandão and Feijó, 1994; de Figueiredo et al., 2007). Open-marine clastic deposition started during the late Albian (~102 Ma) with the deposition of deepwater mudstones and siltstones and lasted until the late Paleocene (the Limoeiro Formation).

The Cenozoic sedimentary history of the basin was dominated from the late Paleocene to the late Miocene (~61.7 to ~9.5 Ma) by carbonates of the Marajó and Amapá Formations, which were periodically disrupted by siliciclastic deposition (Wolff and Carozzi, 1984; Gorini et al., 2014), resulting in the buildup of a mixed carbonate-siliciclastic platform as thick as 4000 m, laterally equivalent to deepwater calcilutites and mudstones of the Travosas Formation (Figure **F4**).

Sedimentation on the mixed carbonate-siliciclastic platform of the Foz do Amazonas Basin, like that of the late Quaternary shelf/slope system, was very sensitive to small excursions of sea level, and a series of drowning phases were intercalated with major regressive phases (de Figueiredo et al., 2007). These apparent sea level–induced changes have previously been interpreted (Gorini et al., 2014) in a sequence stratigraphic framework utilizing the eustatic sea level curve of Haq et al. (1988) updated with the timescale of Hilgen et al. (2012); however, given the significant discrepancies between the eustatic curves of Haq et al. (1988) and Miller et al. (2005, 2011), we expect that previous interpretations will be substantially improved as a result of the proposed drilling. The last and most important drowning phase on the platform occurred in the middle Miocene, during the Langhian (~15.2 Ma). Following this event, coastal depositional systems of the Marajó Formation prograded, whereas the carbonate platform continued to develop on the outer continental shelf. This sedimentation lasted until the late Miocene, when lower sea levels partially exposed the shelf, resulting in the permanent cessation of significant carbonate platform building. Siliciclastic input increased until the late Pliocene, occurring mostly as prograding shelf clinoforms, and developed across the proximal basin. This increase of terrigenous sediment was likely associated with the onset of the transcontinental Amazon, continued Andean uplift, and increasing rates of physical erosion in the Andes. During the Quaternary, siliciclastic input increased dramatically in deepwater settings, particularly in the buildup of the Amazon Fan (Gorini et al., 2014) and on the continental slope to its west where we will drill.

Paleoceanographic history of the western equatorial Atlantic

The longest existing paleoceanographic records from the equatorial Brazilian margin extend back only ~100 ka (Nace et al., 2014) and ~1.7 Ma (A. Sandes et al., unpubl. data). Arz et al. (1998) and Nace et al. (2014) both showed that cold periods in the North Atlantic (i.e., Heinrich events) were associated with wet periods and increased river runoff in northeastern Brazil. A. Sandes et al. (unpubl. data) showed that increased precipitation and runoff with Amazon provenance was related to Heinrich events extending back to 1.7 Ma. During the last 1.7 Ma, sea-surface temperature in the western equatorial Atlantic generally varied only ±1.5°C (A. Sandes et al., unpubl. data). On longer timescales, we lack records of paleoceanographic variability in the western equatorial Atlantic region.

Seismic studies/Site survey data

The seismic data sets available to us are 2-D seismic data provided by the Brazilian National Petroleum Agency (ANP) and other companies and 3-D seismic blocks made available by the French seismic survey company CGG and Norwegian multiclient seismic company Spectrum Geo. Information from industry wells includes composite and geophysical logs and drilling operation reports. Biochronostratigraphic reports for three wells were provided by Petrobras. We reinterpreted biochronostratigraphic data from these wells to better constrain the age model for Cretaceous-Quaternary sequences. The 2-D seismic data were used mainly to correlate the stratigraphy from the wells located outside the 3-D seismic blocks.

Industry Well 1APS 0044AP is located on the 3-D seismic grid, ~17 km from proposed primary Site AM-05B and 70 km from proposed primary Site AM-07A (Figure **F1**). We used the time-depth chart from this well, obtained from the check shots, to calculate the depths of the main horizons interpreted on the seismic data. The formation tops were taken from the composite logs. All other sites are located on 3-D in-line and cross-line crossings. In the Site Survey Databank (**https://ssdb.iodp.org/SSDBquery/SSDBquery.php**; select P859 for proposal number), we include the composite logs for the main industry wells, the time-depth charts for Well 1APS 0044AP and for all the primary and alternate sites, and an appendix detailing the biochronostratigraphic reinterpretation of the industry wells.

Scientific objectives

IODP drilling during Expedition 387 will be the first to recover and accurately date nearly the entire Cenozoic sequence of the Amazon margin. The lower portion of the sedimentary record at our primary drill sites will provide a regional record of the early development of the forest/savannah and climate of the easternmost Amazon as well as the paleoceanographic conditions along the near coastal zone. The upper portion of this section, postdating establishment of the transcontinental Amazon, will provide a record of the more recent history of the forest/savannah and climate of the entire Amazon. An exceptionally thick (~800 m) Quaternary section will be recovered, permitting high-resolution reconstruction of paleoceanography of the western equatorial Atlantic and its role in forcing the climate of the adjacent continent. These sequences will allow us to address the following fundamental questions.

Climate and oceanographic questions

- What was the Cenozoic thermal history of eastern tropical South America? Does this history mirror the paleotemperature evolution deduced from the "Zachos" deep-sea $\delta^{18}O$ record?
- What was the Cenozoic precipitation and water balance (i.e., runoff) history of tropical South America?
- Were the thermal optima of the Cenozoic (e.g., PETM or mid-Miocene climate optimum) wet periods? The Held and Soden (2006) hypothesis predicts a wetter Amazon in past (or future) thermal maxima and a drier Amazon in past cold periods.
- Is there evidence for earlier (pre–late Quaternary) millennial precipitation variability? What may have controlled such variability?

To the extent possible, we would like to deduce the role of various forcing factors in influencing this precipitation history: Pliocene(?) cooling of the eastern equatorial Pacific and enhanced Walker circulation, steadily increasing width of the Atlantic throughout the Cenozoic, and uplift of the Andes. On millennial timescales during the late Quaternary, wetter conditions in the Amazon coincide with cold periods in the North Atlantic (Heinrich events, stadials, and glacial stages) possibly associated with decreased Atlantic Meridional Overturning Circulation (AMOC).

We anticipate that we will be able to reconstruct continental temperature, precipitation, and runoff using organic geochemistry, X-ray fluorescence elemental ratios, detrital mineral quantification, provenance, and many other methodologies. Likewise, we can deduce paleoceanographic history using various organic geochemical markers, minor element concentrations and isotopic ratios in planktonic foraminifers, biotic assemblages of planktonic and benthic organisms, and other methodologies.

Vegetation composition and biodiversity questions

- Does the paleoclimate record show evidence of large-scale drying during the Cenozoic in parallel with global cooling?
- If so, does this drying leave a fingerprint on the plant community (e.g., pollen records, C_3/C_4 ratios, opal phytoliths, cuticles, alkanes, C isotopes, and charcoal)?
- On shorter timescales, an enduring question for the Amazon (e.g., Haffer, 1969) is this: were glacial-age plant communities different in composition from interglacial communities?

In one previous study of tropical South American flora (Jaramillo et al., 2006), plant palynomorph diversity was observed to roughly parallel the trend of the Cenozoic deep-sea $\delta^{18}O$ record, exhibiting the highest diversity during the PETM warm event and lower diversity during the colder Oligocene. However, this conclusion has a few important caveats: it was undertaken in northern South America outside of the Amazon Basin and it did not include any samples younger than 20 Ma with the exception of one sample from the Holocene (a period colder than most of the entire Cenozoic) that contained a pollen diversity equal to the PETM maximum diversity.

There are several possible alternatives to the conclusions of Jaramillo et al. (2006). Perhaps diversity instead steadily increases through time as ever more niches are partitioned and filled, as predicted by the museum model. Or perhaps diversity increases sharply due to the uplift of the Andes (although the age of Andean uplift is itself a fundamental research question) (Hoorn et al., 2010) or the origin of the Amazon River and its tributaries (Ribas et al., 2012), supporting a type of cradle model. Phylogenetics is largely silent about extinction, so the fossil pollen record is one of the few options for understanding the timing of extinction events and tying these events to contemporary environmental change. In general, the question of the history of diversity across the Amazon Basin clearly remains unsolved.

We expect nearly complete recovery of the Quaternary interval at very high resolution with abundant terrigenous input; these multiple glacial-interglacial intervals should allow a definitive answer to this question.

Paleohydrology question

- What was the timing of Amazon drainage reorganization and the origin of west-to-east transcontinental drainage? This question will be addressed during this expedition by examining various measures of provenance including lithology, mineralogy, geochemistry, and palynology.

The hydrology and geomorphology of South America, more so than any other continent, is river dominated. The greatest of these rivers (in terms of discharge and basinal area) is the Amazon, and it has had an important role in global climate and biodiversity. However, we still do not know much about the history of Amazon origins, including the timing of the reversal of continental-scale drainage from westward to eastward. The widely accepted postulate is that the west-to-east transcontinental Amazon drainage was established ca. 10 Ma (e.g., Hoorn et al., 2010), but there is significant evidence (Ribas et al., 2012) that this event took place as recently as the Pliocene or Pleistocene (far later than, and completely unrelated to, major uplift of the Andes).

We will date the first terrigenous-dominated sediments overlying the carbonate platform, inflection points of the sediment accumulation rate, and the first occurrence of Andean provenance. These analyses will be undertaken for all of the drill sites, on land and at sea, along the entire TADP.

Summary of objectives

Expedition 387 was designed to achieve the following scientific objectives:

1. To generate the longest, most continuous record of Cenozoic South American climate at unprecedented resolution.
2. To generate a high-resolution record of Cenozoic paleoceanography of the western equatorial Atlantic.
3. To generate a continuous palynological record of the biodiversity and composition of the forests and savannahs of eastern tropical South America from the early Cenozoic until the late Cenozoic establishment of the transcontinental Amazon.
4. To obtain an integrated record of the more recent history of the forests and savannahs of the entire Amazon and tropical Andes, commencing with the establishment of the transcontinental Amazon drainage into the Atlantic.
5. To determine the timing of the onset of transcontinental drainage of the proto-Amazon River into the Atlantic and the changing rates of proto-Amazon discharge.
6. To provide critical marine biostratigraphic control for correlation with Trans-Amazon Drilling Project continental drill sites in the Marajó and eastern Amazonas Basins.

Operations plan/Drilling strategy

The proposed sites of Expedition 387 are located in shallow water on the uppermost continental slope west of and apart from the Amazon Fan. Coring at these sites in the upper part of the long-lived Foz do Amazonas Basin, we aim to recover, as complete as possible, a high-resolution sedimentary sequence spanning nearly the entire Cenozoic.

To achieve these objectives, two primary sites will be cored and logged in multiple holes to achieve depths of >2000 mbsf and to recover a single complete record to at least 59 Ma (Figure **F5**; Table **T1**). The planned casing for each primary site dictates the logging strategy and is thus contextually included in the operations plan described here. For details, see **Logging/Downhole measurements strategy**.

Proposed primary Site AM-07A will be advanced piston corer (APC)/half-length APC/extended core barrel (XCB) cored to 725 mbsf and subsequently logged. To achieve the deep coring objectives, a set of casing strings (16 and 13⅜ inch) will then be installed in Hole B to stabilize the upper portion of the hole. The length of each casing string is dictated by the water depth and cased hole section at the time of installation. Site AM-07A will then be rotary core barrel (RCB) cored to 1090 mbsf and logged below 725 mbsf. A third casing string (10¾ inch) will then be drilled-in to 1080 mbsf, and the hole will be RCB cored to 2135 mbsf and logged below 1090 mbsf.

Proposed primary Site AM-05B will be APC/HLAPC triple cored to 300 mbsf to obtain multiple records of the upper Quaternary sequence. In the third hole, APC/HLAPC/XCB coring will continue to 800 mbsf, followed by logging. The deep target will then include a reentry installation with drill-in casing (10¾ inch) to 420 mbsf. Between 700 and 800 mbsf is a condensed layer of siliciclastic material; therefore, two copies of this interval are planned. After a drill down to 700 mbsf, we will RCB core from 700 to 1566 mbsf and log this interval.

Alternate sites (Table **T2**) follow the same drilling strategy as the corresponding primary site. Additional copies of the Quaternary sequence may also be recovered at alternate sites, depending on operational time available. We plan to orient all APC cores with the FlexIT orientation tool and use nonmagnetic coring hardware to the maximum extent possible.

Logging/Downhole measurements strategy

Formation temperature measurements

During APC coring in the two deep target holes, we plan to undertake a series of formation temperature measurements at both sites using the advanced piston corer temperature tool (APCT-3).

Wireline logging

This strategy requires a series of casing installations, and the logging of each hole is sequenced with planned casing strings. The wireline logging plan aims to provide information on in situ formation properties (lithologies, structures, and petrophysics) and allow for core-log seismic integration. A modified IODP tool string configuration for the triple combination (triple combo) and Formation MicroScanner (FMS)-sonic will be used. If hole conditions allow, we also intend to conduct check shots with the Versatile Seismic Imager (VSI) in the deeper portions of both primary sites. For more specific information on tools and logging, please refer to **http://iodp.tamu.edu/tools/logging**.

Risks and contingency

Coring and logging operations with deep bottom targets in shallow water present several risks and present challenges with respect to achieving the expedition objectives. The target depth of proposed Site AM-07A (2135 mbsf) is one of the deepest ever attempted by *JOIDES Resolution*.

To allow for the recovery of deep sediments and logging data, a reentry system and casing will be used to stabilize the upper portion of the hole. Extra time may be required for hole remediation (i.e., cleaning and stabilization of the hole). Unconsolidated sediments, such as rapidly accumulated silt and sand, may create unstable borehole conditions for reaching deep targets. The dedication of operational time to these objectives precludes multiple attempts to reach deep targets. To address the potential limitations associated with reaching the deep targets at the two primary sites, a series of two shallow (300 mbsf) APC/HLAPC holes followed by a third hole with APC/HLAPC coring to 800 mbsf are planned at Site AM-05B (see **Operations plan/Drilling strategy**). A similar strategy may also be applied at the alternate sites.

Although the weather window for Expedition 387 is ideal, weather conditions always represent a potential risk. At these sites, surface currents of the NBC may present challenges to establishing casing and making reentries in shallow water. There is currently no scheduled contingency time for delays caused by weather or operational issues, and time is currently the biggest risk to the operational success of this expedition.

Sampling and data sharing strategy

Shipboard and shore-based researchers should refer to the IODP Sample, Data, and Obligations Policy and Implementation Guidelines posted at **http://www.iodp.org/policies-and-guidelines**. This document outlines the policy for distributing IODP samples and data to research scientists, curators, and educators. The document also defines the obligations incurred by recipients of samples and data. The Sample Allocation Committee (SAC; composed of the Co-Chief Scientists, Expedition Project Manager/Staff Scientist, and IODP Curator onshore and curatorial representative aboard the ship) will work with the entire scientific party to formulate a formal expedition-specific sampling plan for shipboard and postexpedition sampling.

Every member of the science party is obligated to carry out scientific research for the expedition and to publish the results. All shipboard scientists and any shore-based scientists are required to submit a detailed research plan and associated samples and data using the IODP Sample and Data Request Database (**http://www.iodp.tamu.edu/sdrm**). Based on the research plans submitted, the SAC will prepare a tentative sampling plan. The sampling plan will be subject to modification depending on the actual material recovered and collaborations that may evolve between scientists during the expedition. The SAC must approve modifications to the sampling strategy during the expedition.

Shipboard sampling will include samples taken for shipboard analyses and samples needed for personal postexpedition research. The minimum permanent archive will be the standard archive half of each core. All sample sizes and sampling frequencies must be justified on a scientific basis and will depend on core recovery, the full spectrum of other requests, and the expedition objectives. Some redundancy of measurements is unavoidable, but minimizing the duplication of measurements among the shipboard party and designated shore-based collaborators will be a factor in evaluating sample requests. We expect a large number of shipboard and personal samples to be taken for geochemical measurements. If some critical intervals are recovered, there may be considerable demand for samples from a limited amount of cored material. These intervals may require special handling or reduced sample size and sampling rate. The SAC may require an additional formal sampling plan to be developed for such critical intervals.

The cores from Expedition 387 will be delivered to the Bremen Core Repository (Germany) for permanent storage. All Expedition 387 data and samples will be protected by a 1 year moratorium period that will start at the end of the expedition. During this moratorium, all data and samples will be available only to expedition shipboard scientists and approved shore-based participants.

Expedition scientists and scientific participants

The current list of participants for Expedition 387 can be found at: **http://iodp.tamu.edu/scienceops/expeditions/amazon_margin.html**.

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Table T1. Operations and time estimates, Expedition 387. EPSP = Environmental Protection and Safety Panel, APC = advanced piston corer, HLAPC = half-length APC, XCB = extended core barrel, RCB = rotary core barrel, FMS = Formation MicroScanner, VSI = Versatile Seismic Imager, HRT = hydraulic release tool.

Site No.	Location (Latitude Longitude)	Seafloor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	Logging (days)
Barbados			Begin Expedition 5.0	port call days		
			Transit ~729 nmi to AM--07A @ 10.5 knots	2.9		
AM-07A	5° 4.4056' N	369	Hole A - APC/HLAPC/XCB to 725 mbsf and log with modified triple combo		3.4	0.5
EPSP	50° 24.2590' W		Hole B - Install 16" casing string to 360 mbsf		2.4	0.0
to 2203 mbsf			Hole B - Install 13 3/8" casing string to 720 mbsf		3.1	0.0
			Hole B - RCB coring from 725 - 1090 mbsf and log with triple combo, FMS sonic and VSI		3.3	0.9
			Hole B - Drill in 10 3/4" casing to 1080 mbsf		3.4	0.0
			Hole B - RCB coring from 1090 - 2135 mbsf and log with triple combo, FMS sonic and VSI		13.4	1.3
			Sub-Total Days On-Site: 31.7			
			Transit ~32 nmi to AM-05B @ 10.5 knots	0.1		
AM-05B	4° 40.8462' N	430	Hole A - APC/HLAPC to 300		1.3	0.0
EPSP	50° 2.6220' W		Hole B - APC/HLAPC to 300		0.9	0.0
to 1550 mbsf			Hole C - APC/HLAPC/XCB to 800 and log with modified triple combo		3	0.4
			Hole D - Reentry Installation - Drill in 10.75" casing with HRT system		2.3	0.0
			Hole D - Drill down to 700 mbsf. RCB coring from 700 - 1486 mbsf		8.6	0.0
			Hole D - Logging with triple combo, FMS sonic and VSI		0.0	1.4
			Sub-Total Days On-Site: 17.9			
			Transit ~861 nmi to Fortaleza, Brazil @ 10.5 knots	3.4		
Fortaleza, Brazil			End Expedition	6.4	45.1	4.5

Port Call:	5.0	Total Operating Days:	56.0
Sub-Total On-Site:	49.6	Total Expedition:	61.0

Table T2. Alternate sites, Expedition 387. EPSP = Environmental Protection and Safety Panel, APC = advanced piston corer, HLAPC = half-length APC, XCB = extended core barrel, RCB = rotary core barrel, FMS = Formation MicroScanner, VSI = Versatile Seismic Imager.

Site No.	Location (Latitude Longitude)	Seafloor Depth (mbrf)	Operations Description
AM-06B	4° 37.0220' N	377	First Alternate for Site AM-05B
EPSP	50° 0.6188' W		APC/XCB to 800 mbsf followed by casing to 750 mbsf. RCB from 800 mbsf to 1560 mbsf
to 1650 mbsf			Modified triple combo and FMS sonic from 300 to 1560 mbsf
AM-12B	4° 43.8258' N	357	Second Alternate for Site AM-05B
EPSP	50° 6.9738' W		APC/XCB to 800 mbsf. Casing to 400 mbsf. Drill down to 800 mbsf. RCB coring from 800 to 1400 mbsf
to 1400 mbsf			Modified triple combo and FMS sonic to 1400 mbsf
AM-15A	4° 41.3814' N	341	Third Alternate for Site AM-05B
EPSP	50° 5.2434' W		APC/XCB to 800 mbsf. Casing to 800 mbsf. RCB from 800 to 1395 mbsf
to 1450 mbsf			Modified triple combo and FMS sonic to 1395 mbsf
AM-13A	4° 41.8917' N	312	Fourth Alternate for Site AM-05B
EPSP	50° 6.6703' W		APC/XCB to 800 mbsf. Casing to 400 mbsf. RCB coring from 800 to 1400 mbsf
to 1400 mbsf			Modified triple combo and FMS sonic to 1400 mbsf
AM-03C	4° 39.7680' N	445	Fifth Alternate for Site AM-05B
EPSP	50° 1.3860' W		APC/XCB to 800 mbsf. Casing to 800 mbsf. RCB from 800 to 1400 mbsf
to 1400 mbsf			Modified triple combo and FMS sonic to 1400 mbsf
AM-08A	4° 41.0792' N	312	Sixth Alternate for Site AM-05B
EPSP	50° 5.8624' W		APC/XCB to 800 mbsf. Casing to 750 mbsf. RCB from 800 to 1149 mbsf
to 1149 mbsf			Modified triple combo and FMS sonic to 1149 mbsf
AM-10B	4° 56.5386' N	443	First Alternate for Site AM-07A
EPSP	50° 15.8208' W		APC/HLAPC/XCB to 725 mbsf. Casing to 720 mbsf. RCB from 725 to 1090 mbsf. Casing to 1080 mbsf. RCB from 1090 to 2283 mbsf
to 2300 mbsf			Modified triple combo to 725 mbsf. Triple combo from 725 to 1090 mbsf. Triple combo, FMS-sonic, and VSI from 1090 to 2283 mbsf
AM-14B	5° 0.2574' N	353	Second Alternate for Site AM-07A
EPSP	50° 21.1194' W		APC/XCB to 800 mbsf. Casing to 800 mbsf. RCB from 800 to 2088 mbsf
to 2200 mbsf			Modified triple combo and FMS sonic to 2088 mbsf
AM-11A	4° 45.6299' N	288	Third Alternate for Site AM-07A
EPSP	50° 11.1095' W		APC/XCB to 800 mbsf. Casing to 500 mbsf. Drill ahead to 750 mbsf. RCB coring from 750 to 1750 mbsf
to 1800 mbsf			Modified triple combo and FMS sonic to 1750 mbsf
AM-04B	4° 37.7363' N	244	Fourth Alternate for Site AM-07A
EPSP	50° 5.3696' W		APC/XCB to 800 mbsf. Casing to 400 mbsf. Drill down to 800 mbsf. RCB from 800 to 2087 mbsf
to 2100 mbsf			Modified triple combo and FMS sonic to 2087 mbsf

Figure F1. Geologic map of the Amazon (Leão Neto et al., 2015) showing location of the five proposed continental ICDP drill sites in the Acre, Solimões, Amazonas (east and west), and Marajó Basins and location of proposed IODP sites.

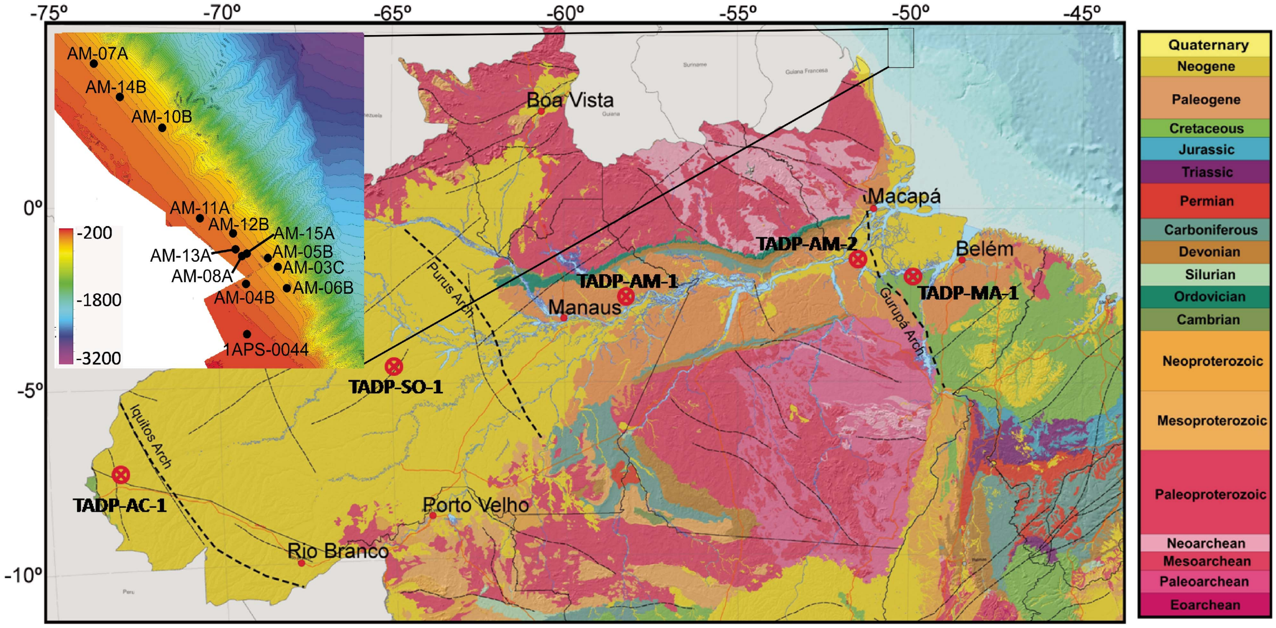


Figure F2. A. Bathymetric contours, proposed sites, prior ODP drill sites, and available seismic data. Gray lines = 2-D multichannel seismic lines. B. Study area. Detailed bathymetry was contoured from the 3-D seismic grid (rectangle in A). Primary and alternate sites are shown, as well as the main industry exploration wells used to construct the biochronostratigraphic models and tie with the seismic horizons.

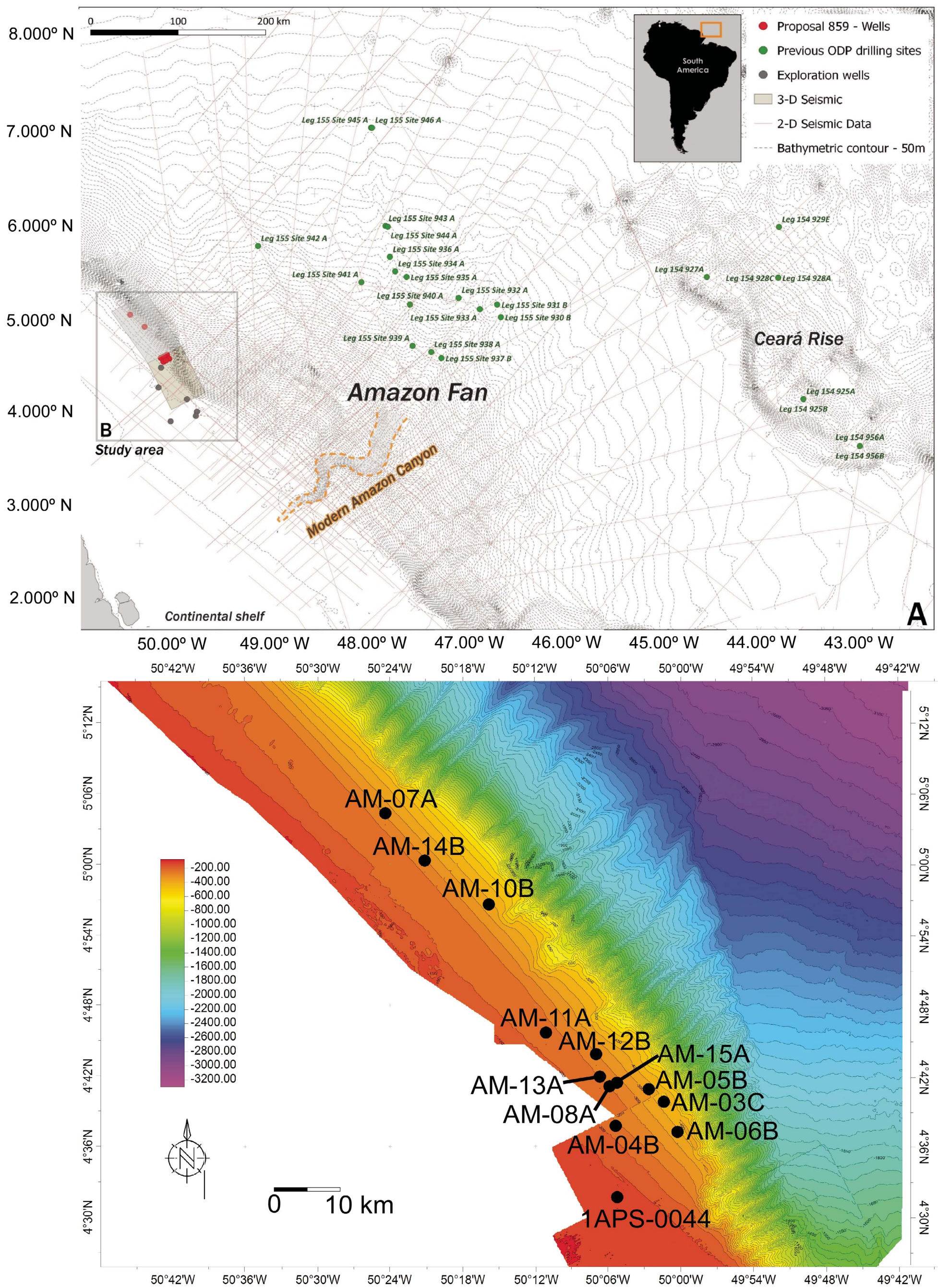


Figure F3. Newly hypothesized sequence of drainage scenarios for the Amazon Basin showing major watersheds, paleohydrologic flow paths (drainage), and paleohydrologic divides (structural arches). masl = meters above sea level. A. For much of the Cenozoic, only the rivers of eastern tropical South America discharged to the Atlantic. The rest of the Amazon Basin may have drained to the Caribbean, perhaps along the present-day Orinoco. B. Headward erosion or tectonic motion of the Gurupá Arch widened the proto-Amazon watershed westward to the Purus divide. C. Headward erosion of the Purus Arch and drainage capture again widened the Amazon watershed, whereas Andean-sourced rivers flowed northward. D. Continued uplift of the Andes, closure of the Vaupés Arch (to the north), and headward erosion of the Iquitos Arch finally connected the Andes to the Atlantic causing the major increase of sedimentation rate on the continental margin.

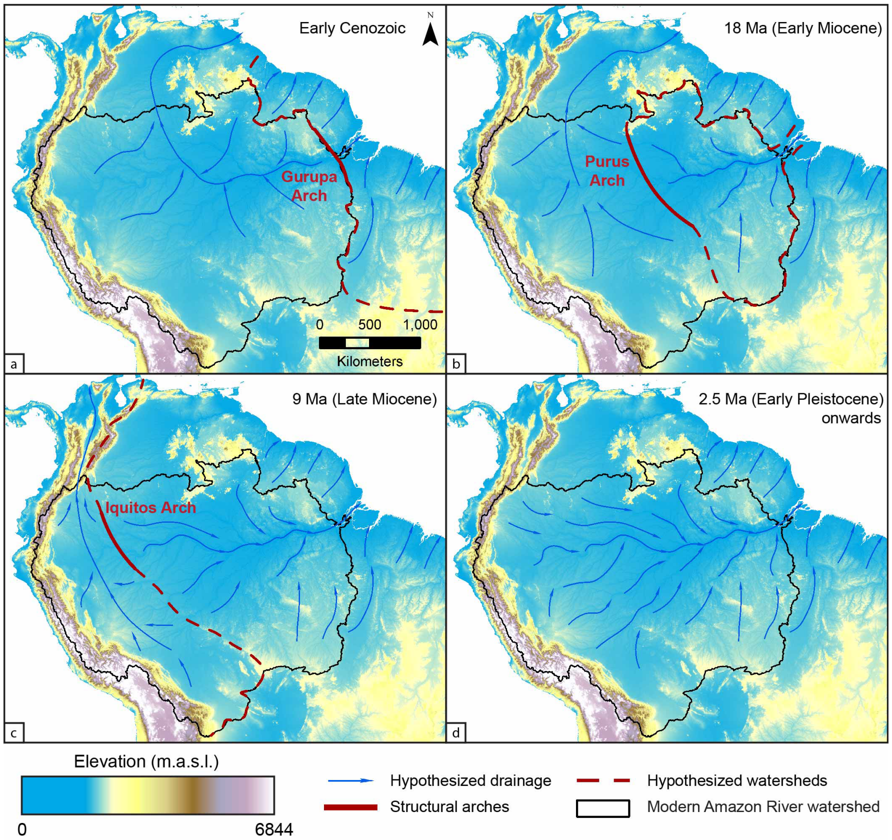


Figure F4. Foz do Amazonas Basin chronostratigraphic chart. Red line = position of proposed primary Site AM-05B on the upper continental slope. TU = Tucunaré Formation, PI = Pirarucu Formation, ORA = Orange Formation, AMA = Amapá Formation, TRA = Travosas Formation, MA = Marajó Formation, LI = Limoeiro Formation, CAS = Cassiporé Formation, COD = Codó Formation, CAL = Calçoene Formation, ? = unnamed igneous (volcanic?) event.

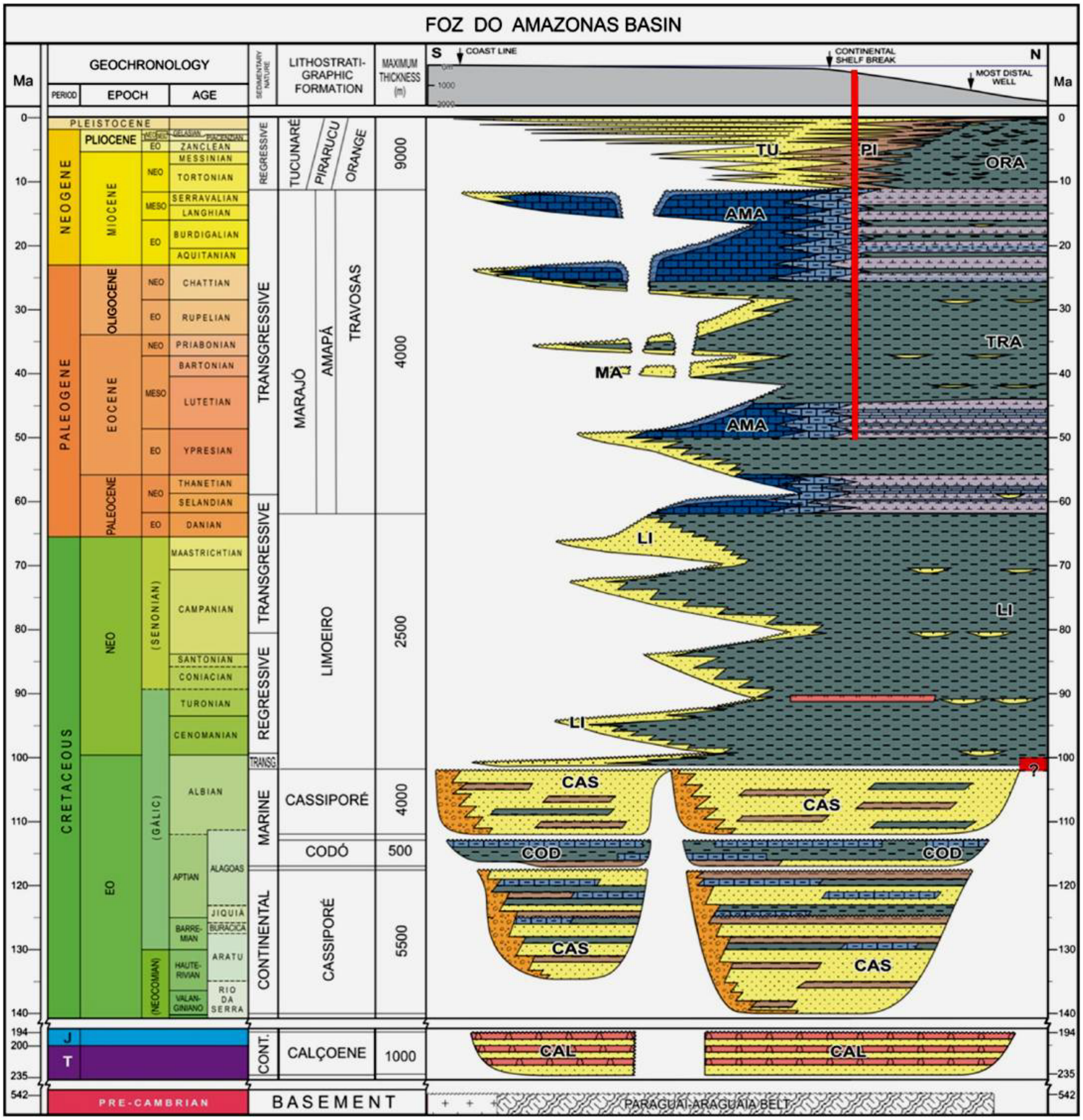
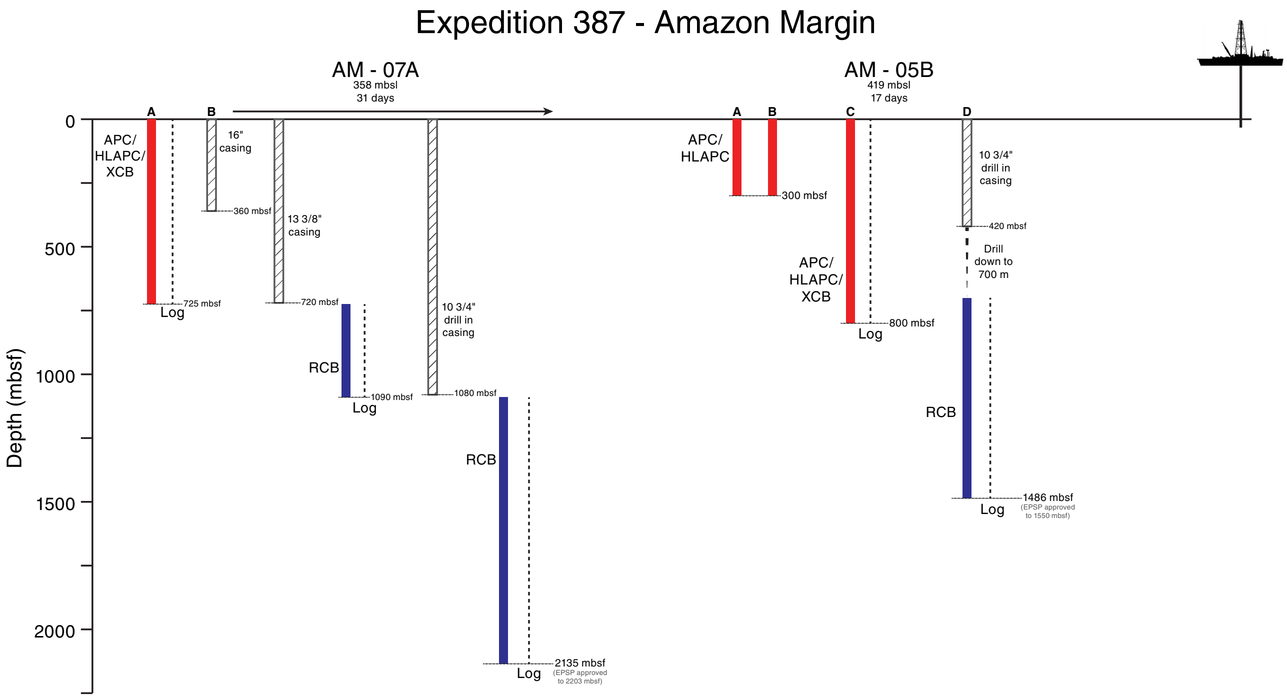


Figure F5. Planned drilling strategy, for Expedition 387. EPSP = Environmental Protection and Safety Panel.

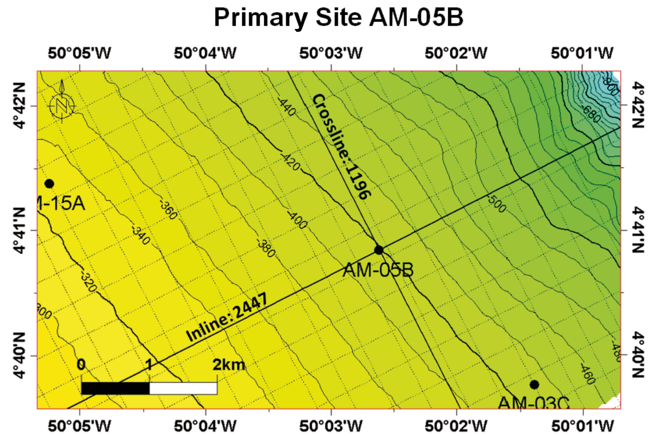


Site summaries

Figure AF1. Top: map with bathymetry derived from 3-D multichannel seismic (MCS) grid showing location of proposed primary Site AM-05B on the intersection of seismic reflection (MCS) In-line 2447 and Cross-line 1196. Bottom: interpreted and noninterpreted MCS In-line 2447 and Cross-line 1196 with location of proposed Site AM-05B. Cross-line (XL) and in-line (IL) numbers are included.

Site AM-05B

Priority:	Primary
Position:	4°40.8462′N, 50°2.6220′W
Water depth (m):	419
Target drilling depth (mbsf):	1486
Approved maximum penetration (mbsf):	1550
Survey coverage (track map; seismic profile):	Bathymetry from 3-D seismic grid. In-line 2447; Cross-line 1196.
Objective(s):	Reach the late Eocene (~38 Ma) horizon at 1486 mbsf.
Drilling program:	Triple APC to 300 mbsf, XCB from 300 to 800 mbsf followed by casing to stabilize the upper section, and RCB from 800 to 1486 mbsf.
Logging/Downhole measurements program:	Modified triple combo from 300 to 800 mbsf; triple combo, FMS-sonic, and VSI from 700 to 1486 mbsf.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).



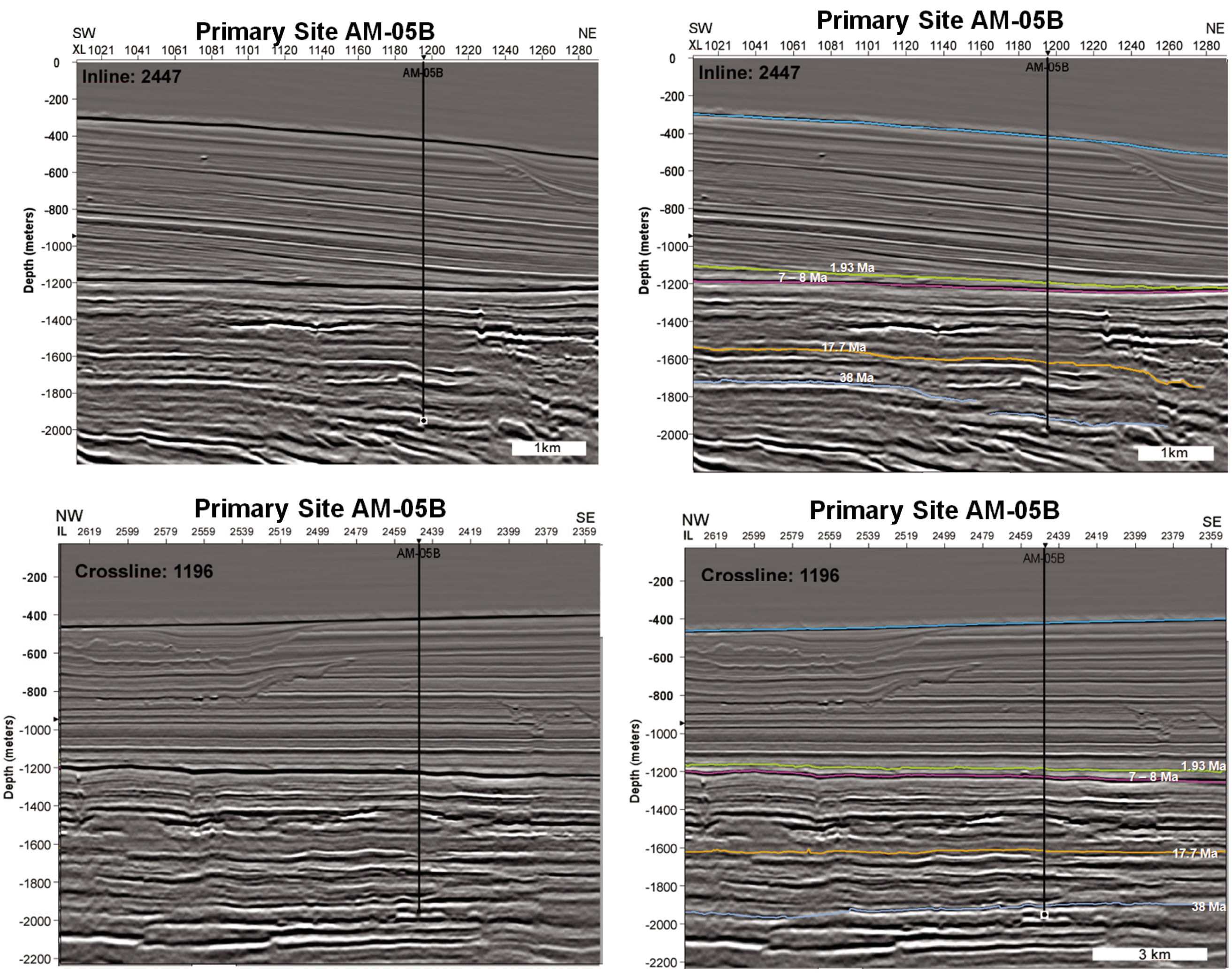
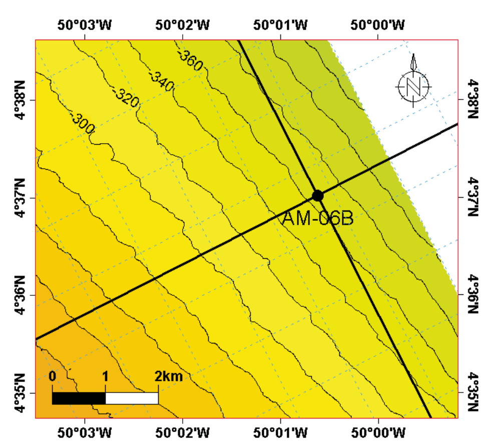


Figure AF2. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-06B on the intersection of MCS In-line 2129 and Cross-line 1200. Bottom: interpreted and noninterpreted MCS In-line 2129 and Cross-line 1200 with location of proposed Site AM-06B. Cross-line and in-line numbers are included.

Site AM-06B

Priority:	First alternate for Site AM-05B
Position:	4°37.0220′N, 50°0.6188′W
Water depth (m):	366
Target drilling depth (mbsf):	1560
Approved maximum penetration (mbsf):	1650
Survey coverage (track map; seismic profile):	In-line 2129; Cross-line 1200. Bathymetry from 3-D grid.
Objective(s):	Reach the late Eocene (~38 Ma) horizon at 1560 mbsf.
Drilling program:	APC/XCB to 800 mbsf followed by casing to 750 mbsf. RCB from 800 to 1560 mbsf.
Logging/Downhole measurements program:	Modified triple combo and FMS-sonic from 300 to 1560 mbsf.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).



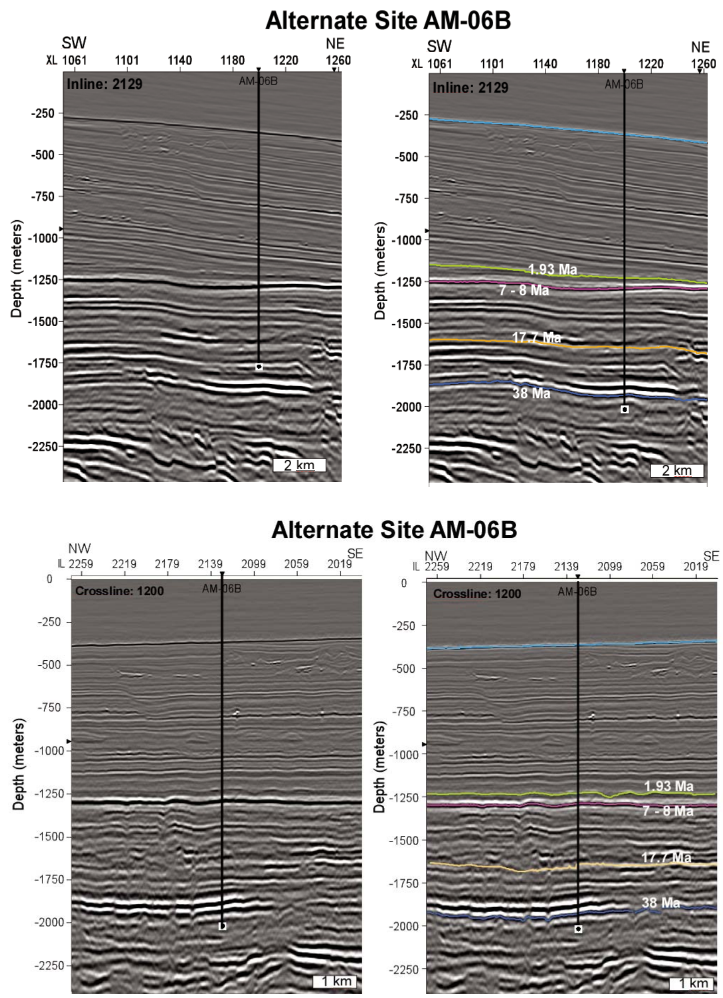
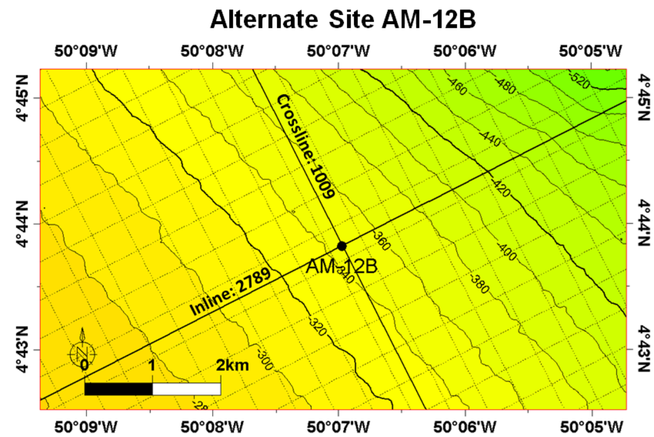
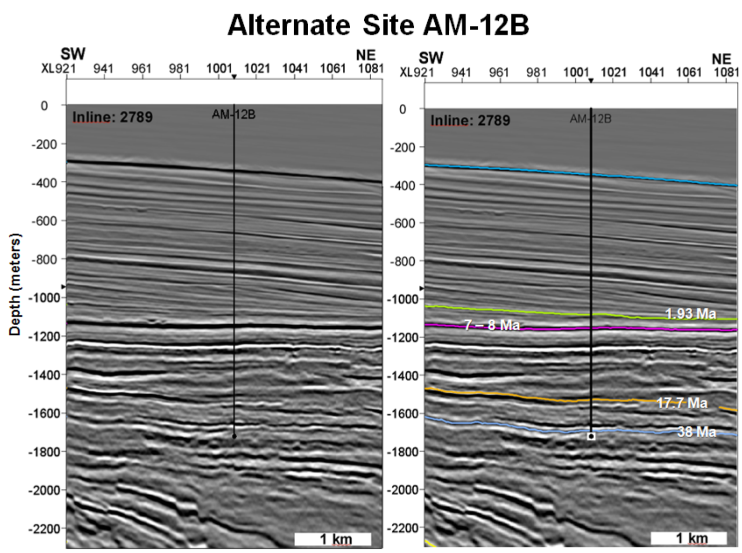


Figure AF3. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-12B on the intersection of MCS In-line 2789 and Cross-line 1009. Bottom: interpreted and noninterpreted MCS In-line 2789 and Cross-line 1009 with location of proposed Site AM-12B. Cross-line and in-line numbers are included.

Site AM-12B

Priority:	Second alternate for Site AM-05B
Position:	4°43.8258′N, 50°6.9738′W
Water depth (m):	346
Target drilling depth (mbsf):	1344
Approved maximum penetration (mbsf):	1400
Survey coverage (track map; seismic profile):	In-line 2789; Cross-line 1009. Bathymetry from 3-D grid.
Objective(s):	Reach the late Eocene (~38 Ma) horizon at 1344 mbsf.
Drilling program:	APC/XCB to 800 mbsf. Casing to 400 mbsf. Drill down to 800 mbsf. RCB coring from 800 to 1400 mbsf.
Logging/Downhole measurements program:	Triple combo and FMS-sonic.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).





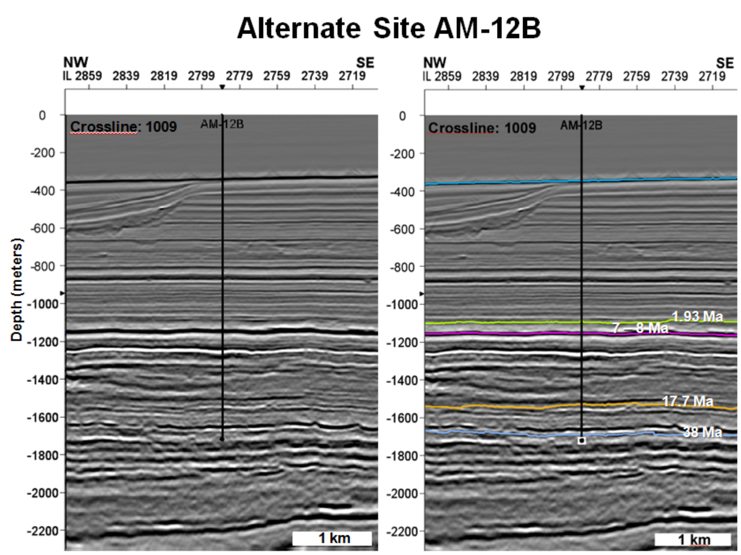
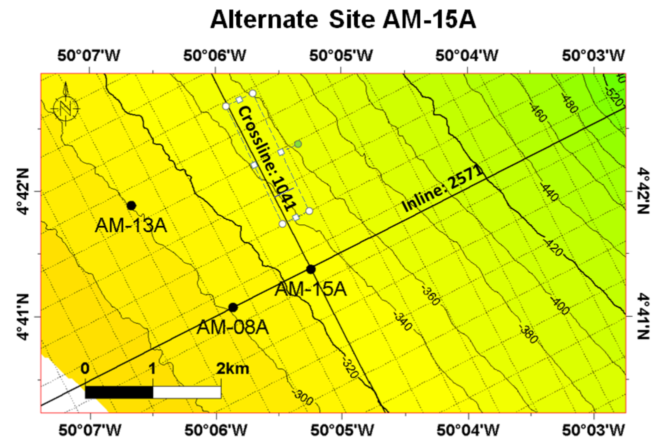
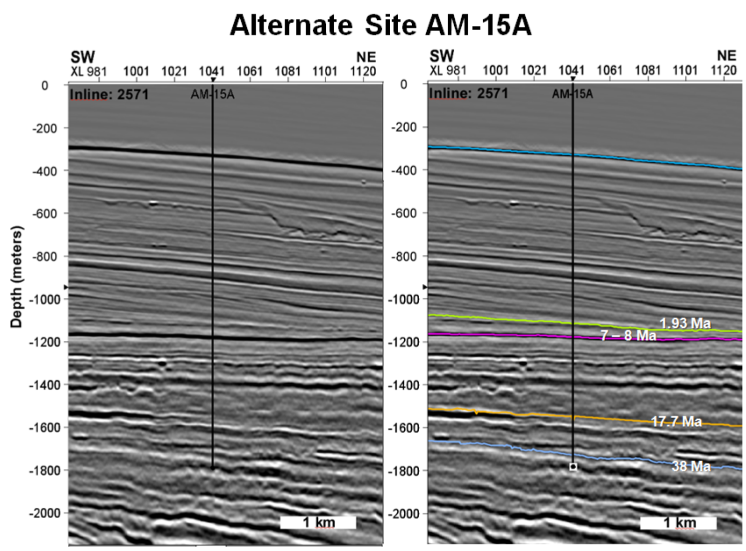


Figure AF4. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-15A on the intersection of MCS In-line 2571 and Cross-line 1041. Bottom: interpreted and noninterpreted MCS In-line 2571 and Cross-line 1041 with location of proposed Site AM-15A. Cross-line and in-line numbers are included.

Site AM-15A

Priority:	Third alternate for Site AM-05B
Position:	4°41.3814′N, 50°5.2434′W
Water depth (m):	330
Target drilling depth (mbsf):	1395
Approved maximum penetration (mbsf):	1450
Survey coverage (track map; seismic profile):	In-line 2571; Cross-line 1041. Bathymetry from 3-D grid.
Objective(s):	Reach the late Eocene (~38 Ma) horizon at 1395 mbsf.
Drilling program:	APC/XCB to 800 mbsf. Casing to 800 mbsf. RCB from 800 to 1395 mbsf.
Logging/Downhole measurements program:	Triple combo and FMS-sonic.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).





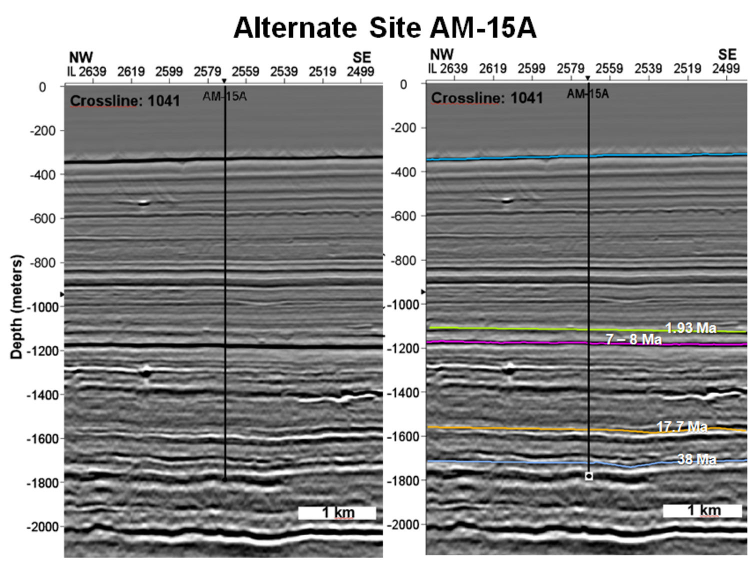
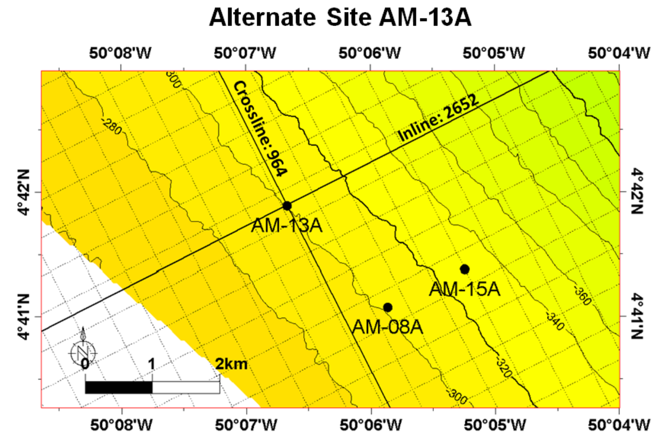


Figure AF5. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-13A on the intersection of MCS In-line 2652 and Cross-line 964. Bottom: interpreted and noninterpreted MCS In-line 2652 and Cross-line 964 with location of proposed Site AM-13A. Cross-line and in-line numbers are included.

Site AM-13A

Priority:	Fourth alternate for Site AM-05B
Position:	4°41.8917′N, 50°6.6703′W
Water depth (m):	301
Target drilling depth (mbsf):	1365
Approved maximum penetration (mbsf):	1400
Survey coverage (track map; seismic profile):	In-line 2652; Cross-line 964. Bathymetry from 3-D grid.
Objective(s):	Reach the late Eocene (~38 Ma) horizon at 1355 mbsf.
Drilling program:	APC/XCB to 800 mbsf. Casing to 400 mbsf. RCB coring from 800 to 1400 mbsf.
Logging/Downhole measurements program:	Triple combo and FMS-sonic.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).



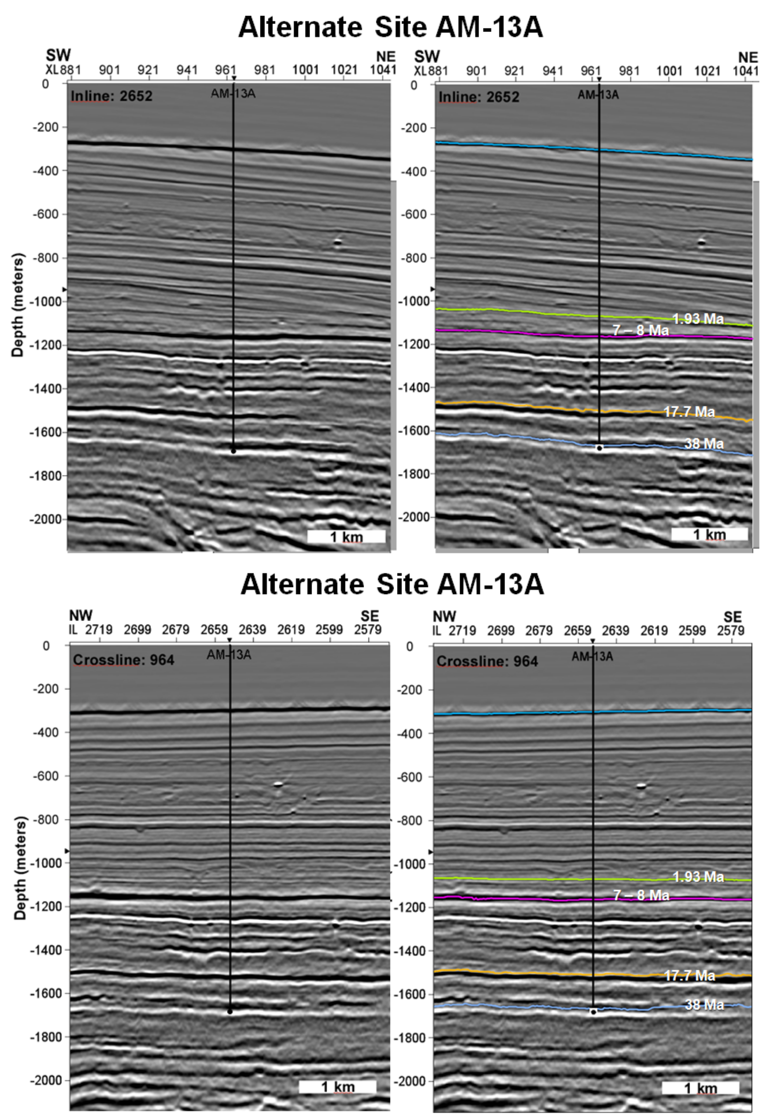
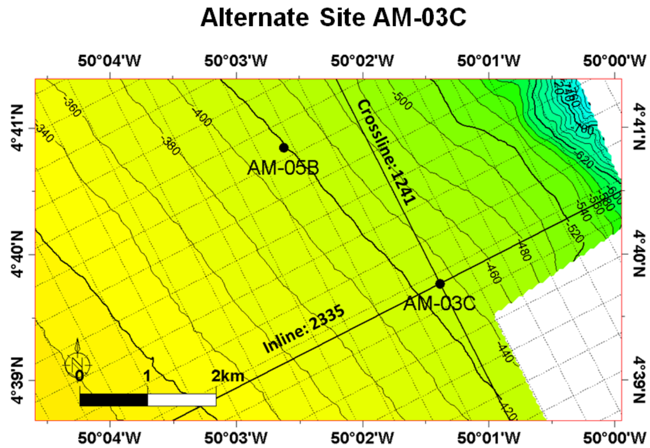


Figure AF6. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-03C on the intersection of MCS In-line 2335 and Cross-line 1241. Bottom: interpreted and noninterpreted MCS In-line 2335 and Cross-line 1241 with location of proposed Site AM-03C. Cross-line and in-line numbers are included.

Site AM-03C

Priority:	Fifth alternate for Site AM-05B
Position:	4°39.7680′N, 50°1.3860′W
Water depth (m):	434
Target drilling depth (mbsf):	1400
Approved maximum penetration (mbsf):	1400
Survey coverage (track map; seismic profile):	In-line: 2335, Cross-line: 1241. Bathymetry from 3-D grid.
Objective(s):	Reach the late Eocene (~38 Ma).
Drilling program:	APC/XCB to 800 mbsf. Casing to 800 mbsf. RCB from 800 to 1400 mbsf.
Logging/Downhole measurements program:	Triple combo and FMS-sonic.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).



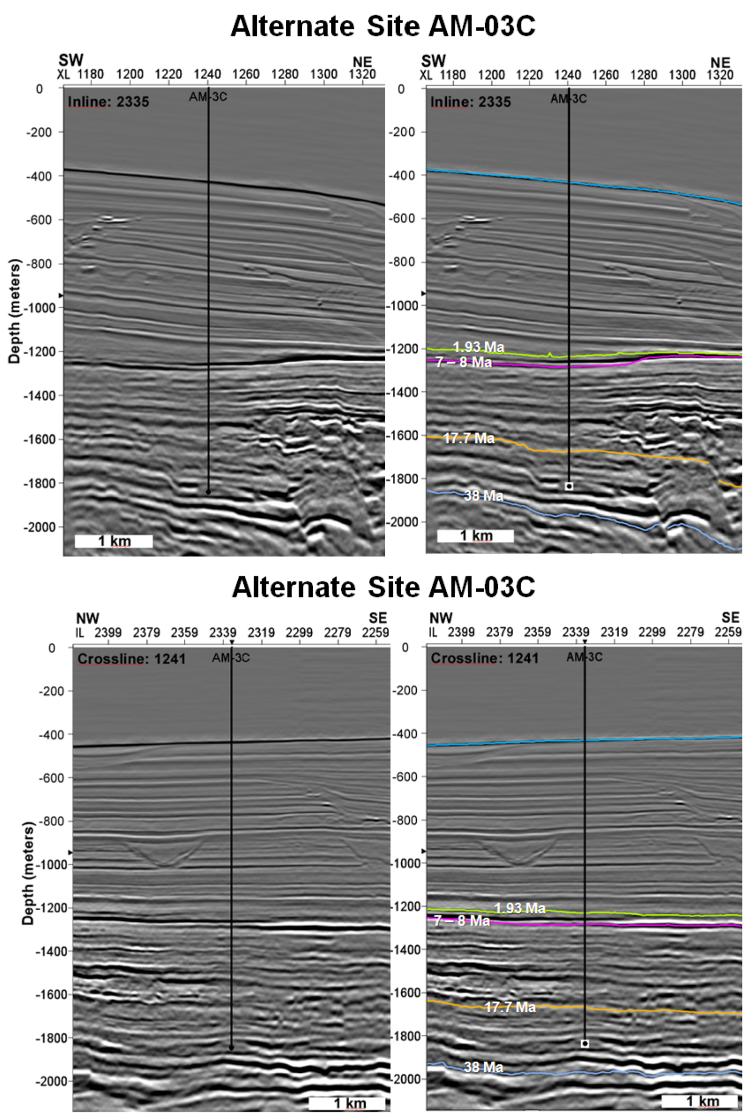
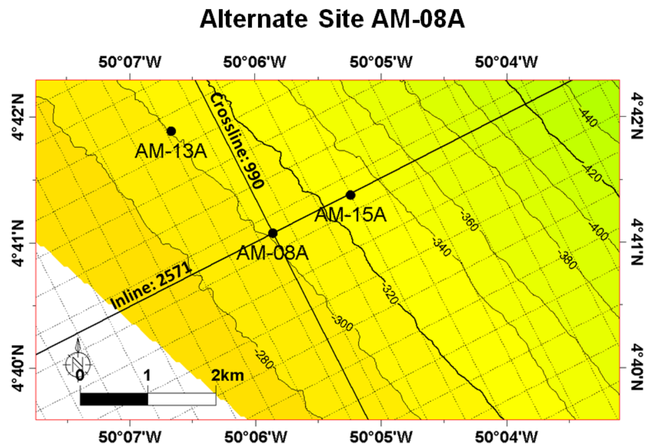


Figure AF7. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-08A on the intersection of MCS In-line 2571 and Cross-line 990. Bottom: interpreted and noninterpreted MCS In-line 2571 and Cross-line 990 with location of proposed Site AM-08A. Cross-line and in-line numbers are included.

Site AM-08A

Priority:	Sixth alternate for Site AM-05B
Position:	4°41.0792′N, 50°5.8624′W
Water depth (m):	301
Target drilling depth (mbsf):	1149
Approved maximum penetration (mbsf):	1149
Survey coverage (track map; seismic profile):	In-line 2571, Cross-line 990. Bathymetry from 3-D seismic grid.
Objective(s):	Reach the late Eocene (~38 Ma).
Drilling program:	APC/XCB to 800 mbsf. Casing to 750 mbsf. RCB from 800 to 1149 mbsf.
Logging/Downhole measurements program:	Triple combo and FMS-sonic.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).



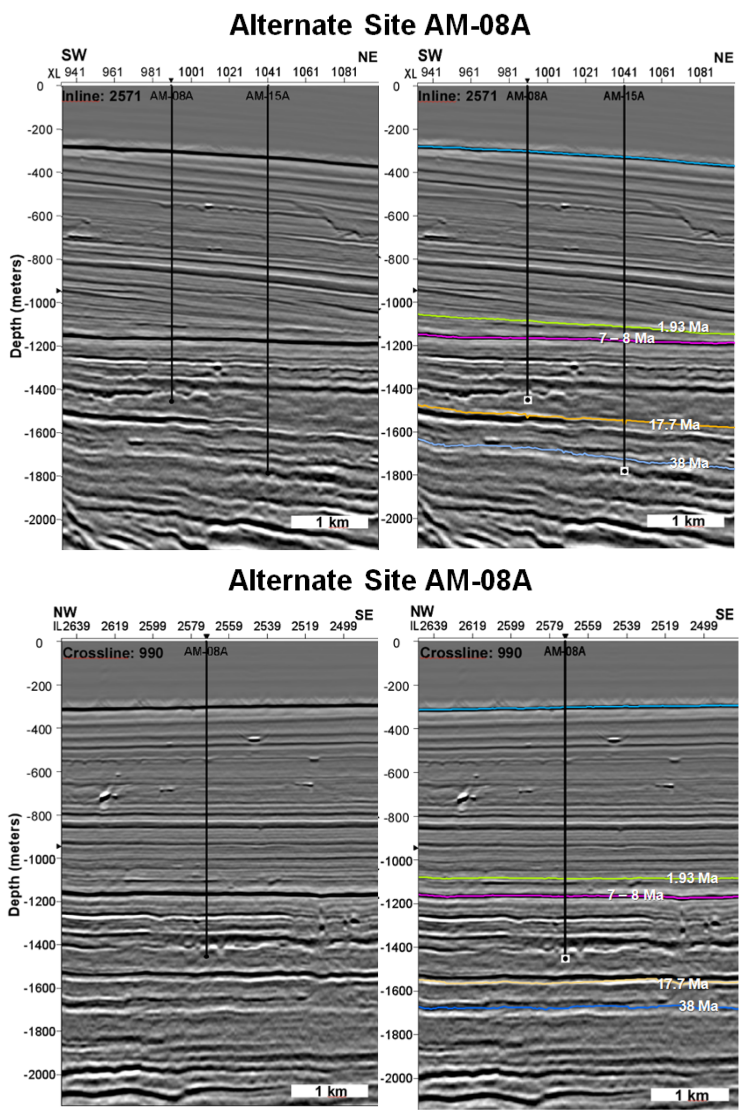
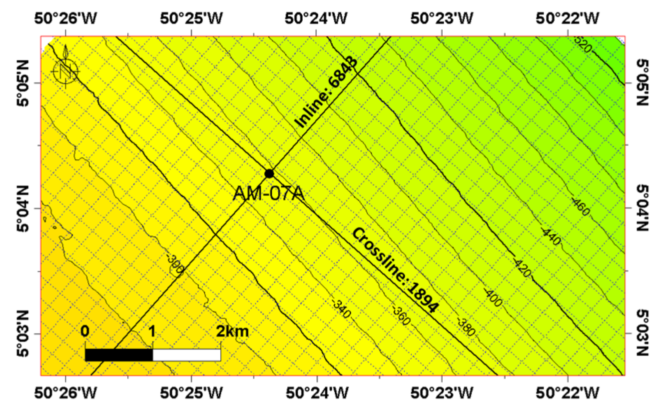


Figure AF8. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed primary Site AM-07A on the intersection of MCS In-line 6843 and Cross-line 1894. Bottom: interpreted and noninterpreted MCS In-line 6843 and Cross-line 1894 with location of proposed Site AM-07A. Cross-line and in-line numbers are included.

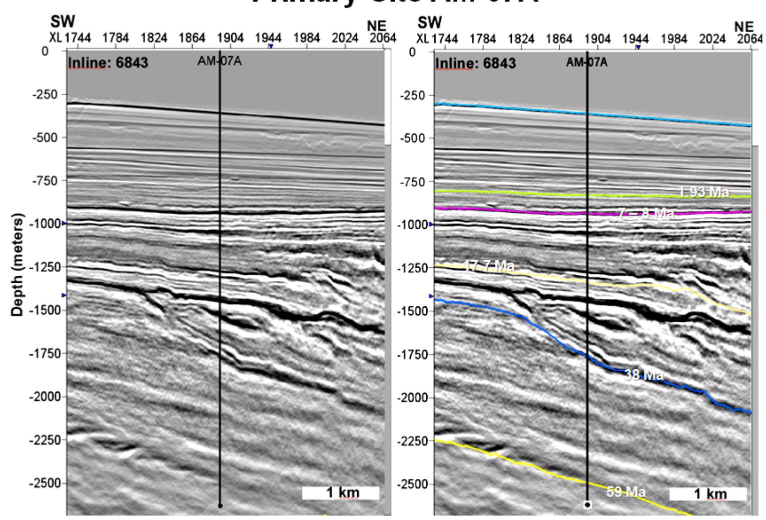
Site AM-07A

Priority:	Primary
Position:	5°4.4056′N, 50°24.2590′W
Water depth (m):	358
Target drilling depth (mbsf):	2135
Approved maximum penetration (mbsf):	2203
Survey coverage (track map; seismic profile):	In-line 6843, Cross-line 1894. Bathymetry from 3-D grid.
Objective(s):	Reach the top of the Limoeiro Formation (~59 Ma) horizon at 2135 mbsf.
Drilling program:	APC/HLAPC/XCB to 725 mbsf. Casing to 720 mbsf. RCB from 725 to 1090 mbsf. Casing to 1080 mbsf. RCB from 1090 to 2135 mbsf.
Logging/Downhole measurements program:	Modified triple combo to 725 mbsf. Triple combo from 725 to 1090 mbsf. Triple combo, FMS-sonic, and VSI from 1090 to 2135 mbsf.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).

Primary Site AM-07A



Primary Site AM-07A



Primary Site AM-07A

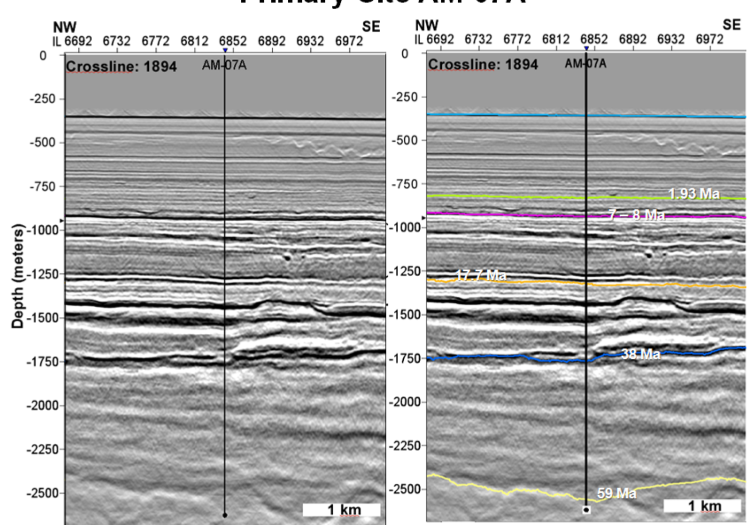
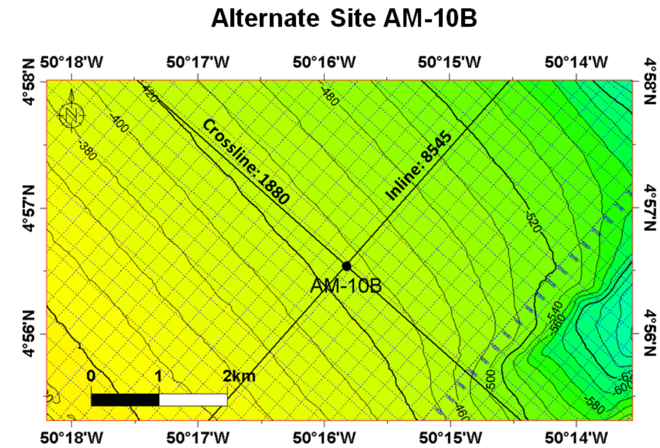


Figure AF9. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-10B on the intersection of MCS In-line 8545 and Cross-line 1880. Bottom: interpreted and noninterpreted MCS In-line 8545 and Cross-line 1880 with location of proposed Site AM-10B. Cross-line and in-line numbers are included.

Site AM-10B

Priority:	First alternate for Site AM-07A
Position:	4°56.5386′N, 50°15.8208′W
Water depth (m):	432
Target drilling depth (mbsf):	2283
Approved maximum penetration (mbsf):	2300
Survey coverage (track map; seismic profile):	In-line 8545; Cross-line 1880. Bathymetry from 3-D grid.
Objective(s):	Reach the top of the Limoeiro Formation (~59 Ma) horizon at 2283 mbsf.
Drilling program:	APC/HLAPC/XCB to 725 mbsf. Casing to 720 mbsf. RCB from 725 to 1090 mbsf. Casing to 1080 mbsf. RCB from 1090 to 2283 mbsf.
Logging/Downhole measurements program:	Modified triple combo to 725 mbsf. Triple combo from 725 to 1090 mbsf. Triple combo, FMS-sonic, and VSI from 1090 to 2283 mbsf.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).



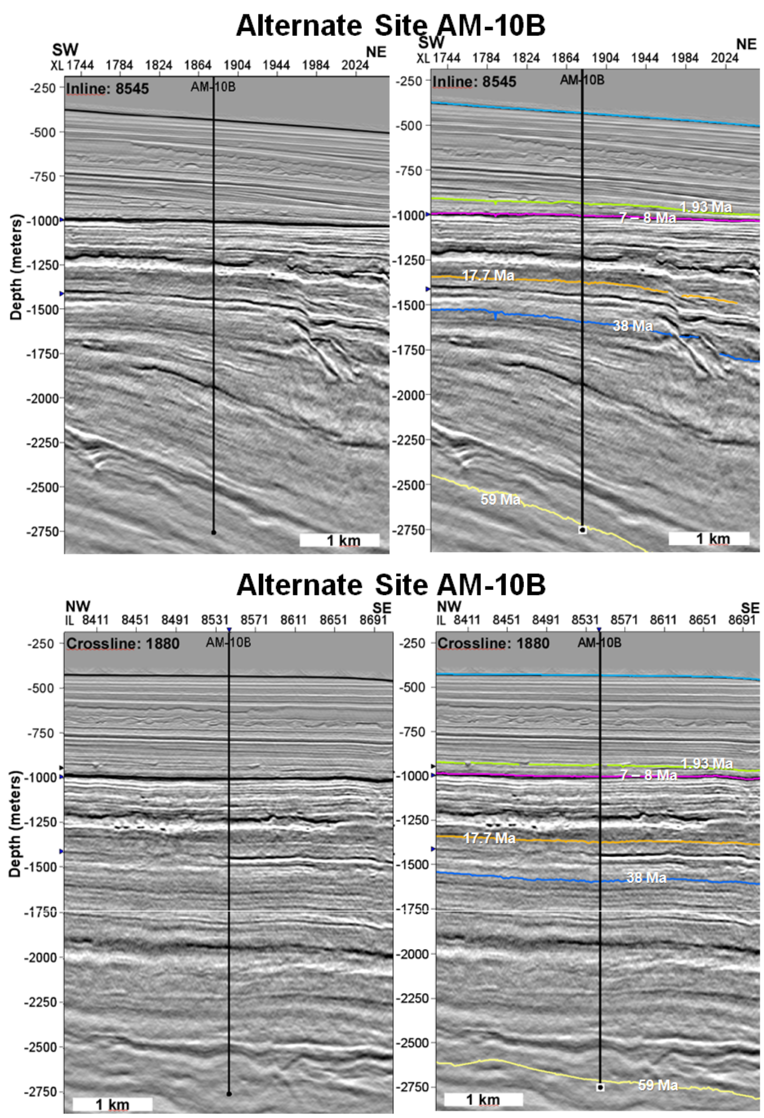
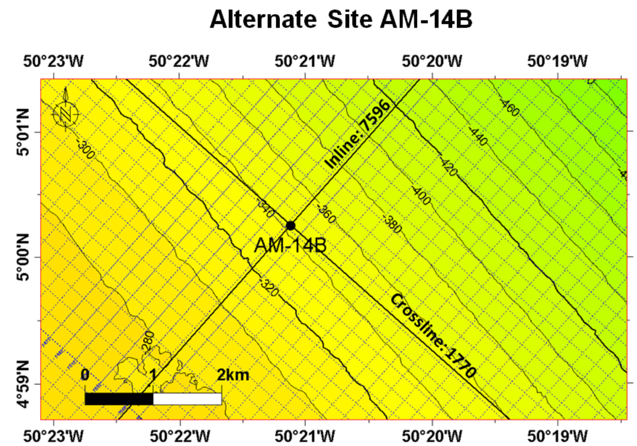


Figure AF10. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-14B on the intersection of MCS In-line 7596 and Cross-line 1770. Bottom: interpreted and noninterpreted MCS In-line 7596 and Cross-line 1770 with location of proposed Site AM-14B. Cross-line and in-line numbers are included.

Site AM-14B

Priority:	Second alternate for Site AM-07A
Position:	5°0.2574′N, 50°21.1194′W
Water depth (m):	342
Target drilling depth (mbsf):	2088
Approved maximum penetration (mbsf):	2200
Survey coverage (track map; seismic profile):	In-line 7596; Cross-line 1770. Bathymetry from 3-D grid.
Objective(s):	Reach the top of the Limoeiro Formation (~59 Ma) horizon at 2088 mbsf.
Drilling program:	APC/XCB to 800 mbsf. Casing to 800 mbsf. RCB from 800 to 2088 mbsf.
Logging/Downhole measurements program:	Triple combo and FMS-sonic.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).



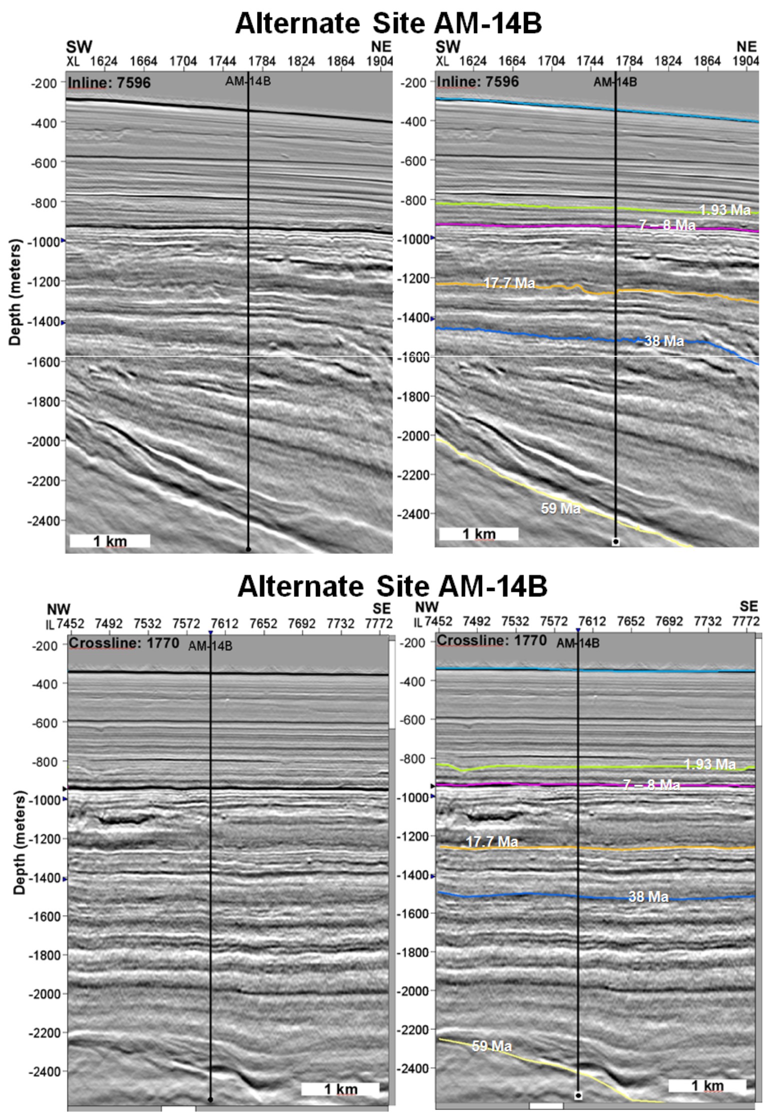
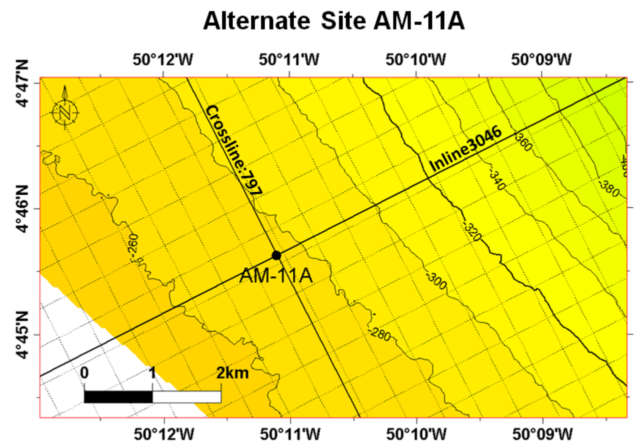


Figure AF11. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-11A on the intersection of MCS In-line 3046 and Cross-line 797. Bottom: interpreted and noninterpreted MCS In-line 3046 and Cross-line 797 with location of proposed Site AM-11A. Cross-line and in-line numbers are included.

Site AM-11A

Priority:	Third alternate for Site AM-07A
Position:	4°45.6299′N, 50°11.1095′W
Water depth (m):	277
Target drilling depth (mbsf):	1750
Approved maximum penetration (mbsf):	1800
Survey coverage (track map; seismic profile):	In-line 3046; Cross-line 797. Bathymetry from 3-D grid.
Objective(s):	Reach the top of the Limoeiro Formation (~59 Ma) horizon at 1750 mbsf.
Drilling program:	APC/XCB to 800 mbsf. Casing to 500 mbsf. Drill ahead to 750 mbsf. RCB coring from 750 to 1750 mbsf.
Logging/Downhole measurements program:	Triple combo and FMS-sonic.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).



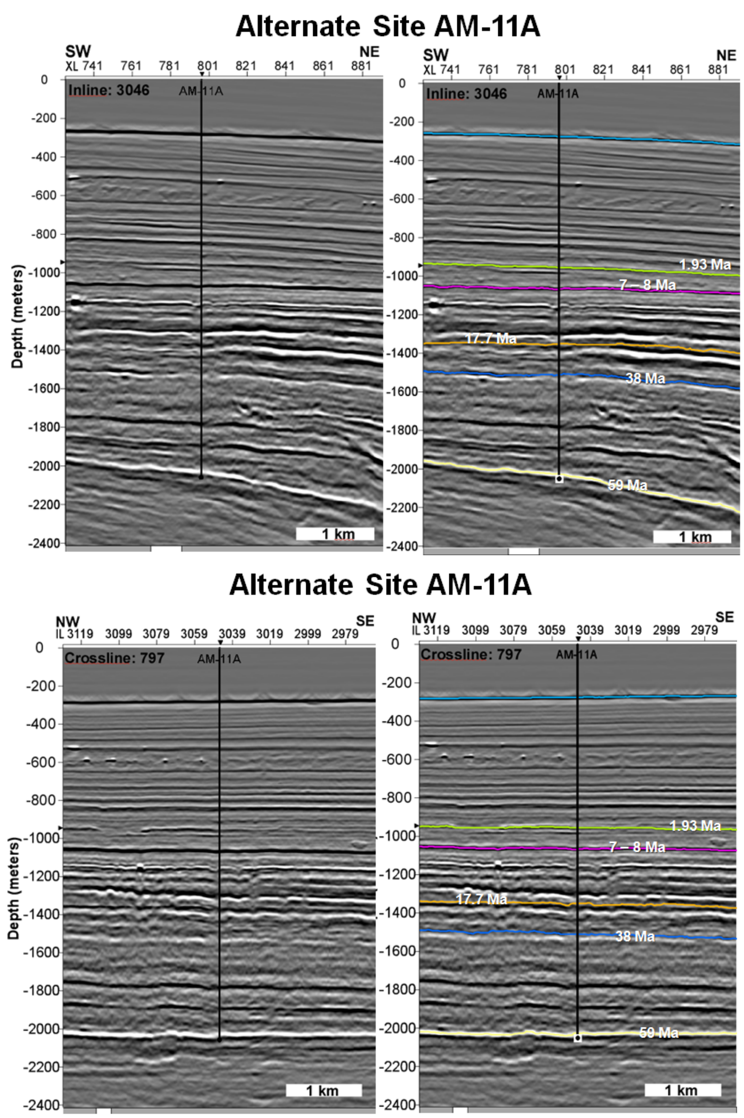


Figure AF12. Top: map with bathymetry derived from 3-D MCS grid showing location of proposed alternate Site AM-04B on the intersection of MCS In-line 2335 and Cross-line 911. Bottom: interpreted and noninterpreted MCS In-line 2335 and Cross-line 911 with location of proposed Site AM-04B. Cross-line and in-line numbers are included.

Site AM-04B

Priority:	Fourth alternate for Site AM-07A
Position:	4°37.7363′N, 50°5.3696′W
Water depth (m):	233
Target drilling depth (mbsf):	2087
Approved maximum penetration (mbsf):	2100
Survey coverage (track map; seismic profile):	In-line 2335; Cross-line 911. Bathymetry from 3-D grid.
Objective(s):	Reach the top of the Limoeiro Formation (~59 Ma) horizon at 2087 mbsf.
Drilling program:	APC/XCB to 800 mbsf. Casing to 400 mbsf. Drill down to 800 mbsf. RCB from 800 to 2087 mbsf.
Logging/Downhole measurements program:	Triple combo and FMS-sonic.
Nature of rock anticipated:	Shales, sandstones, and carbonates (calcarenites and calcilutites).