The structure and tectonics of the Guyana Basin

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Abstract: The Guyana Basin formed during the Jurassic opening of the North Atlantic. The basin margins vary in tectonic origin and include the passive extensional volcanic margin of the Demerara Plateau in Suriname, an oblique extensional margin inboard at the Guyana–Suriname border, a transform margin parallel to the shelf in NW Guyana, and an ocean–ocean margin to the NE, which morphed from transform to oblique extension. Plate reconstructions suggest rifting and early seafloor spreading began with NNW/SSE extension (c. 190–160 Ma) but relative plate motion later changed to NW/SE. The fraction of magmatic basin floor decreases westwards and the transition from continental to oceanic crust narrows from 200 km in Suriname to less than 50 km in Guyana. The geometry and position of the onshore Takutu Graben suggest it formed a failed arm of a Jurassic triple junction that likely captured the Berbice river during post-rift subsidence and funneled sediment into the Guyana Basin. Berriasian to Aptian shortening caused crustal-scale folds and thrusts in the NE margin of the basin along with minor inversions of basin margin and basin-segmenting faults. Stratigraphically trapped Liza trend hydrocarbon discoveries are located outboard of inverted basement faults, suggesting a link between transform margin structure and their formation.

The deep structure of the Guyana Basin received relatively little attention before the last decade. Despite hydrocarbon exploration beginning in the early twentieth century, discovery of the onshore Suri-
name Tambaredjo and Calcutta oilfields in the 1960s (Wong et al. 1998) and recoverable reserves estimated by the USGS at 13.6 billion barrels of oil (Schenk et al. 2012), legacy seismic data lacked sufficient offset to image deep crustal structures. The lack of deep data, coupled with sparse two-dimensional seismic coverage, precluded clear seismic imaging and characterization of the continent–ocean transition and limited most studies to onshore and shallow-water margins of the basin (Yang and Escalona 2011; Nemčok et al. 2015a, b).

We present interpretations of newly reprocessed seismic data that clearly image the deep structure of the Guyana Basin, including the western transform margin. These new data engender a fuller understanding of the tectonic evolution and plate model, the nature, distribution and interaction of crustal structures and magma, and the implications for the petroleum system within the basin.

The discovery of both the giant Liza Field in 2015 and subsequent discoveries totaling over 10 billion barrels of recoverable oil equivalent in Guyana (ExxonMobil 2021) spurred a new phase of data acquisition and industry activity that has clearly revealed previously unknown elements of the deep structural and tectonic architecture. Within offshore Guyana, images of the western basin boundary depict a transform margin – confirming plate models that link the basin with the extensional Venezuelan proto Caribbean margin (Pindell and Kennan 2009; Escalona and Mann 2011; Nemčok et al. 2015a; Reuber et al. 2016).

Efforts to extend exploration success into Suriname and French Guyana fostered acquisition, processing, and interpretation of long-offset seismic data that both complete seismic coverage of the Guyana Basin and provide new insights into the structure of the eastern portion of the basin and the Demerara Plateau. These data image a magma-rich, Jurassic extensional margin (Reuber et al. 2016; Basile et al. 2020; Museur et al. 2021) abutted at its southern end by the Guyana western transform margin. Moreover, the position of the junction between the extensional and the transform margin relative to the onshore Takutu Graben suggests a triple junction with the Takutu as a failed arm (Szatmari 1983; Nemčok et al. 2015a).

Tectonic setting

The Guyana Basin, offshore northeastern South America, is bounded on all sides by active or ancient plate boundaries (Fig. 1b). We briefly describe those boundaries here but offer fuller descriptions and supporting data under the interpretation headings of this paper.

The southeastern and oldest basin-bounding feature is the Demerara Plateau, a 25–30 km thick succession of c. 185–165 Ma basalt flows (Fig. 2a, b).
Fig. 1. (a). The bathymetry/topography digital elevation model (DEM) compiled by Getech Inc. The primary bathymetric data source for this compilation is GEBCO 2020 (General Bathymetric Chart of the Oceans, 2020) which was combined with other marine surveys. The topography data are from SRTM15 + V2. Locations of seismic lines from Figure 3 are overlaid. Locations of the wells Ranger-1, Liza-1, Yellowtail-1, Turbot-1 (ExxonMobil 2020) and Demerara A2-1 are shown. (b). The Bouguer gravity anomaly map was compiled by Getech Inc. A 3D Bouguer correction, with density 2.20 g cm$^{-3}$, was applied to the Free Air. Tectonic boundaries based on all available geological/geophysical data; structural axes and faults based on 2D & 3D seismic interpretation. LALOC, landward limit of oceanic crust.
that dip gently westward to form both a sequence of seaward-dipping reflectors (SDRs) and a prominent bathymetric high (Reuber et al. 2016; Museur et al. 2021).

The southwestern basin boundary was a transform plate boundary between North America and South America during the Jurassic. The Guyana Basin floor formed during opening of the Central Atlantic to accommodate Jurassic separation of North America away from the still-joined continents of Africa and South America (Fig. 2c). With continental separation, the boundary evolved from a continent–continent transform to an ocean–continent transform, resulting in the sharp southwestern boundary between the Jurassic basin floor and continental South America.

The northwestern basin boundary is the active Barbados accretionary prism at the leading edge of the eastward advancing Caribbean plate. It first impinged on the Guyana margin in the early Paleocene (Escalona and Mann 2011). Earthquake data indicate active subduction of the Atlantic Plate. The overlying Barbados prism is composed of highly deformed Eocene to Holocene sediments scraped from the subducting Atlantic Plate (Alvarez et al. 2022).

The northeastern margin of the basin is bound by the NW–SE-trending oblique divergent boundary between the variably extended Jurassic ocean crust of the Guyana Basin and Cretaceous-aged oceanic crust of the Equatorial Atlantic (Fig. 1b). This boundary evolved from a transpressional oceanic transform in the Early Cretaceous to an oblique divergent plate boundary in the mid Aptian, as Africa moved away from South America during the opening of the Equatorial Atlantic. The opening direction was highly oblique to the northern margin of the Guyana Basin (Fig. 2f). The boundary extends SE of the basin and cuts the eastern margin of the Demerara Plateau, which sheared away from its Equatorial Atlantic conjugate, the Guinea Plateau, in the Aptian–Albian (Greenroyd et al. 2008; Basile et al. 2013; Casey et al. 2016; Olyphant et al. 2017).

A Barremian–Aptian compressional event preceeded opening of the Equatorial Atlantic (Casson et al. 2021) (Fig. 2c, d) and deformed the Demerara Plateau, causing up to 50 km of NE–SW shortening and 6 km of erosion (Casey et al. 2016). That event is also recorded by smaller compressional structures of the same age and shortening direction in the Guyana Basin floor.

**Methods**

**Data**

Our tectonic understanding combines analyses of multiple data types and datasets, some acquired in the past few years, with the existing literature.

The bathymetry/topography map (Fig. 1a) was produced from a digital elevation model (DEM) compiled by Getech Inc. The primary bathymetric data source for this compilation is GEBCO 2020 (General Bathymetric Chart of the Oceans 2020) which was combined with other marine surveys. The topography data are from SRTM15 + V2.

The Bouguer gravity anomaly map (Fig. 1b) was compiled by Getech Inc. It was derived from the Free Air gravity anomaly, which is based upon marine gravity surveys and satellite-measured variations in sea surface height. A 3D Bouguer correction, with density 2.20 g cm⁻³, was applied to the Free Air gravity to dampen the strong signal associated with the density contrast at the water bottom.

The plate reconstructions (Fig. 2) were built using PaleoGIS (The Rothwell Group). The initial plate model was developed at the University of Texas at Austin and was both the starting point and the basis for our model. However, our present model is an adaptation that incorporates crustal stretching and other modifications, including variations in crustal boundaries and minor changes in poles of rotation.

Seismic data used in this paper over Guyana were acquired and processed by PGS in 2008 with 12 km streamer length and record length of 14 s, as a multi-client survey. In 2017, the data were subsequently reprocessed on a proprietary basis by PGS as a PSDM migration. Seismic data over Suriname were acquired and processed by ION in 2012 with 10 km streamer length and record length of 18 s. They were subsequently reprocessed by ION in 2016 as a PSDM migration.

**Interpretation of gravity data**

The deep crustal structure and tectonic setting of the Greater Guyana Basin are both apparent from, and well constrained by, the long wavelength components of the Bouguer gravity field (Fig. 1b). Short wavelength anomalies correlate to shallow density contrasts within the geological section. Long wavelength anomalies correlate directly to variations in the depth of the crust/mantle density contrast at the Moho. Those variations in Moho depth and crustal thickness define the crustal architecture, which in turn provides a framework to interpret and understand tectonic history.

The shallowest Moho in our study area sits beneath the Cretaceous oceanic crust, NE of the Guyana Basin proper. Refraction data indicate mantle depths less than 12 km b.s.l. (Greenroyd et al. 2008). High amplitude, long wavelength gravity maxima support the shallow Moho refraction interpretation. Shorter wavelength linear gravity anomalies (strike azimuth = 104°) in the same area are superposed on the long wavelength features. They
Fig. 2. The plate reconstructions interpreted from all available geological and geophysical data using PaleoGIS (The Rothwell Group). The initial plate model was developed at the University of Texas, Austin and was both the starting point and the basis for our model. The present model is an adaptation that incorporates crustal stretching and other modifications, including variations in crustal boundaries and minor changes in poles of rotation. (a) 180 Ma – Toarcian; initiation of SDRS on the Demerara Plateau (DP) and the Bahamas Bank (BB); the Florida Block and Guyana Margin are in oblique extension. (b) 170 Ma – Bajocian; rift-related volcanism along Guyana transform margin; continuation of expulsion of magmas (SDRS) on the DP, BB and the Guinea Plateau (GP).
correlate to shorter wavelength variations in both basement topography and crustal thickness along oceanic fracture zones.

The linear gravity fabric of Cretaceous oceanic fracture zones dominates the northeastern quadrant of the map. That fabric terminates in the NW against the gravity signal of the Barbados accretionary prism. The high amplitude gravity minima associated with the Barbados accretionary prism springs from a pronounced deepening of the Moho and Atlantic plate actively subducting below the Caribbean Plate and Barbados Prism (Alvarez et al. 2022). The linear gravity signature of the Cretaceous oceanic crust ends abruptly in the south against the gravity signal of the Fifteen Twenty Fracture zone (FTF); magmatic addition continues to build the Barbados margin. Crustal shortening in the oceanic domain and between the volcanic additions of the DP and GN. (e) 120 Ma – Aptian; final stage of crustal shortening of oceanic and exhumed mantle in the outer Guyana Basin and SDR crust of the DP and GN. (f) Seafloor spreading provides for clear separation between the DP and the GN.

A distinct gravity gradient is also associated with the contact between the Cretaceous oceanic crust and the northern edge of the Demerara Plateau where crustal thickness changes rapidly and dramatically at the boundary (Greenroyd et al. 2008).

A series of gravity anomalies, both maxima and minima, are mapped inboard of the contact between the Cretaceous oceanic crust and the Jurassic crust of the Guyana Basin and Demerara Plateau. The anomalies reflect folds and thrusts, formed during Barremian to Aptian transpression (Fig. 2d, e), in the dense Jurassic crust that floors the basin. Fold axes, faults and thrusts are shown in Figure 1b.

Inboard from the anomalous region of large-scale crustal transpression, the crustal thicknesses of the outer Guyana Basin averages near 5000 m with Moho depths averaging 15 000 m b.s.l. Integrated 3D gravity/seismic modelling implies a complex architecture that does not correspond to the classic Penrose-defined oceanic crust (Vine and Moores 2000), with temporary shallowing between 90 and 130 myr (Crosby et al. 2006). Both the Cretaceous crust and Moho are shallower than their older Jurassic equivalents. The abrupt depth contrast between them generates the observed gravity gradient at their boundary.

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Instead, the basin is floored by a combination of deformed Jurassic oceanic crust, subsequent extrusive lavas, and exhumed mantle. That arrangement seemingly arose from a magma budget that varied with time and space within a margin undergoing oblique extension (Fig. 3f, g).

The gravity maxima of the outer Guyana Basin are bracketed by steep gradients in three directions. To the NW the gravity signal drops by 100 mGal where the Jurassic igneous crust flexes downward and subducts beneath the Barbados accretionary prism. To the SE the anomalous gravity signal drops 50–60 mGal where the mantle flexes down beneath the Demerara Plateau: a crustal load of Jurassic volcanics (SDRs) with an overlying blanket of Mesozoic and Cenozoic sediments. The contact zone between the oceanic and SDR domains is the landward limit of oceanic crust, labelled LALOC in Figure 1b.

Along the southwestern margin of the outer Guyana Basin a steep gravity gradient extends 500 km at the boundary of the inner and outer Guyana Basin. The gravity field drops 100 mGal across a narrow zone, approximately 50 km wide, containing the landward limit of oceanic crust (LALOC). SW (or continent-ward) of this narrow zone, the inner Guyana Basin comprises a thick succession of Mesozoic and Cenozoic sediments underlain by continental crust. This zone contains the abrupt ocean–continent boundary. It evolved from an early to mid-Jurassic continental transform with both oblique extension and shearing (Pindell and Kennan 2009), through a continent–ocean transform in the Callovian (Nemčok et al. 2015a), before finally becoming a tectonically quite ocean continent boundary in the wake of the passing ridge. The steep gravity gradient indicates crustal thickening and flexure under the sediment load over
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A short distance. Moho depths beneath the inner Guyana Basin increase from 15,000 m to over 28,000 m from NE to SW across this zone.

A series of aligned, linked, linear gravity maxima, which correlate to the modern-day shelf edge, mark the inboard limit of the Guyana Basin. Integrated seismic and gravity map interpretations indicate the source of this series of high frequency anomalies as Jurassic carbonates above a basement hinge line.

Plate reconstruction

The plate reconstruction sequences in Figure 2 are a subset of sequences from the Triassic to the present day, selected to illustrate specific steps in the separation of North America: (1) the timing of build-up and break-up of the Demerara Plateau, Guinea Plateau, and Bahamas Bank’s igneous provinces; (2) development and evolution of the transform margin between the South American continent and the Florida Block; (3) the oblique transpression of the Guyana Basin margin; and (4) the spatial and temporal relationship between Jurassic and Cretaceous oceanic crust.

During the Early Jurassic, the South American Plate and its conjugates changed shape as the continental crust stretched and Gondwana began to break apart (Kneller et al. 2012). Large volumes of magma extruded on the Demerara Plateau and its conjugate Bahamas Bank. We interpret this massive magmatic outpouring to have occurred episodically over a span of 20 myr beginning in the Early Jurassic (Fig. 2a) based on: (1) anomalous (21 km) thicknesses of SDRs (Reuber et al. 2016); (2) a complex signal on marine magnetic data (acquired with the ION 2D seismic data) consistent with episodic eruption during rapid magnetic reversals; and (3) our plate model. Magma may have also underplated the
attenuated continental crust of the northern Bahamas Bank, adding isostatic support. In the Middle Jurassic, magma likely continued to build volcanic edifices on three continents (Reuber et al. 2016). Dredge samples (Basile et al. 2020) taken along the northeastern flank of the Demerara Plateau (60 Ridge location) indicate Aalenian (173.4 Ma) aged volcanics, in agreement with our plate interpretation. The dredge sample locations are labelled as DS in Figure 2b. A second dredge sample site, on the Bastille Plateau, provided a similar age but we interpret that location to be a toe thrust detached from the Demerara Plateau, now overlying Aptian oceanic crust.

Throughout the Early and Middle Jurassic, as North America drifted away, the inner Guyana Basin developed between the South American Plate and the western margin of the Florida Block (Pindell and Kennan 2009). The western margin of the Florida Block is a complex fault zone encompassing regions of extension and regions of compression that we interpret as having once extended from the Tampa Embayment south to the Guyana Basin. We also interpret continent–continent transpression along this regionally extensive fault zone as the underlying cause of Jurassic granitoid emplacement in Cuba. A key sample, located onshore Cuba, is labelled as RCG in Figure 2b. A second dredge sample site, on the Bastille Plateau, provided a similar age but we interpret that location to be a toe thrust detached from the Demerara Plateau, now overlying Aptian oceanic crust.

Also, we interpret an area of rift-related volcanics (labelled ‘RRV’ on Fig. 2b), based on seismic images and a proprietary aeromagnetic database, that straddles the South American–Florida (NA) plate boundary. The strong positive magnetic anomaly, observed on the South American Plate, is
interpreted as the signal of normally polarized Aalenian-age volcanics based on published magnetic polarity (Walker 2019) – an inferred age date that again agrees with our plate model. This region on the conjugate Florida block was overridden by the Great Arc of the Caribbean during the Paleocene (Escalona and Mann 2011) and therefore the presence of Aalenian volcanism has been inferred, though not observed, on the NA plate through time. Note also on Figure 2b that the southwestern margin of the Bahamas Bank hot spot volcanism has also been subducted beneath Cuba and Hispaniola and thus its presence is also inferred, not observed.

The aforementioned regional fault zone may have linked to the failed Berbice Rift and Takutu Graben (Fig. 2a, b) as a Jurassic triple junction (Szatmari 1983; Nemčok et al. 2015a) Figure 4 illustrates the proposed Jurassic triple junction of Guyana and the Afar Triple Junction as a modern-day analogue.

In our plate model, oceanic crust began to form the floor of the outer Guyana Basin in the Callovian and had built the northwestern boundary of the Demerara Plateau by the Oxfordian (Fig. 2c). During the Oxfordian the hotspot which had supplied abundant magma to the margins of three continents migrated northward – away from plate boundaries to a location beneath the Oxfordian oceanic crust of the North American Plate to begin an extended period of North American volcanism that formed the long promontory of the Bahamas Bank.

For the next 40 million years the Guyana Basin was a passive margin at a ‘tectonic elbow’ connecting the oceanic domain of the Central Atlantic to the Proto Caribbean. The South American and NW...
African plates behaved as a single unit moving SE relative to the North American Plate. Oceanic crust and/or exhumed mantle continued to form the floor of the outer Guyana Basin and conjugate plates. To the north the Bahamas Bank continued to build (Fig. 2d).

In the Aptian, the tectonic setting changed dramatically as the African Plate began to separate and move SE relative to the South American Plate (Fig. 2e) (Pindell and Kennan 2009). This plate separation was not entirely extensional, the South American plate rotated clockwise, shortening the Jurassic oceanic crust of the outer Guyana Basin as well as the igneous crust flooring the Demerara Plateau. After this initial period of compression, the Equatorial Atlantic opened with seafloor spreading in a direction locally oblique to the NE boundary of the Guyana Basin. The result is apparent in a set of fracture zones with a trend significantly less than perpendicular to the basin margin.

**Seismic interpretation**

**Extensional margin**

We interpreted a grid of long offset 2D seismic data that cover the Guyana Basin. Our work largely

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**Fig. 3.** Continued. (e) Zoom-in on continent–ocean transitional zone from (d). Minor inversion evident above basement faults. Aptian–Albian-age onlap evident as seen on other sections. New here is evidence of younger deformation that extends up to the top Cretaceous. Growth of the structure is cryptic with no mappable onlap. However, Liza–Turbot trend hydrocarbon discoveries lie above and downdip of the fold. Location of the Turbot-1 well is shown.
agrees with, but expands upon, published interpretations of seismic lines oriented NW–SE (parallel to Jurassic extension) across the Demerara Plateau and Guyana Basin margin (Basile et al. 2013; Nemčok et al. 2015a; Reuber et al. 2016; Museur et al. 2021). These data and interpretations show a sequence of SDRs in a stack of sub-horizontal to folded, but predominantly west dipping, high-amplitude events below the top basement. Figure 3a shows those SDRs extending down to the lower part of the crust. Seismic refraction data in the Demerara Plateau indicate a 30 km thick crust, mainly composed of flood basalts overlying 6–7 km of underplated intrusions (Museur et al. 2021). Further east, in French Guyana, the same authors interpret a transition from underplated SDRs to heavily intruded continental crust of the former West African Jurassic Margin.

The central portion of Figure 3a images the Moho (the Moho image is absent in the eastern half of the line). The Moho rises under the continental margin until it descends again under the Ranger high. This block is interpreted as a similarly underplated volcanic edifice to that seen in (d). Outboard of this there is a lack of continuous planar oceanic Moho. The top oceanic crust is rugose and disorganized suggesting a volcanic origin. The basement minibasin outboard of the Ranger high is elevated above regional on a thrust. Post-Aptian-age sediments onlap and fill the deformed surface. Location of the Ranger-1 well is shown.

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Fig. 3. Continued. (f) NE–SW-trending line across the Guyana transform margin. A Jurassic and likely older age syn-rift basin lies adjacent to the oceanic domain. The Moho rises under the continental margin until it descends again under the Ranger high. This block is interpreted as a similarly underplated volcanic edifice to that seen in (d). Outboard of this there is a lack of continuous planar oceanic Moho. The top oceanic crust is rugose and disorganized suggesting a volcanic origin. The basement minibasin outboard of the Ranger high is elevated above regional on a thrust. Post-Aptian-age sediments onlap and fill the deformed surface. Location of the Ranger-1 well is shown.
Figure 3a. In the central portion of the image, SDRs have apparent northward dips, implying an increase in accommodation space. The top basement in the southern half on the transect is relatively horizontal, but near mid-transect it develops a progressively increasing northward dip. Directly below, the Moho reflection rises from south to north and peaks near a depth of 20 km mid transect before it descends to the north, sub-parallel to the north-dipping top basement in an apparent crustal fold. North of this feature, the top basement, top Jurassic and Moho are all vertically offset by 5 km (upthrown to the north). They dip to the north parallel to the apparent basement fold situated below and to the south. The north dip of the apparent basement fold seemingly extends under both the large offset fault and the upthrown crust to the north. We interpret this geometry as a thrust offsetting the SDR-dominated crust on top of itself in apparent nascent obduction, with vergence to the SW. An alternate interpretation explains this feature as an inverted normal fault dipping south. In either case the northward-thickening pre-Aptian sedimentary wedge (mid transect) has been inverted by deep seated north–south-directed shortening.
The inverted top Aptian is the youngest syn-deformation surface in the overlying shelf collapse feature, which extends across the Western Demerara Plateau. Aptian topography in the deformed section was infilled by the Albian, suggesting Aptian and older deformation had largely ceased by the Albian. This is consistent with deformation observed on the Demerara Plateau and dated by the A2-1 well (Basile et al. 2013; Nemčok et al. 2015a; Loncke et al. 2016; Casson et al. 2021).

Compressional deformation of the crust is also apparent in the northern (right) part of Figure 3c (west of Fig. 3b). The oceanic crust is deformed into a series of folds or fold-like structures with 6 km vertical amplitude and 50 km wavelength. The crust and top Moho are parallel, implying that the whole crust and upper part of the Moho are deformed. The top basement is also deformed, albeit less intensely, in the southern half of the transect. A gentle fold, over 100 km in length, deforms the thick SDR-dominated crust. On the southern limb of the fold the Jurassic to Aptian shelf dips to the south parallel to the top basement. The Albian shelf sediments downlap onto this surface dating the deformation. Similarly, at the northern end of the line the Aptian is the youngest deformed surface, with Albian onlap onto structures. Internal basement reflectivity in the southern half of the section is dominated by bright SDR geometries that onlap the continental crust to the south (off the section).

**Transform margin**

A series of lines west of the Demerara SDRs, all trending orthogonal to the Guyana coast (Fig. 3d–f) show an outboard domain of relatively thin oceanic crust juxtaposed against much thicker continental crust. The transition from continental crust to oceanic crust occurs over a distance that is generally less than 50 km (but up to 100 km in Fig. 3f). The short transition zone is consistent with other transform margins, e.g. the Falkland–Agulhas fracture zone, Romanche fracture zone (Bird 2001; Antobreh et al. 2009), and we interpret it as a transform boundary.

A few large offset normal faults cut and thin the continental crust in that narrow zone, adjacent to oceanic crust, but few of these faults are entirely through-going and none cut up to, or through, the top basement. They are commonly capped by reflections that extend from – and correlate to – the oceanic crust, implying onlap of seafloor volcanics onto continental crust.

There is a basement high in the middle of Figure 3d, with intra-basement reflections dipping away from the crest in both directions. The Moho reflection beneath the high is locally depressed to approximately 20 km (also visible on Fig. 3a). We interpret this basement-high/Moho-low pair as a volcanic edifice with an associated cone-shaped, underplated keel within an area of normal thickness.
oceanic crust. At the SW margin of Figure 3d the Moho dips to the west and descends under the thick South American continental crust. The seismic expression of the top of oceanic crust tracks SW through gentle folds where its lateral equivalent onlaps the continental crust. A clear angular unconformity separates it, and the sequence below, from the overlying Jurassic to Albian section. The zoom in (Fig. 3e) shows minor inversion of the top basement surface by reactivation of deep faults. The Aptian–Albian-age infill constrains timing of early deformation as coincident with compression in the Demerara Plateau (Basile et al. 2013; Nemčok et al. 2015a; Casey et al. 2016). The folds extend as gentle monoclines up to the top Cretaceous, with minor expression in the Oligocene. The timing of this later deformation is cryptic without obvious onlap or stratigraphically constrained thinning onto structure. However, the reduction in amplitude of the folds from c. 500 to 100–200 m at the top Maastrichtian suggests that the folds grew semi-continuously to the Oligocene. The Yellowtail and Turbot oil fields lie outboard of the most westerly fold.

A 50–100 km wide (Fig. 3) zone of faulting lies inboard of the outer edge of Guyana Margin continental crust. The central portion contains a syn-rift basin (Fig. 3f) adjacent to the edge of the oceanic crust. Below the graben the continental crust thins, and the Moho rises. The graben is filled by a section exhibiting seismic reflectivity with multiple bright reflections that indicate large impedance contrasts. Furthermore, gravity and magnetic modelling suggest both that a significant portion of the graben fill is volcanic and that the bright events are basalt flows.

The top basement reflection on the right half of Figure 3f is rugose at a regional 10 km depth. The depth is consistent with oceanic crust, but the non-planar nature of the surface with numerous underlying events that dip in multiple directions suggests a volcanic origin potentially similar to slow spreading domains (Ranero et al. 1997). There is no continuous Moho reflection. Instead, a broken event undulates between 12 and 13 km depth. If it is a top Moho event, it implies a serpentinized mantle proximal to the seafloor with a volcanic carapace (Gillard et al. 2019).

The Ranger-1 hydrocarbon discovery was drilled in 2018 in a carbonate build up on top of the large block in the centre of Figure 3f. This crustal block shows bright reflectivity with bidirectional dip in its upper 5 km. The Ranger High is underlain by a three-dimensional keel, similar to that seen in
An Early Jurassic triple junction developed between the South American, North American and NW African plates. Two of the boundaries of this junction developed into oceanic spreading centres whereas the third boundary is a failed rift, as implied from 2D seismic data. The present-day Afar Triple Junction serves to illustrate a possible geological scenario for Guyana in the early to mid-Jurassic.
Figure 3d, suggesting it too has a volcanic origin. We interpret the crustal block as attenuated, underplated, lower continental or oceanic crust; more likely in our opinion to be the latter. Interpreting the Ranger High and its keel as continental crust would imply a seemingly unlikely origin as a tectonic outlier within the oceanic domain.

On our westernmost seismic transect (Fig. 3g) we observe a very abrupt transition, no more than 40 km wide, from unfaulted continental crust to palaeo-ocean floor. The width of this zone is commensurate with other interpreted transform margins, e.g. the Romanche and Falkland–Agulhas fracture zones (Bird 2001). The top of the oceanic domain is 10–12 km deep, with an undulating and rugose nature. It is directly underlain by a 1–3 km section of bright events that dip in multiple directions, similar to the volcanic packages in Figure 3f. There is no mappable Moho reflection below. The oceanic volcanics onlap continental rifted blocks. The top of the package is deformed into a fold above the outermost of these. The main structure includes the Aptian and is capped by an Albian unconformity. The Albian is also deformed in a gentle monocline that continues up to the top Miocene-aged section. This represents a second later phase of inversion. However, there is no onlap visible on seismic to date this folding, save for its propagation to Miocene stratigraphy.

We include here two oblique seismic lines that strike across the Guyana transform margin and the Western Demerara Extensinal margin (Fig. 3h, i). The western (left) half of Figure 3h is dominated by c. 30 km thick continental crust. The continental crust thins to the east as the line obliquely cuts through the transform margin with a series of faults with a component of normal displacement. The eastern half of the line is dominated by a similarly thick crust dominated by SDR geometries. The SDR-dominated crust thins to the west, with minimum thickness against the continental crust. The top basement surface of the SDR-dominated crust is contiguous with the fill of the syn-rift basin above the faulted continental crust, suggesting that a significant part of the rift basin fill is volcanic, in agreement with our gravity map interpretation. A similar geometry can be seen in the parallel seismic line outboard (Fig. 3i). Here the SDR-dominated crust thins to the west as the Moho rises, until it sits at c. 15 km depth under c. 6–7 km thick oceanic crust. The oceanic crust is juxtaposed against attenuated continental crust with contiguous volcanic material filling the continental margin basin.

In summary, we observe the juxtaposition of SDR geometries that dip obliquely towards the Guyana Continental crust followed outboard by oceanic crust adjacent to continental crust. The SDRs and subsequent oceanic crust were created at a spreading centre directly adjacent to the continental crust in the southernmost corner of the basin. This places a close constraint on the geometry of the South American Plate boundary (Fig. 1b) that can be, in turn, used to infer the direction of early plate movement.

Discussion

Transform margin and direction of plate movement

The Demerara Plateau forms the southeastern margin of the Guyana Basin. The upper crust of the plateau is a stack of volcanic SDRs emplaced during ‘hot-spot related volcanic rifting preceding the Jurassic opening of the Central North Atlantic’ (Museur et al. 2021, p.1). As such, the Demerara Plateau is part of an extensional margin. The complex three-dimensional nature of lava vents and topography created by flows, coupled with the lack of true dip directions on two-dimensional seismic data, mean that the SDR dip does not precisely indicate either the direction of extension or the direction of relative plate motion. However, when viewed on multiple seismic lines, SDR dip directions range from west (Fig. 3a, h and i) to north (Fig. 3b, c). If we accept that SDRs are sourced from a spreading ridge (Planke and Eldholm 1994), then the direction of extension of the Jurassic rift must lie within this west to north range. That range is compatible with, and may be further narrowed by, the geometry of the continent–ocean transition on the Guyana margin (Fig. 1b). We interpret that geometry as a right-lateral stepping array of highly oblique normal/strike-slip faults that trend NNW–SSE in the eastern part of the Guyana Margin. Our interpretation of that geometry implies that initial Jurassic rifting had a somewhat limited component of westerly extension. Otherwise, significant compressional structures would have been produced. This agrees with the interpretation of NNW–SSE-trending anomalies in the most landward parts of the oceanic crust in maps of the total horizontal derivative of isostatic residual gravity anomaly by Nemíček et al. (2015a). Similarly, in the same area, we observe NNW-trending linear offsets in the oceanic crust, some inverted, that can be traced across closely spaced (5 km) seismic lines. These may represent oceanic transforms that would have paralleled the early extension direction.

In addition, we highlight the 100 + km long trough in the top basement surface (Fig. 3a, c) that trends ENE/SWS, normal to the extension direction, and we suggest it is likely an extensional structure generated during or soon after crustal formation. The NNW initial extension direction fits our plate model, which, though derived independently, has similar vectors of plate motion. Our model of plate
motion is built upon the relative movement of the Florida Block, which, since early Toarcian, has been a southern extension of the North American Plate with well-defined motions relative to NW Africa and South America (Kneller et al. 2012). Variation in spreading vector in the early drift phase has been modelled offshore Ghana (Nemčok et al. 2013). The edge of the Guyana Margin continental crust changes strike from NNW/SSE in eastern Guyana to NW–SE in the west (Fig. 1b). The crustal boundary of the westernmost part of the margin may be a pure transform margin, absent continental rift blocks. This fits the plate model (Fig. 2b, c) which places a significant transform zone through the area while the southeastern part of the basin was forming oceanic crust.

This is also consistent with the nature of volcanic crust and basin floor apparent on seismic data. It changes with relative age from the extensional margin of the Western Demerara SDRs in the SE, through younger constant thickness oceanic crust in the Central Guyana Basin, to even younger ‘rugose-topped’ slow-spreading crust or exhumed mantle with overlying volcanics in the NW.

**Petroleum systems implications**

We show data supporting a well-defined edge of continental crust and a basin floor of various compositions, varying from SDRs in the SE of the basin, to normal thickness oceanic crust, to rugose-topped slow spreading, possibly serpentinitized exhumed mantle in the NW. Each of these are non-granitic and none generate radiogenic heat. The great thickness of sedimentary fill (7–12 km) and the burial of the Albian–Cenomanian–Turonian (ACT) source rock were clearly enough to generate hydrocarbons without input of continental heat.

The edge of continental crust can be traced to the SE in Guyana until there is an apparent 90–100° elbow in the continental/magmatic crustal boundary such that in the Suriname area the boundary is near orthogonal to the fault traces on the Guyana margin (Fig. 1b).

This implies that the Western Demerara Margin was an extensional margin, at least until sufficient oceanic crust had been formed offshore to allow a change in extension direction from NNW to more NW trending (Fig. 2c). The position of the sharp angle change in the rift margin at the Guyana–Suriname border area aligns well with the projection of major structures onshore, notably the Takutu Graben (Fig. 4): a similarly aged Triassic to Jurassic continental rift basin (Crawford et al. 1985). We propose, like Szatmari (1983) and Nemčok et al. (2015a), that the Takutu Graben represents the failed propagation of the Central Atlantic rift into South America. We also suggest that this structural alignment and focus towards some of the deepest parts of the basin along the Guyana–Suriname border (Fig. 3d) caused the capture of the Berbice river system, which was responsible for much of the pre-Oligocene sedimentary fill of the Guyana Basin and is a key driver of the petroleum system. The very steep drop-off in basement depth adjacent to the continental margin has also allowed a significant accumulation of sediment and maturation of the prolific source rocks. Although the Berbice-derived fill of the basin is important for the petroleum system, a secondary post-Oligocene influx of 3–5 km sediment is responsible for both further maturing source rocks and pushing reservoirs beyond the 80°C biodegradation window (Wilhelms et al. 2001). This fill is largely mass transport complexes dominated by mud rocks (Fig. 3e). The source of the mud is interpreted to be the Amazon River (Allison and Lee 2004). Mud is transported by longshore currents to the Guyana Basin where it accumulates, presumably on the slope, and periodically collapses into the basin.

We have shown through interpreted seismic lines (Fig. 3a–g) that the Guyana Basin has undergone similarly-aged pre-Albian age inversion over a widespread area. Inversion is most intense over the eastern margin of the basin including the outboard Demerara Plateau (Casey et al. 2016; Casson et al. 2021) and outboard oceanic crust (Fig. 3b, c). Inversion is less intense further inboard, but it is clearly visible on multiple seismic lines (Fig. 3c–g). Inversion was likely caused by an episode of transpression prior to the opening of the Equatorial Atlantic (Fig. 2).

There is a spatial correlation of many of the hydrocarbon discoveries made to date in the Stabroek block with basement inversion features (Figs 1a & 3e). The accumulations are stratigraphic traps with changes in the up-dip sealing facies over inversions. The seismically mappable onlap onto inversion features is Albian age, with much more subtle deformation above extending up to the top Cretaceous or Oligocene in some cases. This deformation may be due to differential compaction but we cannot rule out minor fault reactivation due to long-range crustal forces associated with Andean compression, the impingement of the Barbados subduction zone or Miocene–Pleistocene shortening between the North American and South American plates (Pichot et al. 2012). The second of these is consistent with Miocene-age inversion on the seismic line closest to the Barbados prism (Fig. 3g).

The presence of reservoir sands and stratigraphic traps outboard of inversion features suggests a link between seafloor topography and turbidite deposition. Subtle seafloor inversions may control the position of reservoir, seal and stratigraphic traps in the prolific Liza play. The inversion features may also facilitate hydrocarbon migration and create deeper structural traps.
Conclusions

The inner margins of the Guyana Basin vary in tectonic origin, from the Western Demerara extensional volcanic margin, through an oblique extensional margin at the Guyana–Suriname border, to a transform margin in NW Guyana. The fraction of volcanic material decreases westward throughout the basin floor and the transition from continental shelf to ocean floor narrows from 200 km in Suriname where it is dominated by SDRs and other volcanics, to less than 50 km in Guyana where it is essentially a transform fault zone. Seismic data from the western transform margin of the basin show 35 km thick continental crust that thins rapidly to the NE over a 50 km wide zone, landward of its boundary with ocean crust. At the junction between the transform and extensional margins, SDR-dominated crust is juxtaposed against extended continental crust. The boundary between those crustal types is clear on seismic data.

The mapped geometry of the continent/ocean boundary and our plate model both indicate NNW/SSE extension during rifting and incipient seafloor spreading (c. 190–165 Ma). After this initial phase, the extension and basin-opening directions changed to NW/SE to accommodate the opening of the Central Atlantic.

Berriasian to Aptian compression generated widespread NE–SW-directed shortening and inversion structures throughout the basin. Large-scale crustal shortening of the Demerara Plateau and the Jurassic oceanic crust, near the present-day northern margin of the basin, was contemporaneous with both compressionally driven inversion of faults in the Jurassic basin floor and inversion of faults at the Guyana transform margin. Our plate model combined with seismic mapping agrees with previous studies wherein shortening and inversion occurred during a period of transpression in the early opening stages of the Equatorial Atlantic, prior to the oblique extension that dominated from the Albian onwards. Quite separately, the NW margin of the basin underwent and continues to undergo minor inversion and shortening linked to the impingement of the Tobago accretionary prism.

In accordance with earlier studies, the Takutu Graben likely represents an early extension of the north Atlantic rift that died out in the Jurassic as a failed arm of a tectonic triple junction. We propose that its location and age suggest that post-tectonic subsidence of the Takutu and greater Central Atlantic rift captured the Berbice drainage system and funneled voluminous sediment into the basin. That sediment input buried and matured the ACT source rock and it deposited the high-quality reservoirs of hydrocarbon discoveries.

Stratigraphically trapped hydrocarbon discoveries of the Liza trend sit just outboard of inverted basement faults. The relative locations suggest a link between transform margin structure and development of stratigraphic traps. Although fault inversion ended in the Aptian, dated by Albian onlap, in some spots a subtle (compaction?) monoclinal structure extends through to the Oligocene, suggesting gentle deformation of the seafloor during reservoir deposition. That seafloor deformation, and its bathymetric expression, may have localized turbiditic deposition of sands to act as reservoirs to more than 10 billion barrels of oil equivalent recoverable reserves (discovered to date) in the Liza stratigraphic play.

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