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Maia de Almeida, Narelle, Alves, Tiago M. , Nepomuceno Filho, F., Freire, George Satander Sá, Souza, Ana Clara B., Leopoldino Oliveira, Karen M., Normando, Márcio Nunes and Barbosa, Thiago Henrique S. 2020. A three-dimensional (3D) structural model for an oil-producing basin of the Brazilian Equatorial margin. *Marine and Petroleum Geology* 122 10.1016/j.marpetgeo.2020.104599

Publishers page: <http://dx.doi.org/10.1016/j.marpetgeo.2020.104599>

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1 **A THREE-DIMENSIONAL (3D) STRUCTURAL MODEL FOR AN**
2 **OIL-PRODUCING BASIN OF THE BRAZILIAN EQUATORIAL**
3 **MARGIN**
4

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23 **ABSTRACT**

24 Hydrocarbon discoveries in regions such as the Brazilian Equatorial Margin,
25 Equatorial Africa and French Guiana have recently confirmed their importance as new
26 exploration frontiers. The Mundaú sub-basin, located on the Brazilian Equatorial Margin, is an
27 oil and gas producing region with four producing fields in shallow water: Xaréu, Atum, Espada
28 e Curimã. In order to understand the structural and seismic-stratigraphic frameworks of an oil-
29 producing area of the Brazilian Equatorial Margin, this work addresses the 3D geometry and

30 spatial distribution of main faults in the Curimã and Espada fields. The occurrence of
31 hydrocarbons in the Mundaú sub-basin is compared with fields in other parts of the Brazilian
32 Equatorial Basin, and in Equatorial Africa. Data from 12 wells and a 3D post-stack time-
33 migrated multichannel seismic volume are used to define nine (9) main seismic-stratigraphic
34 units: the syn-rift Mundaú Formation (Units 1, 2, 3 and 4); the transitional Paracuru Formation
35 (Unit 5) and the drift Ubarana (Uruburetama and Itapagé Members, Units 6 and 7), Tibau and
36 Guamaré Formations (Units 8 and 9). The study area is dominated by NW-SE planar normal
37 faults, basinward-dipping, that formed multiple half-grabens and tilted blocks with small
38 anticlines and synclines genetically related to a transtensional system. Three types of plays are
39 recognised in the Mundaú sub-basins: structural, combined (structural-stratigraphic) and
40 stratigraphic (turbiditic). In the eastern part of the region where the basement is shallow, no oil
41 was found. Conversely, oil was discovered in an anticlinal trap formed on a hanging-wall block
42 analogous to fields in Côte D'Ivoire-Ghana transform margin. This work shows that combined
43 traps on footwall blocks are successful plays near the shelf break of the Mundaú sub-basin, in
44 similarity with the Espoir and Baobab fields in Ivory Coast Basin. Furthermore, turbiditic
45 reservoirs in drift units are analogous to the Stabroek block in Guyana and prospects in the
46 Gulf of Guinea. The structural and petroleum-play analyses in this work are therefore crucial
47 to understand the multiple geological processes leading to the trapping of hydrocarbons in the
48 larger Equatorial Atlantic Ocean.

49

50 **Keywords:** Atlantic Ocean; Equatorial Brazil; Ceará Basin; 3D seismic; oil fields; 3D
51 modelling.

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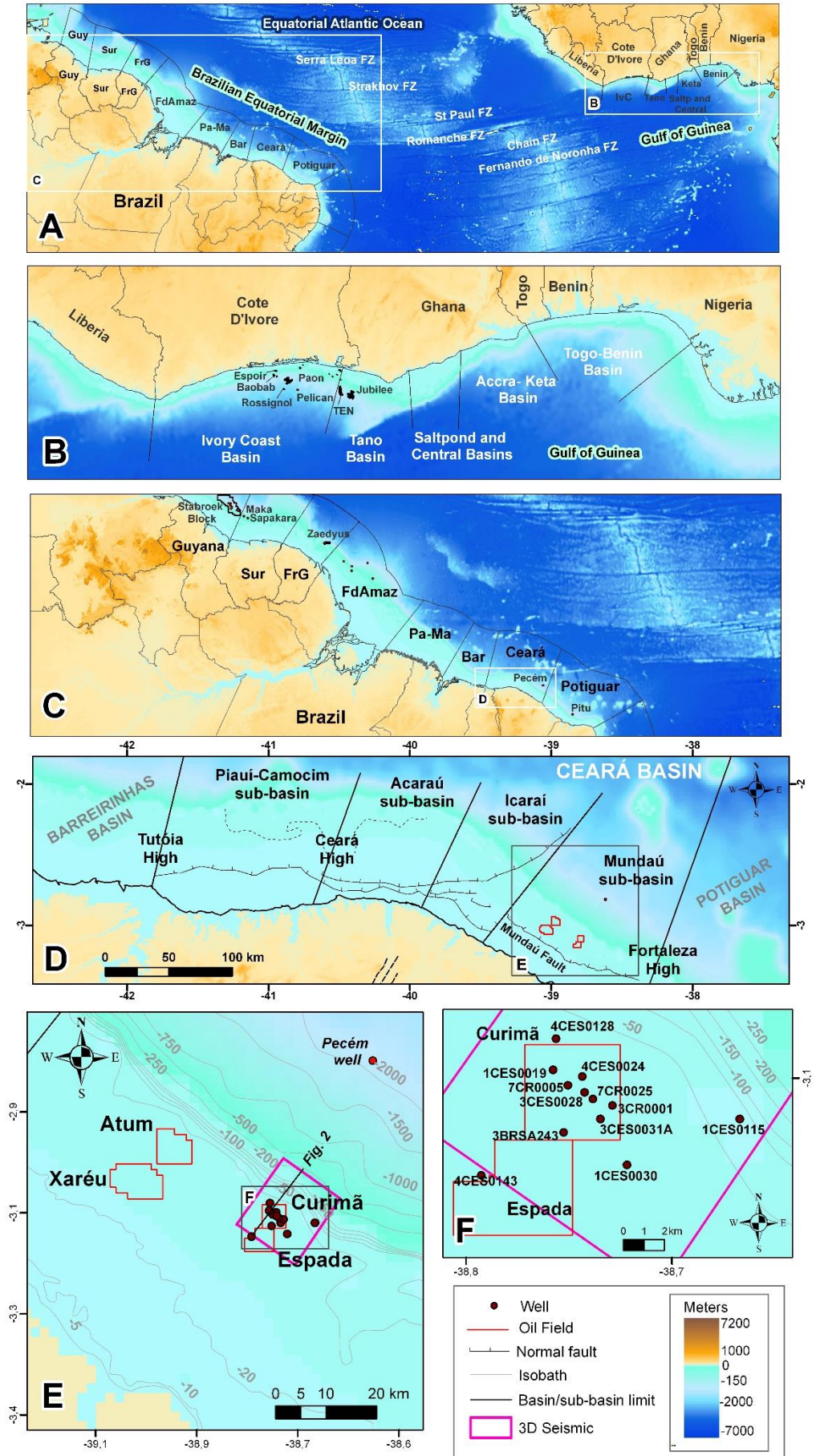
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54

55 1. INTRODUCTION

56 The Ceará Basin is located on the Brazilian Equatorial Margin (BEM) between the
57 Potiguar Basin to the southeast and the Barreirinhas Basin to the northwest (Fig. 1). The
58 BEM developed as a typical continental margin of the transform type (Matos, 2000). The
59 bulk of its development was dominated either by oblique extension (transtension) or by pure
60 and simple shear movements, all responding to a dominant dextral sense of movement in
61 transfer (syn-rift) and transform (post-rift) faults. In this portion of the late Gondwana
62 supercontinent, continental rupture and breakup took place in an East-West direction,
63 creating shorelines with two predominant directions: NW-SE in transtensional portions, and
64 E-W in purely transcurrent portions (Zalán, 2015).

65 The Ceará Basin has been considered, since the 1970's, a modest oil and gas producer in
66 shallow water, where production rates have reached only a few thousands of boe/d. In
67 contrast, the neighbouring Potiguar Basin recorded significant yields during the 1990s, with
68 its onshore fields reaching a production rate of ~100,000 boe/d. The onshore portion of
69 Barreirinhas Basin also reached production rates of a few tens of thousands of boe/d into the
70 1980s. However, there is no significant production in this basin at present, as well as in other
71 basins of the BEM such as Pará-Maranhão and Foz do Amazonas (ANP, 2020) (Fig. 1). More
72 recently, in 2012, Petrobras (Petróleo Brasileiro SA) drilled the Pecém well to announce the
73 first ever deep-water oil discovery in the Ceará Basin. Subsequently, Maia de Almeida et al.
74 (2020) proved that reservoirs in the Pecém well comprise Cretaceous sandstones in a
75 combined trap related to both an erosional unconformity and a normal fault. Leopoldino
76 Oliveira et al. (2020) later identified a series of potential stratigraphic and structural traps,
77 and associated petroleum plays, in rift and drift sequences of the Ceará Basin.



79 Figure 1. A) Map of the Equatorial Atlantic Ocean highlighting the fracture zones and the marginal basins (Guy:
80 Guyana, Sur: Suriname, FrG: French Guiana, FdAmaz: Foz do Amazonas, Pa-Ma: Pará-Maranhão, Bar:
81 Barreirinhas, IvC: Ivory Coast, Saltp: Saltpond). B) Gulf of Guinea basins and their oil fields and discoveries
82 correlated with this work. C) Fields and discoveries of the Brazilian Equatorial Margin, French Guiana, Suriname
83 and Guyana. D) The Ceará Basin sub-divided into four sub-basins: Piauí-Camocim, Acaraú, Icaraí and Mundaú.
84 The study area is located in the Mundaú sub-basin. Structural data was compiled from Zalán and Warme (1985)
85 and Morais Neto *et al.* (2003). The basins boundaries were provided by the Brazilian National Agency of oil, gas
86 and biofuels (ANP) and boundaries of sub-basins were based on Morais Neto *et al.* (2003). E) Relative location
87 of the four producer fields (Xaréu, Atum, Curimã and Espada) of the Mundaú sub-basin. The location of the wells
88 and 3D seismic data are shown. F) Details of the well data used in this study, as provided by the ANP. The
89 topographic model in the figure was provided by NOAA (ETOPO1).

91 The first deep-water discovery in Potiguar Basin occurred in 2013 with the drilling of the Pitu
92 well. Soon after, the Brazilian Agency of Petroleum (ANP) opened new exploratory
93 opportunities in structured sandstones of Aptian age, and in Upper Cretaceous, Paleogene and
94 Neogene turbidite sequences, within the Potiguar Basin (ANP, 2018).

95 On the African conjugate margin of the BEM, the Gulf of Guinea Province (Côte
96 d'Ivoire, Ghana, Togo, and Benin), including the western part of the coast of Nigeria, relatively
97 little hydrocarbon exploration occurred until the 1990s. Until 1995, most discoveries were
98 located in water depths of less than 500 m (Brownfield and Charpentier, 2006). In the 2000s,
99 new discoveries in deep-water areas of Equatorial Africa were made public. The first deep-
100 water in Equatorial Africa was the Baobab field in Ivory Coast (2005). Two years later, the
101 discovery of the giant Jubilee field, offshore Ghana, drew attention to the whole of the
102 Equatorial Atlantic as a major hydrocarbon province. The Jubilee field is now producing more
103 than 100,000 boe/d and has a planned peak production of 120,000 boe/d (Dailly *et al.*, 2017).
104 Further increasing the importance of the Equatorial Atlantic as a petroleum province, the
105 Tweneboa-Enyenra-Ntomme (TEN) fields in Ghana's deep-water were discovered between
106 2009 and 2012, and began producing oil in 2016 at relatively large rates of 80,000 boe/d.

107 Offshore French Guyana, significant discoveries have included the Zaedyus Field
108 (2011) with recoverable reserves of 130×10^6 toe (Huaicun, 2014), and the Lisa field of the
109 Stabroek Block, drilled in 2015, this latter comprising potential recoverable reserves of 109 to
110 191×10^6 toe (OGJ, 2016). Other successful discoveries in the Stabroek Block included the

111 Payara, Liza deep, Snoek and Turbot fields (2017), the Ranger, Pacora, Longtail, Hammerhead
112 and Pluma fields (2018), the Tilapia, Haimara, Yellowtail and Tripletail fields (2019); and the
113 Mako field of 2020 (Exxon Mobil, 2020). More recently, the Maka and Sapakara discoveries
114 offshore Suriname led to the identification of at least seven distinct play types (Offshore, 2020).

115 Most oil and gas discoveries on Equatorial margins of the Central Atlantic are
116 associated with the presence of stratigraphic traps in turbidites. Structural and combined traps
117 are also present (Dailly et al., 2017; Jianping et al., 2010; Kelly and Doust, 2016; Maia de
118 Almeida et al., 2020; Tetteh, 2016; Yang and Escalona, 2011). In such a setting, faults have an
119 important role with regards to controlling oil migration from source intervals to main
120 reservoirs. Faults can act as either conduits or barriers for hydrocarbon migration because they
121 have anisotropic flow properties owing to their complicated three-dimensional structure (Jiang
122 et al., 2015). Thus, a predictive knowledge of fault zone structure and transmissibility can have
123 an enormous impact on the economic viability of new exploration targets, resulting in
124 significant benefits during reservoir management. Understanding the effects of faults and
125 fractures on fluid flow behaviour and distribution within hydrocarbon provinces has, therefore,
126 become a priority in many an offshore prospect (Knipe et al., 1998).

127 Costa et al. (1990) have shown that hydrocarbon plays in the shallow water of the Ceará
128 Basin are of the stratigraphic (turbiditic), combined (structural-stratigraphic) and structural
129 types. Structural plays may be classified as rotational, transpressional, transtensional or
130 footwall-related. In addition, Pessoa Neto (2004) showed that the Atum and Curimã oil fields
131 in the Mundaú sub-basin comprise classical examples of combined traps generated by the
132 erosional truncation of tilt blocks limited by normal faults. Though Pessoa Neto (2004) was
133 able to demonstrate that hydrocarbon traps are usually of the mixed type (structural-
134 stratigraphic), and others several structural interpretations have been proposed for the area
135 based on 2D seismic data (Costa et al., 1990; Matos et al., 1996; Morais Neto et al., 2003;

136 Antunes, 2004; Pessoa Neto, 2004; Medeiros et al., 2007; Antunes et al., 2008; Maia de
137 Almeida et al., 2020; Leopoldino Oliveira et al., 2020), the geometry and distribution of
138 subsurface faults is still poorly known in the larger Ceará Basin. Against such a backdrop, this
139 work aims at recognising the 3D geometry and spatial distribution of faults in the Mundaú sub-
140 basin, Ceará Basin, and explain their control on the occurrence of hydrocarbons in the area
141 encompassing the Curimã and Espada fields (Fig. 1). The results will be compared to other
142 basins of the BEM and Equatorial Africa. Three-dimensional (3D) seismic data and a suite of
143 exploration wells are used to address four fundamental research questions:

- 144 a) What are the typical fault geometries in the Curimã and Espada fields? How are they
145 distributed in these two subsurface prospects?
- 146 b) How structural elements in the Mundaú sub-basin fit within the regional context of
147 continental rifting of the Equatorial Atlantic Ocean?
- 148 c) In what way(s) these structures influence local petroleum plays and subsequent
149 hydrocarbon accumulations in an economically significant region of Equatorial
150 Brazil?
- 151 d) How the present findings compare with similar petroleum basins elsewhere in
152 Equatorial areas of the Central Atlantic?

153

154 Significant advances in mapping structural and stratigraphic features in the Mundaú
155 sub-basin are presented in this work. The possibility of replicating the successful plays mapped
156 in this work in other parts of the BEM, as well as in Equatorial Africa, is demonstrated in the
157 following sections.

158

159 **2. GEOLOGICAL SETTING**

160

161 The Brazilian Equatorial Margin is related to the opening of the Central Atlantic Ocean,
162 itself formed by the fragmentation and continental breakup of northwest Gondwana during the
163 Lower Cretaceous. During this time, a transtensional shear corridor with a dextral sense of
164 movement was developed at the loci of the present-day north and northern continental margins
165 of Brazil (Azevedo, 1991).

166 The BEM is characterized by the presence of east-west and northwest-southeast margin
167 segments, forming *en echelon* structures that are typically associated with the predominant
168 strike-slip tectonics of transform margins (Gorini, 1993). It includes, from east to west, the
169 Potiguar, Ceará, Barreirinhas, Pará-Maranhão and Foz do Amazonas basins. The main
170 characteristics of the BEM's offshore basins are: a) their relatively late continental breakup
171 when compared to the Eastern Brazilian Margin (EBM) (Françolin and Szatmari
172 1987, Szatmari et al., 1987; Matos, 2000), b) a continental breakup stage controlled by strike-
173 slip tectonics with predominant dextral kinematics (Matos, 2000; Basile et al., 2005), c)
174 diachronous subsidence and uplift events on each margin segment controlled by divergent,
175 transtensional or transpressional tectonics (Mohriak, 2003; Zálan, 2004), d) sub-basins that
176 record contrasting histories in terms of their thermal, depositional, magmatic and deformation
177 histories (Milani et al., 2000), and e) the absence of a transitional evaporitic sequence of Aptian
178 age, as well as the absence of structures and sedimentation associated with salt tectonics
179 (Mohriak, 2003; Zálan, 2004; Pellegrini and Severiano Ribeiro, 2018).

180 The Ceará Basin presents transpressional and transtensional segments and, because of
181 its distinct tectonic character along and across the BEM, it has been previously divided into
182 four distinct sub-basins (Morais Neto et al., 2003).

183

184 **2.1. Ceará Basin**

185

186 The Ceará Basin is bounded to the east by the Fortaleza High, to the west by the
187 Tutóia High, to the south by crystalline basement, and to the north by the Romanche Fracture
188 Zone (RFZ) (Costa et al., 1990) (Fig. 1). The basin has been divided into four distinct sub-
189 basins, from east to west, reflecting their different structural style: the Mundaú, Icaráí, Acaraú
190 and Piauí-Camocim sub-basins (Morais Neto et al., 2003) (Fig. 1B). The Piauí-Camocim is
191 separated from the Acaraú sub-basin by the Ceará High. The Acaraú and Icaráí sub-basins
192 have, as common limit, the Sobral-Pedro II lineament. In addition, the Icaráí is separated from
193 the Mundaú sub-basin by an important change in fault trends (Morais Neto et al., 2003).
194 According to Matos (2000), deformation in the Mundaú sub-basin was essentially
195 transtensional in nature, while the Piauí-Camocim sub-basin records one of the most important
196 examples of transpressional deformation on the BEM, with compressive structures such as
197 folds and thrust faults well developed there (Zalán and Warme, 1985).

198 Beltrami et al. (1994) suggested differences in the sedimentary record of the
199 Mundaú, Icaráí-Acaraú and Piauí-Camocim sub-basins. The Piauí-Camocim sub-basin shows
200 the less complete sedimentary fill of the three sub-basins, with unconformities and depositional
201 hiatuses of greater magnitude. The most complete stratigraphic record is that of the Mundaú
202 sub-basin (Fig. 2).

203

204 **2.2. Mundaú sub-basin**

205

206 The Mundaú sub-basin is a hydrocarbon-producing region with four oil and gas
207 fields in its shallow waters: Xaréu, Atum, Curimã and Espada (Fig. 1). According to ANP
208 (2020), this basin produced 4,109 bbl/d oil and 83 Mm³/d gas, totalling 4,632 boe/d. Matos et
209 al. (1996) have demonstrated that faults delimiting the Mundaú sub-basin reveal significant
210 changes in geometry, varying from ‘planar’ to ‘listric’, ‘sigmoidal-listric’ and ‘listric with a

211 flat-ramp profile'. In addition, they proposed three distinct architectures for the Mundaú sub-
212 basin: 1) tilt blocks where the Mundaú Fault shows a planar or listric geometry at depth, 2) tilt
213 blocks with a synclinal next to the Mundaú Fault due to its sigmoidal geometry, and 3) tilt
214 blocks with anticlines and small synclines genetically related to the flat-ramp geometry of the
215 Mundaú Fault. According to Antunes et al. (2008), the structural framework of the Mundaú
216 sub-basin is dominated by a normal fault, the Mundaú Fault, which strikes NW-SE and dips to
217 the NE (Fig. 1).

218 The tectono-sedimentary evolution of the Mundaú sub-basin consists of three
219 major megasequences (Beltrami et al., 1994): syn-rift, transitional and drift. The syn-rift phase
220 is characterized by the development of NW-SE normal faults bounding asymmetric half-
221 grabens, and continental sedimentation marked by fluvial-deltaic sandstones and shales of the
222 Mundaú Formation (Beltrami et al., 1994) (Fig. 2). The top of this unit is a regional
223 stratigraphic horizon, called Electric Mark 100 (Costa et al., 1990) or 1000 (Condé et al., 2007),
224 corresponding to a hard ground (Beltrami et al., 1994; Condé et al., 2007). It is interpreted as
225 resulting from regional flooding affecting the basin during the lower Aptian (Pessoa Neto et
226 al., 2004).

227 The transitional sequence (Paracuru Fm.) marks by the first marine incursions
228 affecting the Mundaú sub-basin, alternating within fluvial, deltaic and lacustrine sandstones.
229 Limestones and subordinate evaporites were also deposited at this stage (Costa et al., 1990;
230 Beltrami et al., 1994; Condé et al., 2007) (Fig. 2). As shown by Maia de Almeida et al. (2020),
231 the Paracuru Formation represents a *breakup sequence* sensu Soares et al. (2012) and Alves
232 and Cunha (2018).

233 The drift or marine megasequence, developed in association with continental drift
234 between the BEM and Equatorial Africa, reflects a prolonged phase of thermal subsidence. The
235 resulting drift strata in the Ubarana Formation comprises two members (Costa et al., 1990;

236 Beltrami et al., 1994; Condé et al., 2007) (Fig. 2). The first of these two members, the
237 Uruburetama Member, corresponds to a marine transgression and consists chiefly of shales.
238 The second member, the Itapagé Member, corresponds to a regressive marine phase and
239 consists of turbiditic shales and sandstones (Costa et al., 1990; Beltrami et al., 1994; Condé et
240 al., 2007). The Guamaré Formation consists of shelf carbonates, while the Tibau Formation
241 comprises proximal sandstones. The clastic continental sediments of the Barreiras Formation
242 comprise the youngest unit in the basin (Condé et al., 2007) (Fig. 2).

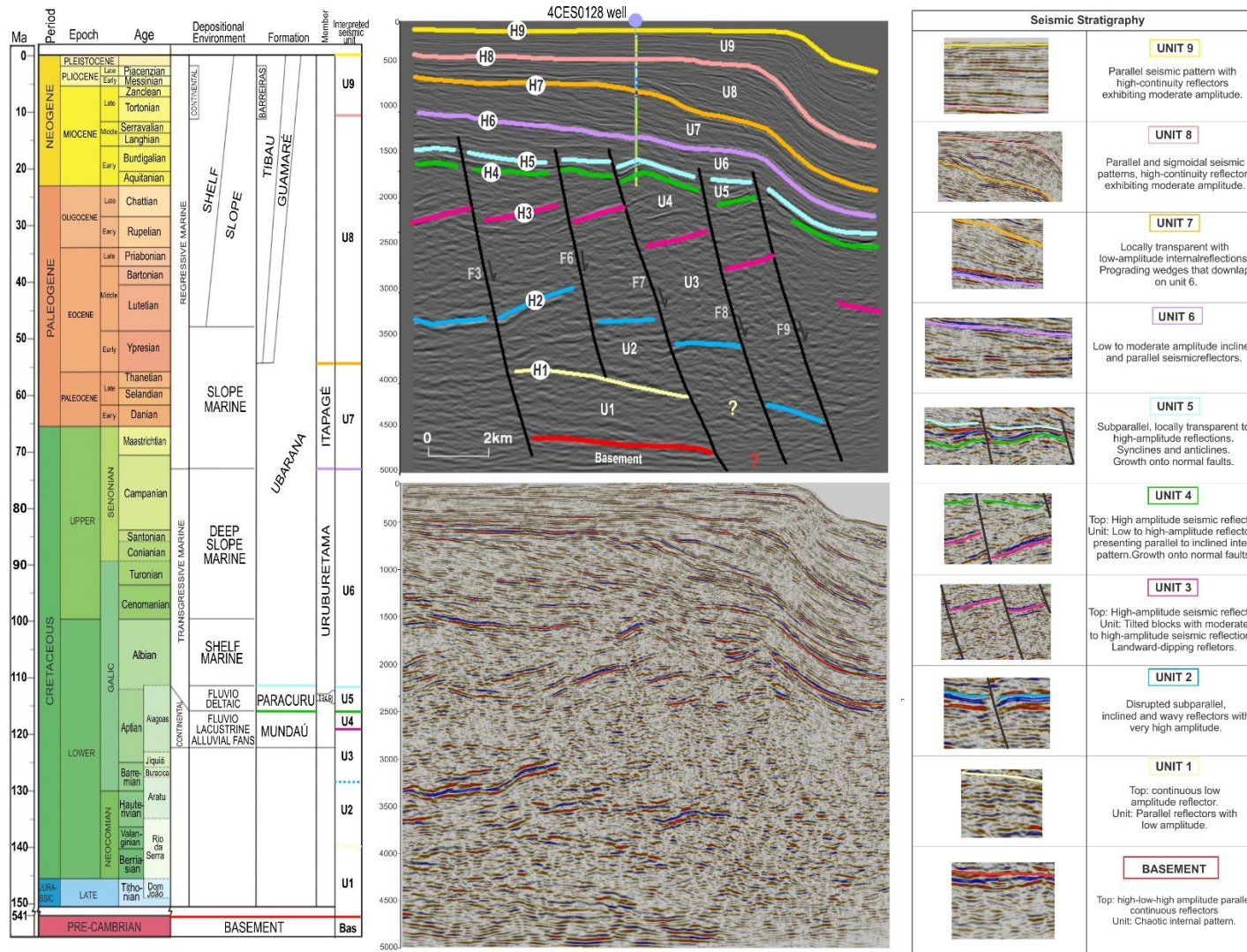
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245 **2.3. Curimã and Espada fields**

246

247 The Curimã field is a classic example of a combined hydrocarbon trap resulting
248 from the erosional truncation of large, active tilt blocks. The combined trap is made up of
249 rotated blocks composed of Aptian strata that are truncated at the top by an angular
250 unconformity, therefore juxtaposing Aptian reservoirs and Albian-Turonian transgressive
251 shales (Pessoa Neto, 2004). The main reservoirs in the Curimã field comprise fluvial and
252 deltaic sandstones with good permeability and porosity characteristics, which are laterally
253 continuous in the Mundaú and Paracuru Formations. Porosity varies from 15.6% to 22.3% in
254 the Paracuru Formation and 18.4% to 27.7% in the Mundaú Formation, while permeability
255 varies from 27.4 mD to 401.6 mD in the Paracuru Formation and from 65.2 mD to 212.8 mD
256 in the Mundaú Formation (ANP, 2016). Reservoirs in the Paracuru Formation are filled with
257 31° API oil, whereas the Mundaú reservoirs contain 29° API oil. In the Paracuru Formation, the
258 primary mechanism of production is gas in solution. In addition, water injection has been
259 applied since 1985 with the aim of enhancing oil recovery.



260
261
262

Figure 2. Correlation panel amongst interpreted seismic units and stratigraphic information from the Ceará Basin (Condé *et al.*, 2007). See location of the seismic section in Figure 1.

263 In the Mundaú Formation, the primary mechanism of production is combined water inflow due
264 to an adjacent aquifer and resulting expansion of a gas cap (ANP, 2016).

265 The main reservoirs in the Espada field are located in a turbiditic play comprising
266 sandstones intercalated to shales of Ubarana Formation (Costa et al., 1990). The reservoirs are
267 filled with 37° API oil (ANP, 2017a). The main producer zone is approximately 10 m thick,
268 porosity varies from 24.5% to 32.3%, and permeability varies from 200 mD to 9000 mD (ANP,
269 2013).

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273 3. MATERIAL AND METHODS

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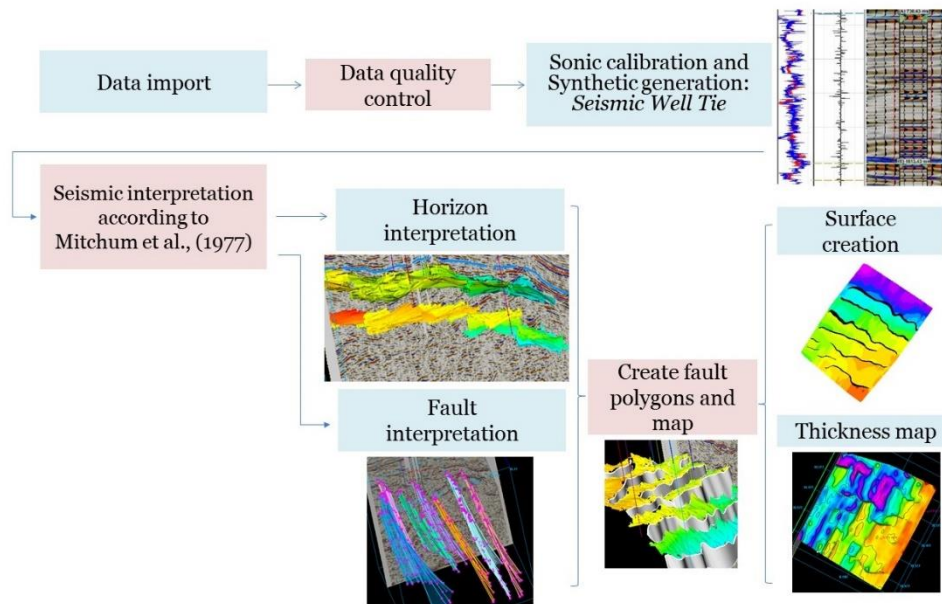
275 Data from 12 exploration wells and a post-stack time-migrated multichannel three-
276 dimensional seismic reflection volume in the time domain
277 (0223_CURIMA_ESPADA_4A.3D. MIG_FIN) were used in this study (Fig. 1). The
278 interpreted seismic volume consists of 171 inlines spaced 75 m (IN95 - IN266) with a
279 35°azimuth, and 662 crosslines (XL77 - XL739) spaced 25 m with a 125°azimuth. It covers
280 part of Espada field and the entire Curimã field, spanning the mid continental shelf, the outer
281 continental shelf and the upper continental slope (Fig. 1). The inline length is ~16.6 km and
282 crosslines are ~12.8 km long, reaching a total area of ~212 km². Penetration depth reaches
283 5,000 ms two-way time (twt) and each seismic trace has 1,251 samples at a 4 ms sampling
284 interval. The 3D post-stack seismic data was supplied with a standard processing flow
285 (migrated post-stack).

286 The interpreted well data include standard log suites (i.e. gamma ray, sonic, density
287 and resistivity), lithological data and formation tops. Some wells (e.g. 4CES0128, 4CES0143

288 and 1CES0115) display check-shot surveys. All these data were acquired by Petrobras and
289 supplied by the Brazilian National Agency of oil, gas and biofuels (ANP).

290 Well and seismic data integration was performed on Schlumberger's Petrel E&P
291 Software Platform. The interpretation of the seismic data (horizons and faults) was performed
292 in the time domain. Thus, we converted the well data into the time domain using the check-
293 shots and sonic logs (Fig. 3). We produced a synthetic seismogram and correlated it to the real
294 seismic data. Seismic interpretation was based on the general principles of seismic stratigraphy
295 (Mitchum et al., 1977), which rely on the recognition of seismic patterns such as seismic
296 terminations, seismic facies and seismic units. First, we interpreted the main seismic horizons
297 and faults in the Mundaú sub-basin. In a second stage, we created fault polygons and their
298 boundaries. Finally, the horizons and faults interpretations were used to generate surfaces and
299 then to extract the thickness maps (Fig. 3).

300



301

302 Figure 3. Flow chart summarising the methodology used in this work.

303

304 4. RESULTS

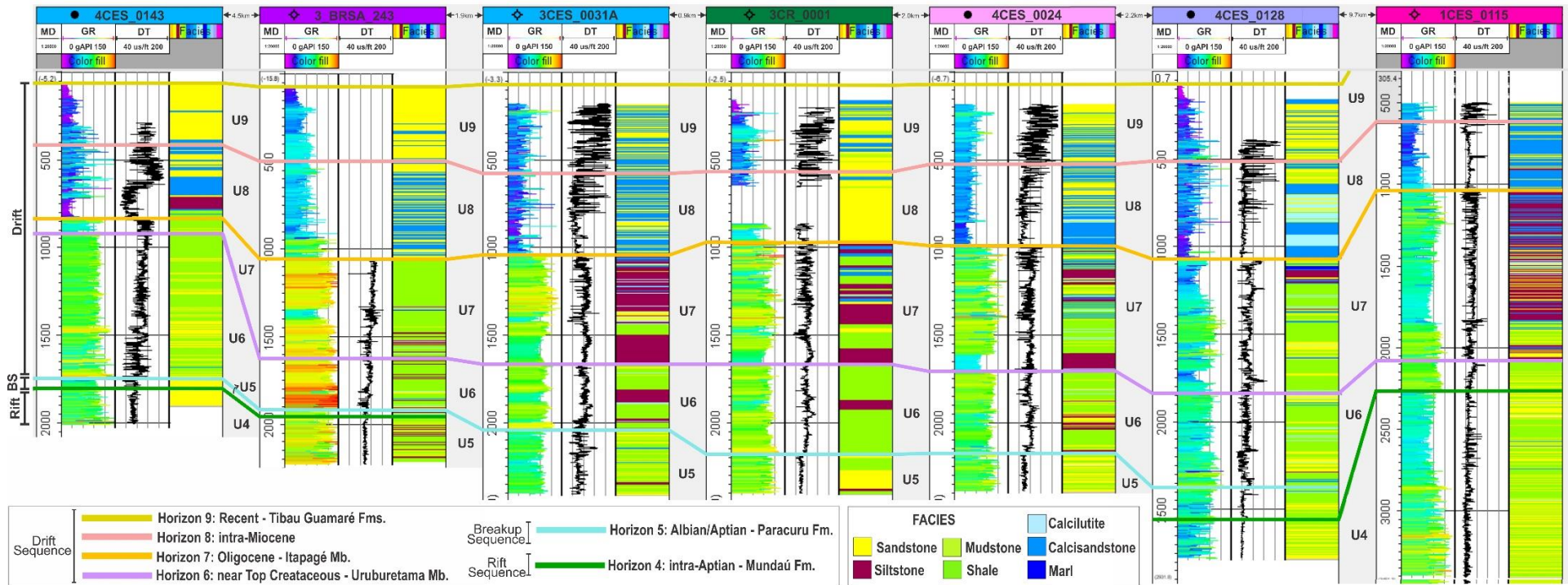
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306 4.1 Seismic Stratigraphy

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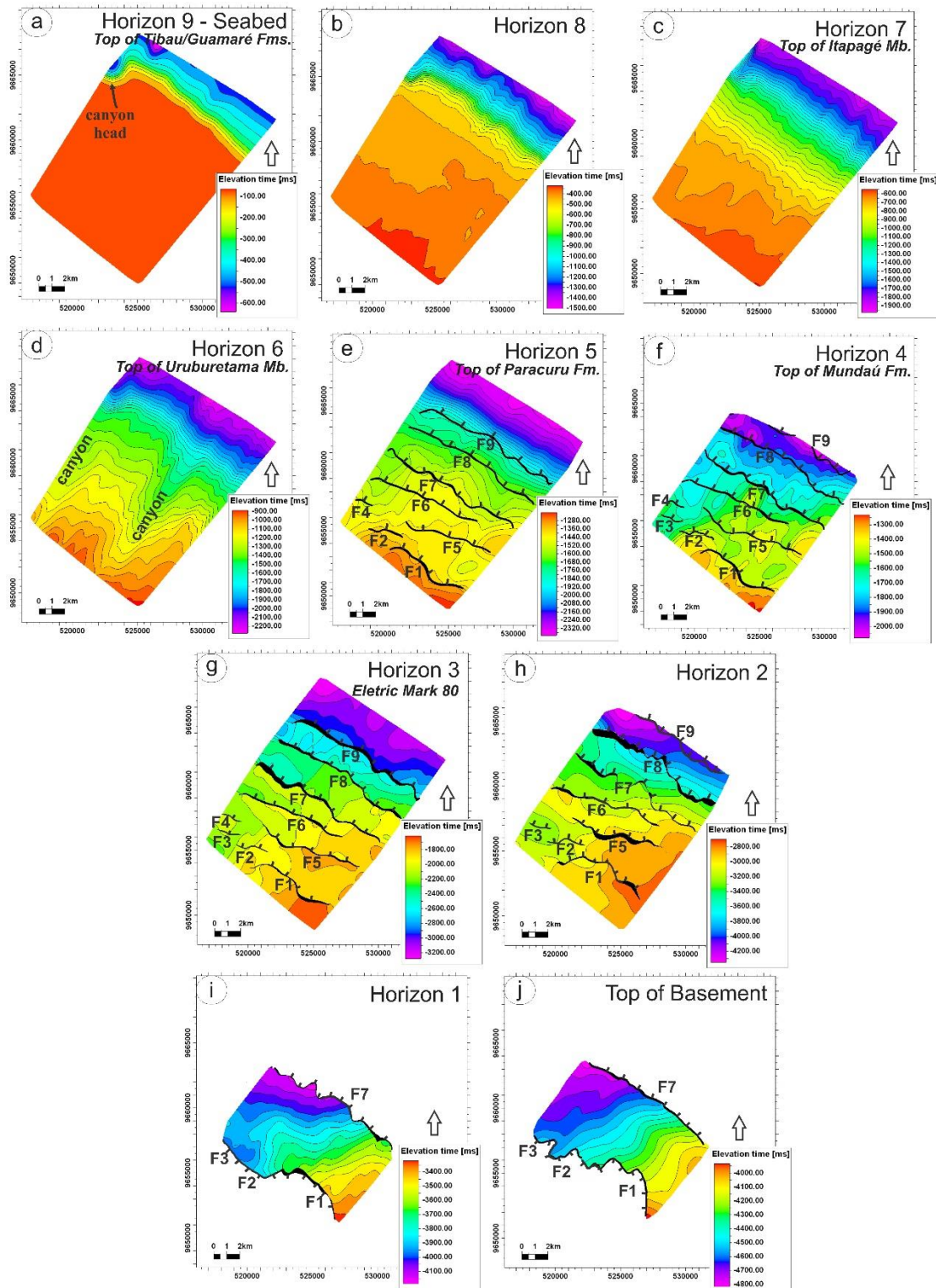
308 Nine seismic sequences were interpreted and correlated with the regional
309 lithostratigraphic framework of Condé et al. (2007) (Figs. 2 and 4). Units 1, 2, 3 and 4 comprise
310 the syn-rift Mundaú Formation.

311 The **top basement** reflection was mapped in the central part of the study area (Figs.
312 5j and 6). In the study area, basement rocks are characterised by their chaotic internal pattern,
313 with the top of this unit comprising a continuous reflection of variable amplitude (Fig. 2). The
314 top basement reflection generally dips to the NNW at an angle varying from 0° to 72°, with an
315 average dip of 15°.



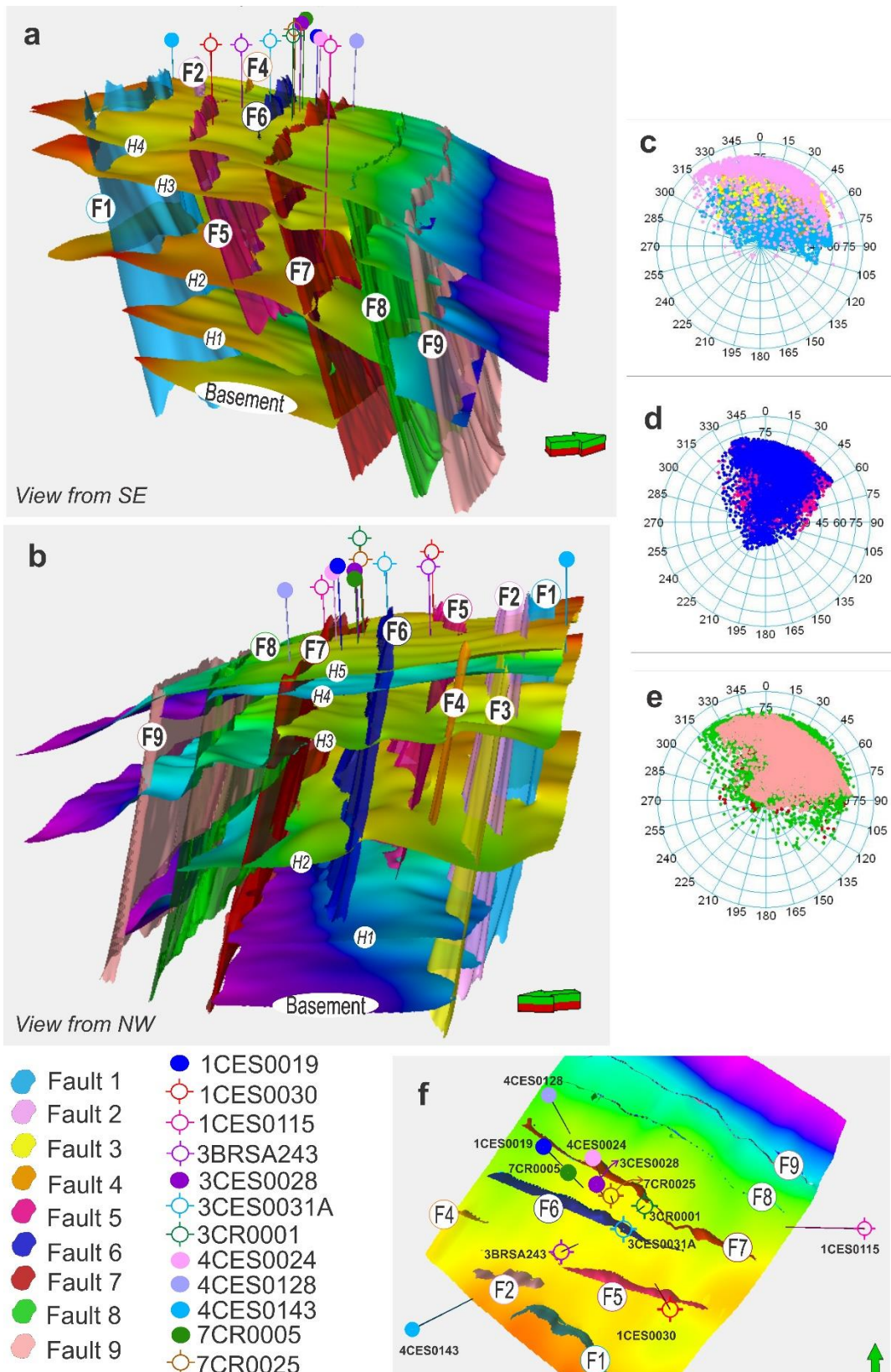
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317 Figure 4. Well correlation panel showing interpreted seismic units, gamma ray, sonic logs and facies, highlighting the sequences: rift, transitional (breakup sequence - BS)
 318 and drift.



319

320 Figure 5. Time-structural maps of various horizons at the study area: A) Sea floor (Top of the Tibau and
 321 Guamaré Formations) revealing submarine canyons in the shelf-edge region and on the continental slope. B)
 322 Horizon 8. C) Horizon 7 (Itapagé Member). D) Horizon 6, which corresponds to the top of the Uruburetama
 323 Member. Two submarine canyons incised the continental slope at this stage. E) Horizon 5 (Top of the Paracuru
 324 Formation) revealing the reactivation of faults during the transitional phase. F) Horizon 4, correlating with the
 325 top to the Mundaú Formation. This horizon was offset the syn-rift faults. G) Mark 80 horizon (top of Unit 3). H)
 326 Horizon 2 showing a faulted surface with a structural high to the SSE. I) Top of Unit 1 (Horizon 1) as mapped in
 327 the central part of the study area. J) Top of Basement mapped in the central part of the study area.



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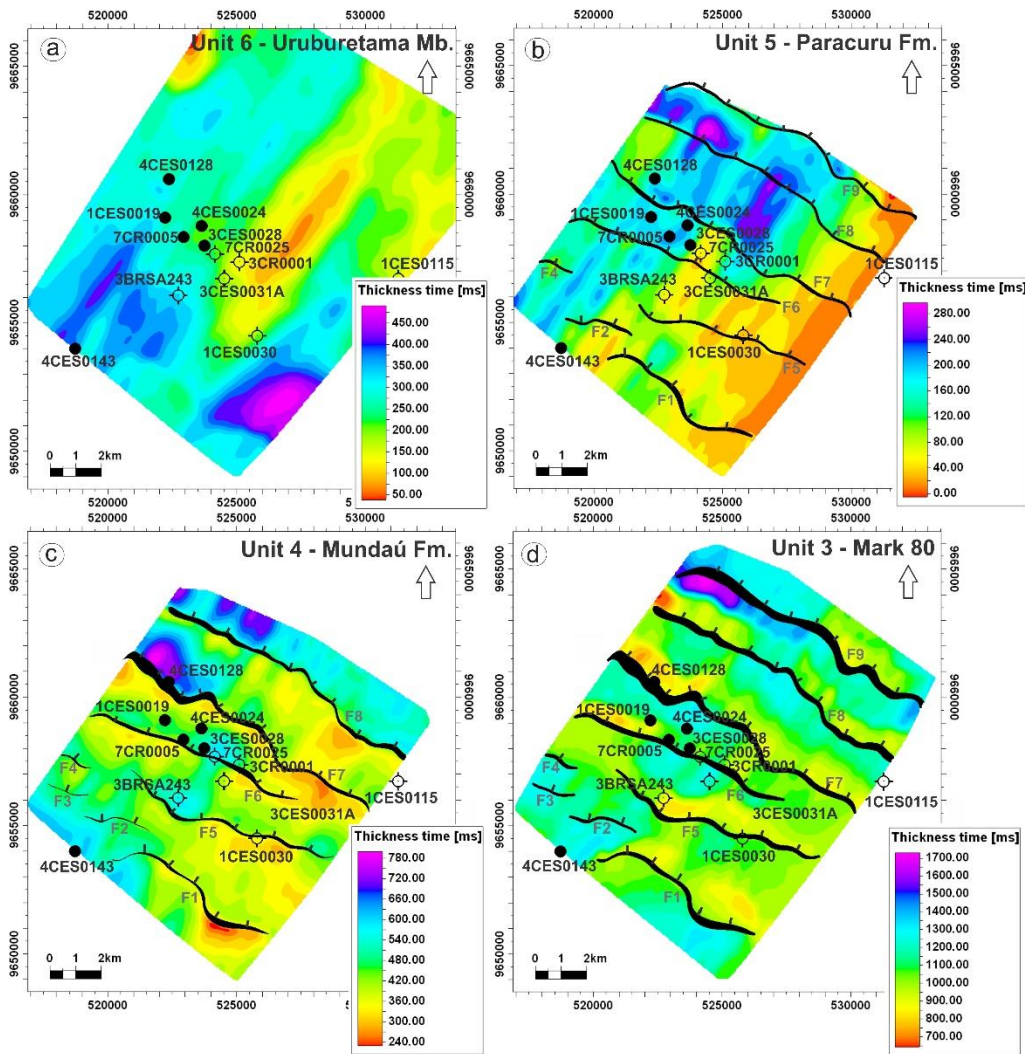
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Figure 6. A) and B) 3D structural models of the study area with view from southeast and northwest, respectively. C) Stereoplot of interpreted fault planes (as interpreted on seismic) showing the dip angle and dip azimuth of Faults 1, 2, 3 and 4. D) Corresponding stereoplot for Faults 5 and 6. E) Corresponding stereoplot for Faults 7, 8 and 9. F) Map view from above showing interpreted faults 1 to 9 and exploration wells.

334 **Unit 1** is characterised by its parallel internal reflections with low amplitude,
335 similarly to the basement, and was clearly mapped in the central part of the study area (Figs. 5i
336 and 6). The top of Unit 1 (Horizon 1) is a continuous low-amplitude reflection (Fig. 2).

337 The top reflection in **Unit 2** is a faulted, high-amplitude horizon that occurs at a
338 depth of ~ 3,000 ms two-way time (Horizon 2). Unit 2 is characterised by its sub-parallel,
339 inclined and wavy internal reflections with very high amplitude (Fig. 2). A basement high
340 affects the unit in the SSE part of the study area, where internal reflections dip to the NNW
341 (Fig. 5h). Units 1 and 2 were not crossed by exploration wells.

342 The top of **Unit 3** (Horizon 3) is correlated with the Electric Mark 80 (Costa et al.,
343 1990) or 800 (Condé et al., 2007). In the study area, it is a high-amplitude seismic reflection
344 with poor continuity (Fig. 2). Horizon 3 is a key to the mapping of faults in the study area when
345 considered together with Horizon 2. Unit 3 shows moderate to high-amplitude seismic
346 reflections tilted by normal faults. These reflections can be landward-dipping in places. Unit 3
347 is composed of intercalated shales and sandstones (Fig. 4), showing strata growth in the
348 immediate footwall of normal faults (Fig. 7d). It reaches a maximum thickness of 1,750 ms.



349

350 Figure 7. Isochron thickness of: A) Unit 6 (Uruburetama Member). In the central part of the study area, there is
 351 a region with smaller thickness - see orange color. B) Unit 5 (Paracuru Formation). Widespread erosion
 352 removed the upper part of this formation reducing its thickness in the south and southeast of the study area. C)
 353 Unit 4, corresponding to the upper part of the Mundaú Formation. This map shows the sedimentary thickening
 354 on the downthrown side of the faults, revealing fault activity. D) Unit 3, showing an increase in thickness as one
 355 gets closer to the upthrown side of normal faults.

356

357 **Unit 4** comprises low- to high-amplitude internal reflections that are sub-parallel
 358 to gently dipping. It is composed of sandstones, siltstones and shales (Figs. 2 and 4). The upper
 359 boundary of this unit (Horizon 4) coincides with the high-amplitude Electric Mark 100 (Costa
 360 et al., 1990) or 1000 (Condé et al., 2007). Unit 4 fills multiple half-grabens where it shows
 361 growth onto active faults, thus reflecting the development of a syn-rift sequence. In contrast to
 362 Unit 3, Unit 4 presents thicker strata on the downthrown side (immediate hanging-wall) of
 363 faults (Fig. 7c). All imaged faults intersect Unit 4 in its entirety (Figs. 5f and 6).

364 **Unit 5** comprises subparallel, locally transparent to high-amplitude seismic
365 reflections, part of the Paracuru Formation. It is composed of thin intercalations of sandstone,
366 siltstone, shales and marls (Figs. 2 and 4). Unit 5 is a transitional unit, a *breakup sequence*
367 sensu Soares et al. (2012) and caps the half-grabens associated with syn-rift faults. Its top
368 (Horizon 5) is an angular unconformity; widespread erosion removed the upper part of this unit
369 (Fig. 7b). As a result, Unit 5 becomes thinner in the east and southeast parts of the study area.
370 In the eastern part, close to the 1CES0115 well, Unit 5 was totally eroded. Units 4 and 5 present
371 growth onto major normal faults, highlighting active tectonic subsidence during their
372 accumulation.

373 **Unit 6** was deposited during the drift phase. However, faults still offset its lower
374 part. Unit 6 displays low- to moderate-amplitude inclined reflections comprising calcareous
375 shales with sandstones and siltstones intercalations (Fig. 4). Marls and calcilutites were drilled
376 in some wells. Unit 6 comprises the Uruburetama Member of the Ubarana Formation (Fig. 2)
377 and its top (Horizon 6) corresponds to an erosional surface associated with the incision of two
378 submarine canyons. The Espada and Curimã fields are located between these two submarine
379 canyons (Figs. 5d and 7a).

380 The upper boundary of **Unit 7** (Horizon 7) is a low-amplitude continuous
381 reflection. Unit 7 is locally transparent with low-amplitude internal reflections (Fig. 2). Internal
382 reflections in Unit 7 reveal prograding wedges of strata that downlap onto Unit 6. Unit 7
383 comprises the regressive Itapajé Member of the Ubarana Formation. Lithologically, it is
384 composed of intercalations of sandstones, siltstone, marls, calcilutites and shales (Fig. 4).

385 **Unit 8** reveals parallel and sigmoidal seismic reflections with high continuity and
386 moderate amplitude (Fig. 2). Lithologically, Unit 8 is composed of calcarenites, calcilutites,
387 sandstones and shales (Fig. 4).

388 **Unit 9** consists of parallel seismic reflections with high continuity and moderate
389 amplitude (Fig. 2). It is mainly composed of sandstones and calcarenites with thin layers of
390 shales. In the northern region of the study area, there is a submarine canyon head incising the
391 continental shelf edge (Fig. 5a). Units 8 and 9 comprise the Tibau and Guamaré Formations.

392

393 **4.2 Tectonic framework**

394

395 The study area presents a synthetic fault arrangement to the main extensional fault
396 bounding the Mundaú sub-basin (Mundaú Fault). In general, normal faults are seaward-dipping
397 and strike to the NW, dipping to the northeast. The faults are planar at depth (Figs. 2 and 6).

398 In the mid continental shelf, Faults 1, 2, 3 and 4 display an *en echelon* geometry
399 (Figs. 5j and 6) and, except for Fault 4, they all offset basement units. Faults 2, 3 and 4 are
400 respectively 2.7, 1.7 and 1.3 km long, being the smallest faults in the study area. They are
401 closely spaced with an average spacing of around 1 km, and with relatively rectilinear traces.
402 This is chiefly the case for Faults 3 and 4 (Figs. 5 and 6).

403 Faults 5 and 6 present sinuous traces and offset Units 2 to 6, tipping out near the
404 top of Unit 1 (Fig. 6). Faults are up to 9 km long and dip to the NNE with an average angle
405 of 41° (Fig. 5).

406 On the outer shelf, the high-angle Faults 7, 8 and 9 are the longest in the study area
407 (~11 km), occurring along the entire seismic volume. Fault 7 is located 2.7 km away from Fault
408 8, while this latter is spaced 1.9 km from Fault 9. All these faults are parallel and sinuous. In
409 addition, they are responsible for the largest offsets observed in the study area.

410

411

412

413 **4.3 Well data from the Curimã and Espada fields**

414

415 After completing detailed seismic and structural interpretations, one can
416 understand that wells 1CES0019, 4CES0024, 3CES0028 and 7CR0005 were drilled between
417 Faults 6 and 7, successfully striking oil in the Curimã field (Table 1, Figs. 6 and 7). Wells
418 3CR0001 and 7CR0025 were also drilled between Faults 6 and 7, but did not find any
419 hydrocarbons.

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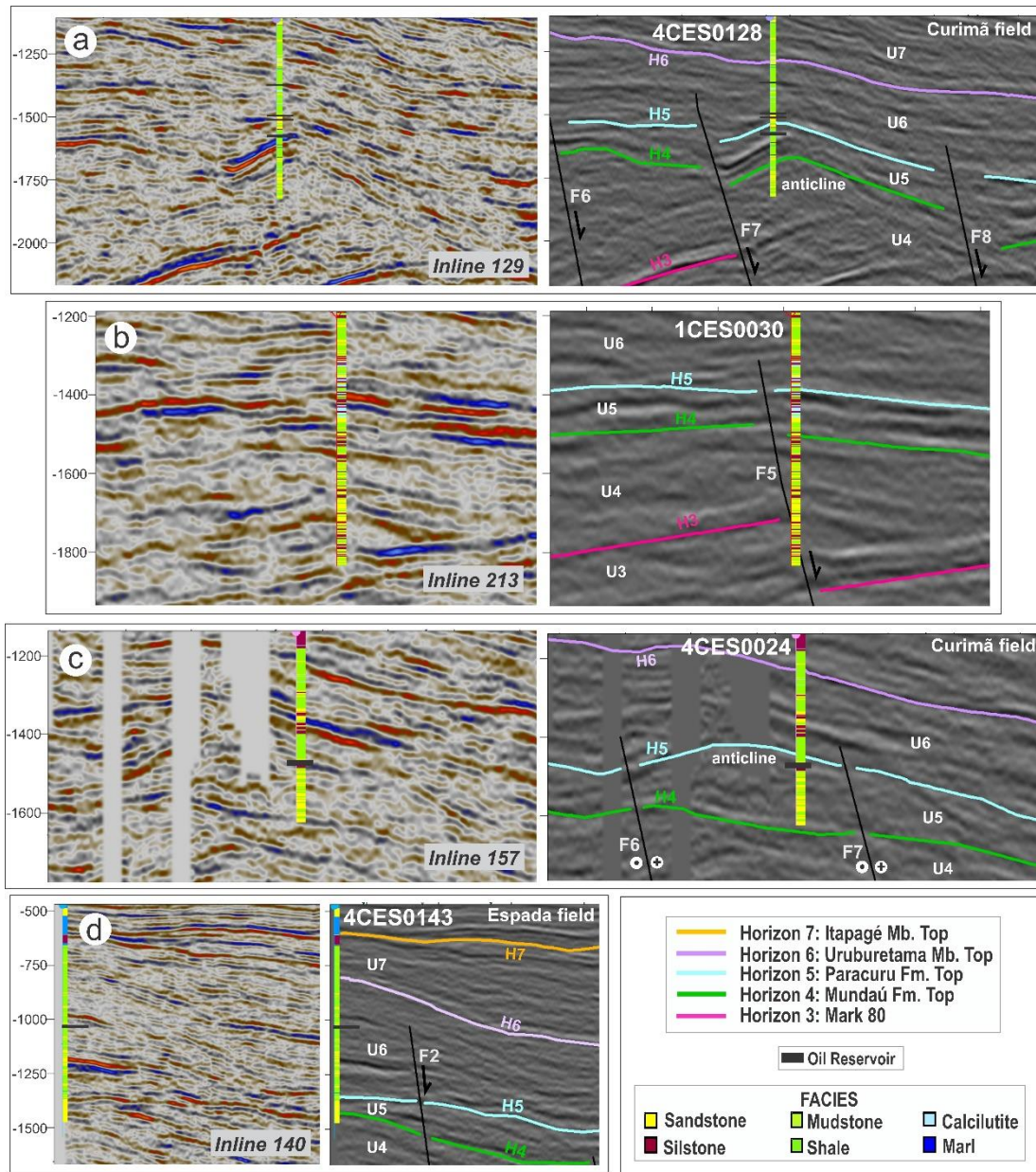
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Table 1. Integrated compilation of data from exploratory wells and seismic interpretation, showing the well location between the interpreted faults, oil field, category, objective, classification and oil finds.

Well	Between the faults	Oil field	Year	Category	Objective	Classification	Oil finds
1CES0019	6 e 7	Curimã	1978	Pioneer	Testing the dome structure next to Paracuru top.Targets: reservoirs of Paracuru and Mundaú Fms.	Discoverer of oil field	Units 5 and 6
4CES0024	6 e 7	Curimã	1978	Adjacent pioneer	Main objective: sandstones of Paracuru Fm. equivalent to 1CES0019 producer. Secondary objective: Turbiditic sandstones of Ubarana Fm.	Subcomercial oil producer	Units 4, 5 and 6
3CES0028	6 e 7	Curimã	1978	Extension	Verifying the SE extension of oil accumulation of Curimã field	Oil producer	Unit 5
7CR0005	6 e 7	Curimã		Exploratory	Knowing reservoir parameters and static pressure level	Comercial oil producer	Unit 5
4CES0128	7 e 8	Curimã	1996	Adjacent pioneer	Testing the dome structure next to Paracuru top	Discoverer of new oil area	Units 4, 5 and 6
3CR0001	6 e 7	Curimã	1979	Extension	Verifying the SE extension of oil accumulation of Curimã field	Dry with oil shows	-
7CR00025	6 e 7	Curimã	1989	Exploratory	Knowing reservoir parameters and static pressure level	Dry with oil shows	-
3CES0031A	5 e 6	Curimã	1979	Extension	Verifying the SE extension of oil accumulation of Curimã field	Dry	-
3BRSA243	5 e 6	Curimã	2003	Extension	Verifying the S extension of oil accumulation of Curimã field	Dry	-
1CES0030	5 e 6	-	1979	Pioneer	Testing tilted block formed by the fault 5	Dry	-
1CES0115	7 e 8	-	1991	Pioneer	Testing tilted block structured between the faults 7 and 8	Dry with oil shows	-
4CES0143	2	Espada	1998	Adjacent pioneer	Turbiditic sandstones of Ubarana Fm.	Subcomercial oil producer	Unit 6

440 Well 4CES0128, drilled between Faults 7 and 8, found new reservoir intervals in
 441 the study area (Table 1, Fig. 8a). Fault activity resulted in the formation of an anticlinal trap
 442 near Unit 5, i.e. in the Paracuru Formation. Well 4CES0128 found oil in Units 4, 5 and 6
 443 (Ubarana, Paracuru and Mundaú Formations).



444
 445 Figure 8. SW-NE seismic section interpreted with faults, horizons and wells, highlighting the seismic units. A)
 446 Well 4CES0128 reached the Unit 4 (Mundaú Fm.) and drilling oil reservoirs in stratigraphic (turbiditic) and
 447 structural (anticline) plays. B) Well 1CES0030 drilled in the fault zone (downthrown side of Fault 5). C) Well
 448 4CES0024 drilled on the footwall of the Curimã Fault (Fault 7). Anticline structure on the tilt-block formed
 449 between Faults 6 and 7 at the level of the Unit 5 (Paracuru Formation). This anticline shows an accumulation of
 450 oil in place. D) Well 4CES0143 crossing the Espada field and corresponding turbiditic reservoir successions in
 451 the Unit 6 (Ubarana Formation).
 452

453 In the eastern part of the area, where the basement is shallow and Unit 5 was eroded,
454 well 1CES0115 was drilled with the aim of testing the half-graben delimited by Faults 7 and 8
455 (Fig. 7). The aim of this well was to reach fluvio-deltaic sandstones in Units 3 and 4 (Figs. 4
456 and 6). However, the well revealed reduced net pays, an undefined oil water contact, low
457 transmissibility and very low productivity. The section below Horizon 3 showed very poor
458 reservoir quality with a marked reduction in porosity with depth – a character further worsening
459 the quality of the reservoirs drilled at this location. The well was classified as ‘dry with
460 hydrocarbon shows’ and was abandoned.

461 Well 3CES0031A was drilled on top of the footwall bounded by Fault 6. This and
462 well 3BRSA243 were drilled between Faults 5 and 6 with the aim of verifying the SE extension
463 of the Curimã field (Figs. 6 and 7, Table 1). They did not find any hydrocarbons and were
464 considered dry.

465 Well 1CES0030 was drilled exactly at Fault 5, reaching the lower part of the block
466 limited by Faults 5 and 6, i.e. the immediate hanging-wall of Fault 5 (Fig. 8b). Well data show
467 clayey sandstones, water saturation and low permeability. The well was eventually abandoned
468 due to the lack of economic volumes of hydrocarbons. Well 1CES0143, in the southwest
469 portion of the study area, is located at the Espada field (Table 1, Figs. 1 and 6). It detected oil
470 shows in Units 5 and 6 and is, at present, an oil producer within the Ubarana Formation. Well
471 tests developed in the interval spanning 1,263-1,278 m produced 26° API oil with a flow of 80
472 m³/day (Fig. 8d).

473

474 **5. DISCUSSION**

475

476 *5.1 3D Structural modelling of an oil producing region of the BEM*

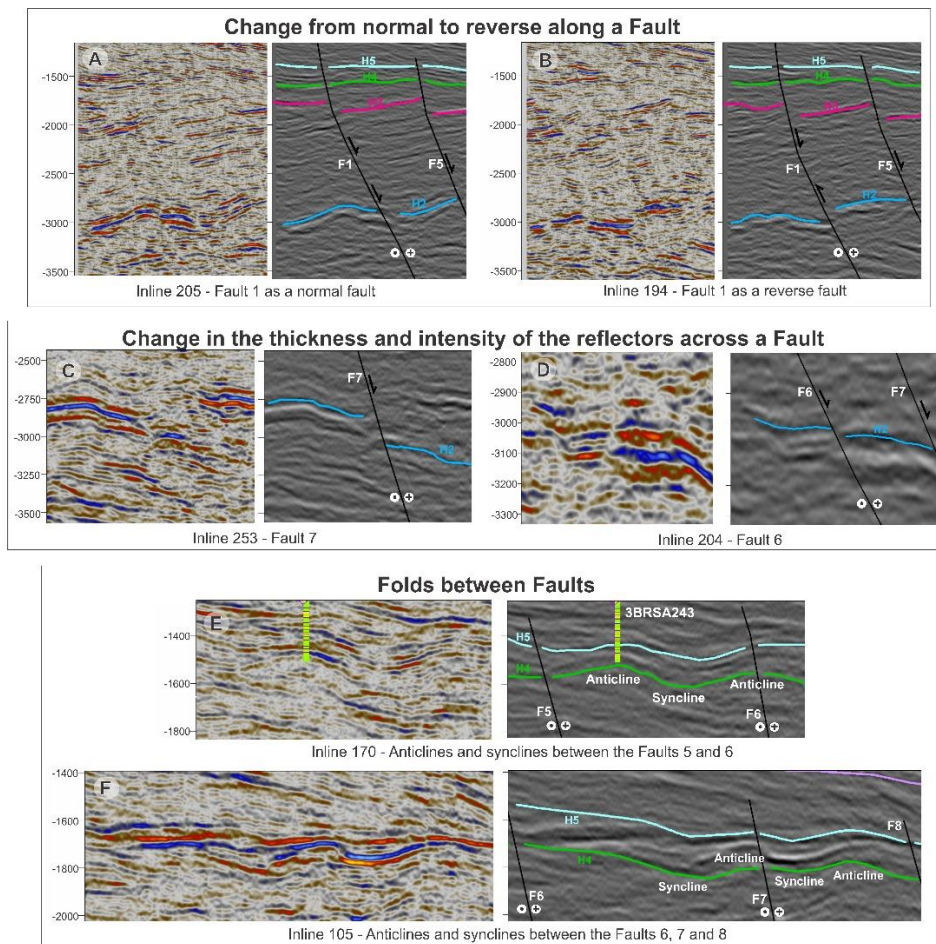
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478 Our 3D structural modelling suggests that the study area, comprising an oblique
479 rift basin with multiple half-grabens, records active faulting during the deposition of Units 1 to
480 4 (syn-rift). [Figs. 7c and 7d](#) show that important fault activity occurred during the deposition
481 of Unit 4 (Aptian). These faults were capable of tilting the blocks where Units 2 and 3 were
482 deposited ([Fig. 7d](#)), resulting in the thickening of Unit 4 next to fault planes (growth faults)
483 ([Fig. 7c](#)). These observations corroborate the published literature and confirm that the
484 continental margins along the Equatorial Rift Segment (EqRS) were affected by a paroxysmal
485 phase of tectonism between South America and Africa during the Aptian, with a major phase
486 of rift-related subsidence being reported from all EqRS basins ([Azevedo, 1991](#); [Brownfield](#)
487 [and Charpentier, 2006](#); [Soares Junior et al., 2011](#); [Heine and Brune, 2014](#)).

488 Near the Xaréú Oil Field ([Fig. 1](#)), [Antunes et al. \(2008\)](#) mapped an array of NW-
489 trending and NE-dipping normal faults forming an extensional system that is very similar to
490 the study area in this work. However, faults in the Xaréú field are listric and rooted along a
491 detachment surface corresponding to the Mundaú Fault, located at the southwest border of the
492 Mundaú sub-basin. In addition, [Antunes et al. \(2008\)](#) interpreted these faults as representing
493 listric or ramp-flat-ramp geometries. According to the interpretations in this work, faults are
494 planar and sub-vertical in the Curimã field, forming tilt blocks. This compares favourably with
495 basins on the BEM ([Watts et al., 2009](#); [Zalán, 2015](#)) and Equatorial Africa ([Tetteh, 2016](#)) such
496 as in the Guyana–Suriname ([Nemčok et al., 2016a](#); [Nemčok et al., 2016b](#)), in which syn-rift
497 planar faults were also recognised.

498 During the deposition of Unit 5 (transitional unit), faults continued to be active as
499 transtensional structures, forming folds between active faults ([Figs. 8a, 8c, 9e and 9f](#)). The top
500 of Unit 5 is an erosional unconformity recognised in the western portion of the Equatorial South
501 America ([Nemčok et al., 2016a](#)), as well as in Equatorial Africa ([Brownfield and Charpentier,](#)
502 [2006](#)), and has been interpreted as a breakup unconformity. The exact location along the EqRS

503 where continental breaup was occurring at the time, or if this stratigraphic surface represents
 504 full lithospheric or mantle breakup, is still under debate (see Soares et al. 2012; Alves and
 505 Cunha, 2018 and Maia de Almeida et al., 2020). Similarly to the study area, Nemčok et al.
 506 (2016a and 2016c) show evidence for folding of strata near the breakup unconformity before
 507 late Aptian–Albian times. They noted the presence of the breakup unconformity on top of a
 508 folded section characterised by significant erosion of the Demerara Plateau. In parallel, Attoh
 509 et al. (2004) confirmed this same episode of subaerial erosion offshore Ghana and attributed
 510 lateral variations in erosional depth to crustal displacement associated with local folding and
 511 uplift.



512
 513 Figure 9. Seismic patterns of strike-slip tectonics. A) Variations of fault throw with depth (Fault 1). B) Change
 514 from normal to reverse fault movement with depth (Fault 1). C) Abrupt change in the seismic character of the
 515 reflector across Fault 7. D) Abrupt change in the seismic character of the reflector across Fault 6. E) Synclines
 516 and anticlines in the breakup sequence (Unit 5) between the faults 5 and 6. F) Synclines and anticlines in the
 517 breakup sequence (Unit 5) between the faults 6, 7 and 8.
 518

519 The development of folds in extensional basins is not common. However, fault-related
520 folds have been recognised close to propagating normal faults (Brandes and Tanner, 2014) as
521 observed in the study area (Figs. 8 and 9). Fault-related folding has been analysed in the field
522 (Howard and John, 1997; Corfield and Sharp, 2000; Sharp et al., 2000), using analogue models
523 (Withjack et al., 1990), and numerical simulations (Khalil and McClay, 2002; Jin and
524 Groshong, 2006). Analogue models developed by McClay and Scott (1991) reveal that small
525 irregularities in the geometry of normal faults can generate reverse secondary faults and local
526 antiforms within a general setting dominated by regional extension. These antiforms are similar
527 to the structure drilled by well 4CES0128 (Fig. 8a).

528 Folds generated between normal faults can be also associated to strike-slip tectonics
529 (Zalán, 1986; Lamarche et al., 1997; Davison et al., 2016). According to Fossen et al. (2013)
530 and Fossen (2016), transcurrent faults zones can develop folds; folds are arranged spatially
531 such that culminations and depressions in successive folds lie along lines that make an acute
532 angle with the (approximately parallel) fold axes. Such folds are stepped, and, in general,
533 arranged in an *en echelon* geometry. In the study area, folds are relatively sub-parallel to faults,
534 showing very acute angles. In addition, folds were mapped in other regions of the BEM such
535 as in Barreirinhas and Pará-Maranhão basins by Azevedo (1991) and Sauerbronn (1996), in the
536 Piauí-Camocim sub-basin by Zalán & Warne (1985), in Icaraí sub-basin by Castro (1993), in
537 Potiguar Basin by Hoerlle et al. (2007), in the Guyanas-Suriname basins by Goss et al. (2008),
538 Nemčok et al. (2016a) and Loncke et al. (2016) and in Equatorial Africa by Attoh et al. (2004),
539 Lamarche et al. (1997) and Davison et al. (2016).

540 The *en echelon* geometry of normal faults observed in the study area is a common fault
541 geometry in transcurrent structures (Hempton and Neher, 1986; Deng et al., 1986; Lonsdale,
542 1989; Moustafa and Abd-Allah, 1992; Zachariassen and Sieh, 1995) (Figs. 5 and 7). Hence,
543 using the criteria of Zalán (1986), other characteristics revealing strike-slip movements were

544 investigated in the study area, such as the sinuous and complex geometries of fault planes and
545 profiles (Figs. 6 and 7). High sinuosity in faults is an important trait of transcurrent faults
546 (Bridwell, 1975). Moreover, Fault 1 changes from normal to reverse along its strike (Figs. 9a
547 and 9b). In Fig. 9a, Horizons 2 and 3 are subtly displaced by Fault 1. However, in Fig. 9b, Fault
548 1 displaced Horizon 2 as a reverse fault and Horizon 3 as a normal fault. Apart from changing
549 from normal to reverse fault along strike, this fault also reveals important changes in throw
550 with depth, two characteristics associated with strike-slip movements (Zalán, 1986). Offshore
551 Ghana, Attoh et al. (2004) also mapped contradictory offsets that indicate strike-slip tectonics.

552 Variations in the seismic character across a fault were also interpreted as relating
553 to strike-slip movements. Seismic facies reveal changes in thickness and intensity of the
554 seismic reflections, and relative scale of deformation in strata (Figs. 9c and 9d), corroborating
555 the idea that strike-slip tectonics affected great part of the study area. Similarly, Andrade et al.
556 (2018) interpreted changes in the seismic reflections close to the Romanche Fracture Zone as
557 revealing a dense set of strike-slip faults. Such interpretations have important economic
558 implications because it increases the variability of potential traps around the Romanche
559 Fracture Zone (Zalán, 1986).

560 Ultimately, the 3D structural model presented in this work is a combination of the
561 geometries 1 and 3 proposed by Matos et al. (1996) (see item 2.1.1 Mundaú sub-basin).
562 Therefore, we propose a fourth complementary geometry that includes tilted blocks with small
563 anticlines and synclines genetically related to transtensional planar faults. This model fits
564 within the regional context of oblique rifting in the Brazilian Equatorial Margin.

565

566 *5.2 Petroleum plays in the Curimã and Espada Fields: Comparison with other Equatorial*
567 *Atlantic plays*

568

569 Three types of petroleum plays were found in the study area: combined, structural and
570 stratigraphic (Fig. 10). They are described as follows:

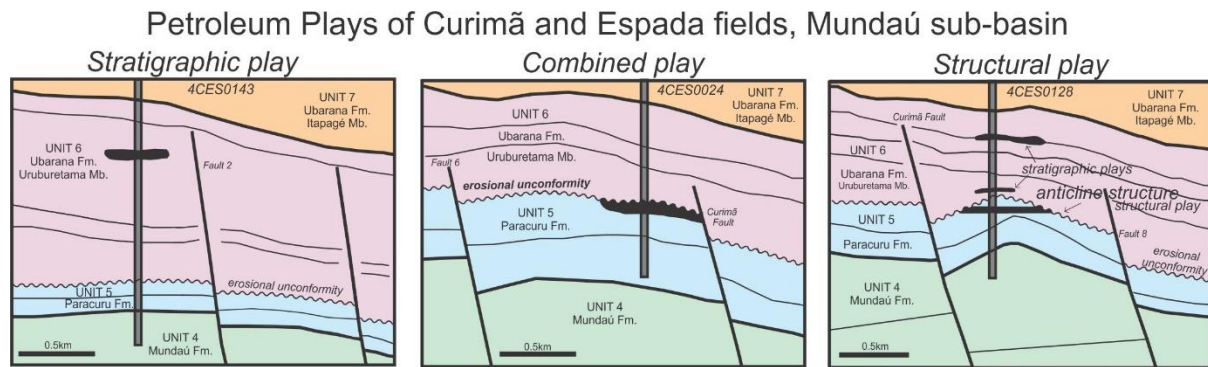
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572 5.2.1. Combined plays

573 Pessoa Neto (2004) summarised the essential conditions to form combined traps in the
574 Curimã field: large-slip faults and the presence of angular unconformities followed by the
575 deposition of thick transgressive marine shales. In addition, three geological settings were
576 considered by Pessoa Neto (2004) to record some degree of inefficiency in hydrocarbon traps:
577 1. juxtaposition of reservoir intervals and sandy layers across fault planes or unconformities;
578 2. the absence of erosional truncation in tilt blocks and; 3. erosion or non-deposition of
579 transgressive marine strata above reservoir intervals.

580 Based on our 3D structural model, Faults 6 and 7 are key to understand the
581 petroleum potential of the Mundaú sub-basin - wells 1CES0019, 4CES0024, 3CES0028 and
582 7CR0005 drilled between these two faults and found oil in the Curimã field (Table 1, Figs. 7,
583 8 and 10). These wells drilled key examples of the **combined plays** proposed by Pessoa Neto
584 (2004). Wells 1CES0019 and 4CES0024 reached a dome structure formed by Faults 6 and 7
585 and reached the upthrown side (footwall) of a mixed trap formed by the block tilted by Fault 7
586 and the shales deposited above Horizon 5 (Figs. 8c and 10). The upthrown sides of normal
587 faults, forming tilt blocks, are classic footwall traps for hydrocarbon (Illing and Hobson, 1981;
588 Brooks and Glennie, 1987; Yielding, 1990; Hardman and Booth, 1991; Nemčok, 2016d).
589 According to Pessoa Neto (2004), Aptian reservoirs are located on the footwall of the main
590 fault bounding the Curimã field, i.e. the Curimã Fault. Thus, we can deduce that Fault 7 is the
591 Curimã Fault proposed by Pessoa Neto (2004).

592



593

594 Figure 10. Three types of petroleum plays in the Curimã and Espada fields, Mundaú sub-basin: stratigraphic,
 595 combined and structural plays.

596

597 The Curimã field is delimited to the north by the Curimã Fault (Fault 7), which affects
 598 Units 4 and 5 (Paracuru and Mundaú Formations). However, Fault 7 also offsets the lower part
 599 of Unit 6 (Uruburetama Member). To the south, the field is delimited by a synthetic normal
 600 fault (Fault 6). Similarly to the Curimã field, there are hydrocarbon accumulations in deep-
 601 water Ceará (Pecém discovery) and Potiguar Basins (Pitu discovery) that show combined plays,
 602 as presented by Maia de Almeida et al. (2020) and ANP (2017b). Aptian transitional reservoirs
 603 were trapped by a normal fault and an erosional unconformity. The Espoir and Baobab fields
 604 in Ivory Coast are also trapped by faulted blocks and the Albian unconformity (Kelly and
 605 Doust, 2016). These authors explained that reactivation of the inherited rift structures helped
 606 forming combined structural and stratigraphic traps.

607 The Jubilee Field in Ghana comprises a combination of structural and stratigraphic
 608 traps associated with the topography created by the transform tectonics during the opening of
 609 the Atlantic (Dailly et al., 2017). It is an Upper Cretaceous high-quality oil pay (Turonian in
 610 age) within a drift submarine fan sequence. In the Mundaú sub-basin, the combined plays occur
 611 in the Aptian transitional sequence. Nevertheless, the presence of more recent combined plays
 612 such as those at Jubilee cannot be ruled out in the Mundaú sub-basin as suggested by Maia de
 613 Almeida et al. (2020) and Leopoldino Oliveira et al. (2020), as well as in other basins of the

614 Equatorial Atlantic as exemplified by the Zaedyus field in French Guiana, considered an
615 analogous example of the African Jubilee field.

616

617 5.2.2. *Structural plays*

618 Well 4CES0128 was classified as a new discovery between the Curimã Fault and
619 Fault 8 (Table 1, Figs. 8a and 10). The Curimã Fault was capable of forming hanging-wall
620 blocks with broad anticline traps as the one reached by this well, i.e. a **structural play**. Close
621 to well 4CES0128, the Curimã Fault shows a relatively large offset, and Fig. 7a shows the
622 deposition of Uruburetama shales. This well proved that hanging-wall block and anticline traps
623 can be successful targets in the Mundaú sub-basin.

624 Jianping et al. (2010) presented different kinds of traps developed in different
625 strata controlled by different tectonic activities along the Côte d'Ivoire-Ghana transform
626 margin. They show that most are structural traps, such as fault-block and anticline traps. They
627 interpreted that anticline traps are related to the transform structures at the end of the St Paul
628 and Romanche Fracture Zones. The Espada field, crossed by well 4CES0143, comprises a
629 **stratigraphic play** composed of Upper Cretaceous turbiditic reservoirs occurring between
630 1,262 and 1,278 m (~1030 ms in the interpreted seismic volume). These reservoirs are located
631 close to Faults 1 and 2 (Figs. 8d and 10). These faults do not trap oil; instead, they are related
632 to the migration of oil into the Espada field. Such an interpretation takes into account that oil
633 accumulated in the Ubarana Formation was generated in the Paracuru Formation and used
634 faults as migration paths to turbidite sands in the Espada field (Costa et al., 1990). In addition,
635 well 4CES0128 also reached Upper Cretaceous pinched-out turbiditic sandstones forming a
636 stratigraphic trap (Fig. 8a and 10).

637 Recent and important discoveries have drawn the attention to these subtle traps
638 (Dolson et al., 2018; Ward et al., 2016; 2018). As an example, the Stabroek block in Guyana

639 includes several prosperous fields such as Liza, Payara, Liza deep, Snoek, Turbot, Pacora and
640 Mako fields. This block contains sediments of Amazonian origin, which were deposited by the
641 Guiana Current. There are multiple play types in this block, including Cretaceous and
642 amplitude-supported plays containing stratigraphic onlaps, turbidites and basin floor fans
643 (Offshore, 2020; Zhang et al., 2019). According to Zalán et al., (2019), the trapping mechanism
644 is invariably stratigraphic in nature, with lateral and updip pinch outs limiting the reservoirs
645 containing hydrocarbons. These authors are hopeful to replicate this success in the Foz do
646 Amazonas and Pará-Maranhão Basins.

647 In the BEM, Pelegrini and Severiano Ribeiro (2018) mapped turbiditic plays in
648 depositional pinch-outs (sandstones inside shales) in shallow and deep waters off Pará-
649 Maranhão. In deep-water Mundaú sub-basin, stratigraphic traps were created by depositional
650 pinch-outs and by volcanic bodies - turbiditic sandstones were interpreted as having reflectors
651 with high acoustic impedance contrasts, low frequency, lensoid geometry, and variable lateral
652 extension, ranging from 5 to 8 km (Leopoldino Oliveira et al., 2020).

653 Finally, the recent discoveries of the Pelican and Rossignol wells confirm that Upper
654 Cretaceous stratigraphic plays in the deep-water Tano Basin (Ghana) comprise prolific
655 reservoir intervals (Scarselli et al., 2018). Daily et al., (2013) also concluded about the
656 importance of stratigraphic plays in the Gulf of Guinea. Thus, the results presented here show
657 successful plays of Mundaú sub-basin that can be replicated in other parts of the Equatorial
658 South Atlantic, as well as in Equatorial Africa.

659

660 *5.3. Exploration Failures in the Mundaú sub-basin*

661

662 Unfortunately, some cases of exploration failures were recorded in the study area.
663 For example, wells 3CR0001 and 7CR0025 drilled strata between Faults 6 and 7 but failed to

664 find any hydrocarbons (Table 1 and Fig. 6). This means that a putative extension of the Curimã
665 field to the southeast cannot be confirmed due to the smaller thickness of Units 5 and 6 in this
666 region (Figs. 7a and 7b). The relatively minor thickness of Unit 5 can be related to widespread
667 erosion during the Aptian-Albian (Morais Neto et al., 2003; Condé et al., 2007; Brownfield
668 and Charpentier, 2006; Nemčok et al., 2016a), which removed part of this formation in the east
669 and southeast parts of the study area. In contrast, the observed thinning of Unit 6 can be
670 attributed to an erosional event of regional expression affecting Maastrichtian strata (Morais
671 Neto et al., 2003).

672 Well 1CES0115 was drilled between Faults 7 and 8, similarly to the successful well
673 4CES0128. However, due to the presence of a structural high in the east and southeast, Unit 5
674 was totally eroded close to well 1CES0115 (Figs. 5 and 7b). Although oil shows were found in
675 Unit 4, reservoir quality was poor. This well confirmed that basement faults controlled
676 deposition during the syn-rift and transitional stages, and that basinwide erosional events
677 contributed to the removal of prolific reservoir intervals in Unit 5.

678 Wells 3BRSA243 and 3CES0031A were drilled between Faults 5 and 6 with the
679 aim of verifying the southeast extension of the Curimã field. Yet, they were considered dry
680 (Table 1) and, based on the data in this work, we can infer that Fault 5 does not form a
681 competent seal. It is worth pointing out that transcurrent faults change their properties along
682 strike (Zalán, 1986). Well 3CES0031A was drilled in a region showing erosion of both Units
683 5 and 6 (Fig. 7), further decreasing its chance for success.

684 Well 1CES0030 was considered a wildcat; the aim was to test the footwall of the
685 Fault 5. Nevertheless, this well reached its fault zone, crossing Unit 5 on the hanging-wall
686 block and the Electric Mark 80 on the footwall (Fig. 8b). This well crossed clayey sandstones
687 of low permeability, with cataclasites in the fault zone reducing their grain size, porosity and
688 permeability. Clay minerals formed in the fault zone tend to compromise reservoir quality.

689 Furthermore, this well was drilled on the margin of a submarine channel incising Unit 6, the
690 main seal interval in the study area, a detail that may have led to the failure of well 1CES0030
691 as a wildcat.

692 This work correlated data with very different resolutions, e.g. seismic data (3D)
693 with a resolution of hundreds of meters and well data (1D) with a resolution of dozens of
694 centimeters. The different scales of seismic and well data do not permit a coherent assessment
695 of reservoir lateral continuity, considering that the main reservoir intervals in the Curimã and
696 Espada fields are thinner than 20 meters. Thus, one seismic reflection in the interpreted seismic
697 volume may represent several porous layers with reservoir potential. Accordingly, we can
698 suggest the future development of a 3D geological model of the area using sequence
699 stratigraphic concepts (e.g. [Catuneanu, 2006](#); [Martins-Neto and Catuneanu, 2010](#); [Holz et al.,](#)
700 [2017](#)). A 3D reservoir model using geostatistic numerical models should be used in a second
701 stage as a basis for simulation and fluid flow analysis ([Consentino, 2001](#)). These two
702 approaches will be crucial to plan the development of the oil fields referred to in this work.

703

704 **6 CONCLUSIONS**

705

706 Three-dimensional (3D) structural modelling integrating a seismic cube and well
707 data from the Mundaú sub-basin, including part of the Espada field and the entire Curimã field,
708 was developed in this research. This work introduced a variety of plays from an oil producing
709 region of the BEM expanding the possibility of future discoveries in this area, and also in the
710 Guyana-Suriname-French Guiana system and Equatorial Africa as a whole. The findings in
711 this research have focused on subtle stratigraphic traps. In addition, we also assess the
712 importance of structural and combined plays, challenging academia and industry to consider
713 these play types as crucial in Equatorial margins of the Central Atlantic; we emphasize here

714 that the historical distribution of the giant fields in all the world is 79% of structural plays
715 (Dolson et al., 2018). Main conclusions are as follows:

716

717 a) Extensional faults in the study area are planar at depth, seaward-dipping, and
718 revealing a NW-SE strike direction and a NE dip direction. They present an *en*
719 *echelon* geometry and are responsible for stepping and tilting of crustal blocks (half-
720 grabens) during the syn-rift phase. Furthermore, the faults were active until the
721 beginning of the drift phase. Some of them root into the basement while others reach
722 the top of Unit 1.

723

724 b) Seismic interpretation indicates transcurrent movement in the mapped faults,
725 recorded in the form of: abrupt change in seismic facies across faults; changes from
726 normal to reverse along their strike and with depth; changes in thickness and intensity
727 of seismic reflections across faults; and synclines and anticlines formed between
728 faults. Strike-slip tectonics reflects the nearby presence of transtensional fault
729 systems associated with oblique rifting of the Equatorial Atlantic.

730

731 c) In the study area are found important oil accumulations in combined, structural and
732 stratigraphic plays.

733

734 **Combined plays** are formed by Aptian reservoirs in block tilted by Faults
735 6 and 7, and the deposition of the transgressive shales of Unit 6 (Uruburetama Mb.)
736 above an erosional unconformity. It is worth stressing the importance of not completely
737 eroding the transitional Unit 5 (Paracuru Formation), which contains better reservoirs
738 in the study area, as well as the Uruburetama Member, sealing underlying reservoir
intervals. The basement structure controlled deposition during the syn-rift and

739 transitional stages. In addition, the structural high in the SE part of the area was largely
740 removed by an erosional event after the transitional phase, contributing to erosion of
741 the Unit 5 and, consequently, the failure of some exploratory wells. This type of play
742 is also found in the African conjugate margin represented by Espoir and Baobab fields
743 in Ivory Coast Basin.

744 **Structural plays** comprise anticlinal traps on the hanging-wall block tilted
745 by Fault 7 (Curimã Fault). The Côte D'Ivoire-Ghana transform margin presents this
746 type of play which is related to the transform structures at the end part of Fracture
747 Zones.

748 **Stratigraphic plays** consist of Upper Cretaceous turbidite sandstones
749 intercalated with shales. Here, faults are not important traps. However, they are
750 responsible for oil migration. Very important discoveries in Stabroek block in Guyana
751 and in Gulf of Guinea were assigned to this type of play.

752

753 d) In summary, the mapping of faults and traps in this work revealed the importance of
754 a multi-faceted structural component to the entrapment of hydrocarbons in the
755 Mundaú sub-basin. These results can assist further geological modelling in the BEM
756 and, consequently, reservoir simulations in order to plan the development of proven
757 and future oil fields. The structural model presented here is a starting point to further
758 exploration work in the remainder of the BEM and in the conjugate Equatorial Africa.

759

760 **Acknowledgements**

761 The authors are grateful to the Brazilian National Petroleum Agency for providing seismic and
762 well data, and to Schlumberger for their software licenses. The authors also thank Cardiff
763 University (3D Seismic Lab) and the Coordenação de Aperfeiçoamento de Pessoal de Nível

764 Superior (CAPES) for an exchange period of the first author in 2017, and the Federal University
765 of Ceará (Laboratórios de Interpretação Sísmica e de Geologia Marinha e Aplicada) for their
766 support to this study. This study was financed in part by CAPES, Brazil, Finance Code 001.
767 The authors are grateful to the anonymous reviewers for their comments to earlier versions of
768 this work.

769
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