



1 **Tectonic control and geometric characterization of hydrothermal vent**
2 **complex using seismic data, Potiguar Basin – Brazil**

COMPLEXES?
OR
OF A HYDROTHERMAL
VENT COMPLEX?

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24 **ABSTRACT**

25 Hydrothermal vent complexes in sedimentary basins are linked to igneous
26 intrusions, which induce structural and thermal perturbations, causing forced
27 folds, hydrocarbon maturation, and fluid remobilization. While their genesis is
28 often associated with magmatic heat and hydraulic fracturing, the controlling
29 factors of their geometry and development remain debated. This study analyzes
30 3D seismic data from the Potiguar Basin (onshore Brazil), identifying vent
31 structures, two of which were extracted in a 3D perspective from the variance
32 attribute. Our results indicate that all the vents are structurally controlled
33 by regional-scale faults, which enhance permeability starting from the hydraulic

1

① REALISTIC?

② WHAT DOES
THIS MEAN?
STARTING
FROM?



34 fracturing and boiling processes. Seismic attributes, such as variance and dip
35 illumination have proven effective in identifying vent structures, fault associations,
36 and fluid pathways, providing insights into their spatial distribution and geometric
37 characteristics. Cosine of phase attribute reveals that hydrothermal vents exhibit
38 varying geometries as they cut different sedimentary units within the basin. Our
39 findings highlight the petrophysical implications of a fault zone in a hydrothermal
40 vent complex and advance understanding of silicification processes in
41 sedimentary reservoirs.

42 **Keywords:** Hydrothermal vents, seismic attributes, fault zones, fluid migration,
43 sedimentary basins.

44 45 1. INTRODUCTION

46 Hydrothermal vents are a complex combination of elements that
47 potentially affect the petrophysical properties of reservoirs. They have been
48 described in sedimentary basins associated with ^{volcanism} ~~volcanic activities~~ as injections
49 of igneous plumbing systems, dikes, and sills (Skoseid et al., 1992; White and
50 McClintock, 2001; Svensen et al., 2003; Jamtveit et al., 2004; Planke et al., 2005;
51 Hansen et al., 2008) These igneous injections are known to induce structures as
52 forced folds, hydrofracturing systems, and seals. They also behave as
53 hydrocarbon traps (Hansen and Cartwright, 2006; Jackson et al., 2013), causing
54 early maturation of hydrocarbons (Kennish et al., 1992; Hansen and Cartwright,
55 2006), increasing the hydrothermal aureole width (Svensen et al., 2004), and
56 remobilizing sand and fluid pipes (Svensen et al., 2006; Jamtveit et al., 2004). All
57 these volcanic processes create disturbances in the ? reservoirs, forming
58 hydrothermal vents with various architectures that relocate gas, mixed fluids, and

③ MEANING?
ODD
STATEMENT

④ VENTS ≠
INTRUSIONS

⑥ MAGMA
RESERVOIRS?
WHICH
RESERVOIRS?

⑤ NO VOLCANIC.
VOLCANIC OR MAGMATIC?



59 ^{FLUID} hot waters (Svensen et al., 2003; Procesi et al., 2019; Finn et al., 2022; Rovere
60 et al., 2022).

61 The hydrothermal vents are associated with igneous intrusions.

⑦ RELEVANCE?

62 However, the intrusive processes and rock parameters that control the pathways
63 and conduit architectures of these structures remain poorly understood, as most
64 interpretations are based on post-mortem seismic data analysis (Cartwright,
65 2010; Jamtveit et al., 2004; Planke et al., 2005; Svensen et al., 2006; Moss and
66 Cartwright, 2010b). The major uncertainty refers to what triggers the hydraulic
67 fracturing mechanisms that guide the nucleation and then propagation of the vent
68 formation. Other than intrusive systems, hydrothermal vents have been described
69 as developed by synsedimentary processes, or erosive fluidization (McDonnell et
70 al., 2007). Depending on the type of sills, intrusions trigger the overpressure
71 region (Svensen et al., 2006; Davies et al., 2012; Alvarenga et al., 2016). Other
72 uncertainties relate to the vent interactions with the seabed cap depending on its
73 geological nature and stratigraphy (Moss and Cartwright, 2010b).

⑧ POST-MORTEM?
SOME SEISMIC
DATA IMAGE
ACTIVE VENTS...

⑨ KIRKHAM ET AL.
AND OTHERS
HAVE
ADDRESSED
THIS ASPECT.

74 In vent complexes, the main pathways have been described by fluid
75 escape structures named fluid pipes, characterized by highly localized vertical to
76 sub-vertical pathways of focused fluid venting from some underlying source
77 region. The term fluid pipe was used as synonymous of gas chimney triggered
78 by a pressure cell, composed of a gas or mud source (Svensen et al., 2006). In
79 literature, the geometry of vents (both methane or hydrothermal) has been
80 classified based on cross-sectional and plan-view characteristics as dome-
81 shaped, eye-shaped, and crater forms (Planke et al., 2005; Cartwright and
82 Santamarina, 2015) (Fig. 1B). The relationship between vent boundaries and
83 surrounding strata have been defined, focusing on concordant, divergent, or



truncated patterns (Fig. 1B), but also using the internal reflections within vents
 (Hansen, 2006). In seismic data, vents (no matter their origin) can be measured
 by the diameters and lengths of conduits, checking the connections between sill
 terminations and upper vent regions identified as cylindrical zones of disturbed
 seismic data (Hansen, 2006; Maestrelli et al., 2017) (Fig. 1A and Fig. 1C).

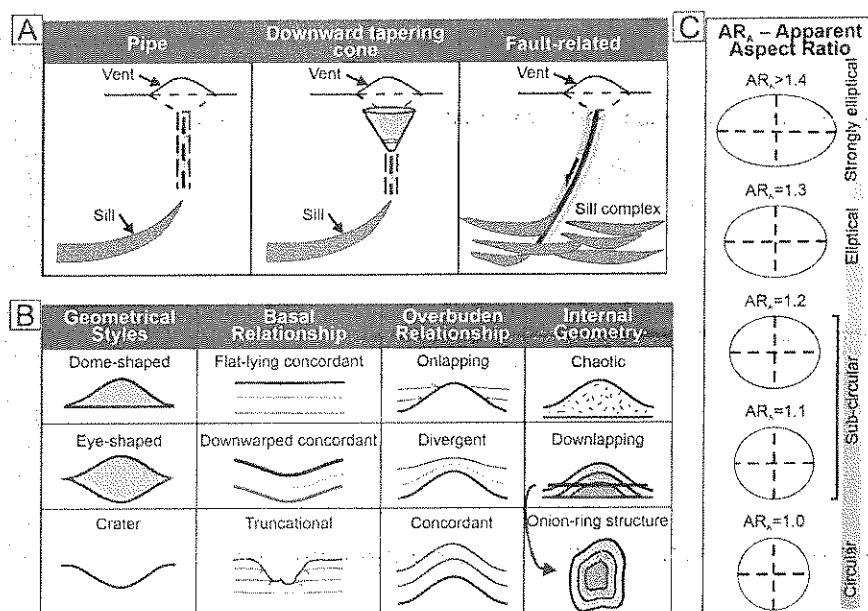


Figure 1 - Vent geometric parameters related to the external (A) and internal (B) shapes and the Apparent Aspect Ratio classification (C) related to the pipes ratio in a map view, which expresses the variation between circular to strongly elliptical shapes. (A), (B) and (C) were modified from Hansen et al (2006), Planke et al (2005), and Maestrelli et al (2017).

In all those contexts, seismic data represent a useful tool for identifying hydrothermal vents in several sedimentary basins (Planke et al., 2005; Hansen, 2006; Cartwright and Santamarina, 2015; Alvarenga et al., 2016; Kjoberg et al., 2017; Omosanya et al., 2018; Wang et al., 2019; Mituku and Omosanya, 2020).

10
 IS THIS
 A LITERATURE
 REVIEW OF
 A THESIS?
 IT GOES
 AROUND IN
 CIRCLES...



102 Seismic attributes have been applied to reveal hydrothermal chimneys, vents,
103 and structures around them, such as faults, fractures, folds, and sag structures
104 (Jackson et al., 2013; Plaza-Faverola et al., 2015; Omosanya et al., 2018; Rovere
105 et al., 2022). Vents associated with preexisting structures have also been
106 previously described as ducts forming at the tops of faults and classified as the
107 'fault-related' (Hansen, 2006; Maestrelli et al., 2017; Wang et al., 2019). These
108 vents typically exhibit a vertical pipe-like shape with a dome or mound at the top
109 (Alvarenga et al., 2016; Magee et al., 2016). Coherence attributes and
110 instantaneous phase were used to highlight the sag collapse structures
111 associated with polygonal faults, vents related to crestal faults, and fault-
112 controlled vents (Hansen, 2006; McDonnell et al., 2007; de Mahiques et al., 2017;
113 Omosanya et al., 2018; Mituku and Omosanya, 2020). However, these attributes
114 applied as tools for identifying vent complex geometry failed to recognize lateral
115 fluid injection features and hydrofractures.

11 NOT REALLY
NOVEL

116 Across several hydrothermal vent complexes, the mechanisms of
117 propagation and the processes of nucleation remain poorly understood. Key
118 scientific uncertainties include whether hydrothermal vent propagation is linked
119 to preexisting fault zones, the extent to which the final architecture is controlled
120 by fault systems, and whether some hydrothermal vents are entirely dependent
121 on overpressure-driven intrusive mechanisms. Another important consideration
122 is whether fault zones can later re-exploit the existing architecture of
123 hydrothermal vents. Additionally, the influence of host rock properties on the
124 development of vent architecture remains an open topic for investigation.

12 NOT
SOMETHING
YOU CAN
ADDRESS WITH
SEISMIC
DATA
ALONG

125 To answer the above questions, we selected the onshore part of the
126 Potiguar Basin, where previous studies identified outcrops with hydrothermal

ON
SEISMIC?



127 silicification related to faults (Menezes et al., 2019). This study aims to describe
128 and characterize the architecture and surrounding structures of hydrothermal
129 vents using 3D onshore seismic data from the Potiguar Basin. We identified and
130 seismically characterized 3 hydrothermal vents and 9 fluid pipes using seismic
131 attributes and extracted geobodies from 2 of them to better interpret their internal
132 architecture. Our interpretations suggest that all the hydrothermal vents are
133 associated with regional-scale faults, with their lateral extensions related to fluids
134 affecting sedimentary formations. The mapped structure suggests faults provide
135 the structural permeability, enhanced by the hydraulic fracturing, and leading to
136 the formation of hydrothermal vents. The result of this study contributes to a better
137 understanding of the hydrothermal vent propagation mechanism and silicification
138 process in sedimentary successions.

139

140 2. GEOLOGICAL SETTINGS

141 The Potiguar Basin is situated in the Brazilian Equatorial Margin (Pessoa
142 Neto et al., 2007) (Fig. 2). This passive margin basin formed during the Early
143 Cretaceous and exhibits a structural framework characterized by half-grabens
144 and horsts bounded by fault systems that reactivated shear zones in the
145 crystalline basement (Matos, 1992, 1999; de Castro et al., 2012). Its evolution
146 comprises three main depositional supersequences: rift, post-rift, and drift,
147 corresponding to distinct tectono-sedimentary phases (Bertani et al., 1990;
148 Pessoa Neto et al., 2007).

13 VERY
SMALL
DATA SET.
SEE
C. BIRKHAM (NILE)
C. ROELOFFSE (NORWAY +
GULF OF MEXICO)
+ MARINE GEOLOGY
PAPERS

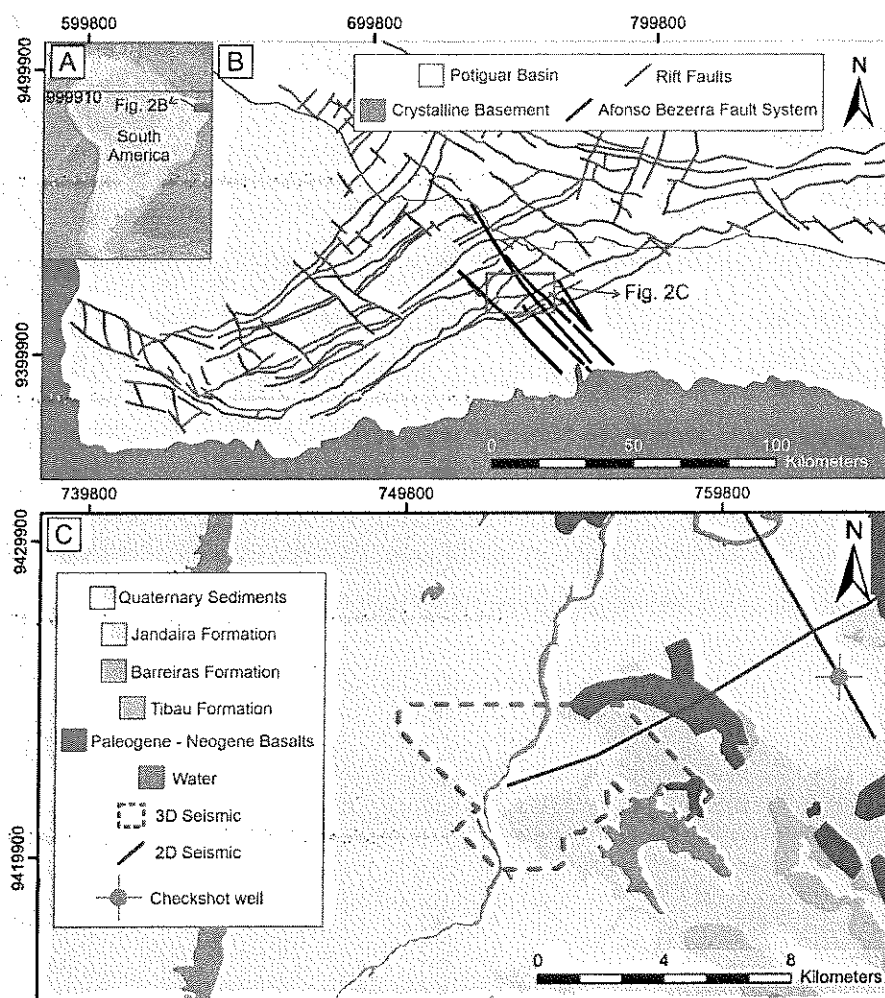


Figure 2 - (A) Study area located on the South American continent. (B) Geological map of the Potiguar Basin and (C) the study area with lithologies, and the seismic and well data location. Modified from Bertani et al. (1990), Bezerra et al. (2009), de Castro and Bezerra (2015).

The Potiguar basin rift phase coincides with the initial breakup of Pangea and the opening of the South Atlantic (de Castro, 2011; de Castro et al., 2014). This phase began during the early Valanginian, a stage characterized by intense crustal stretching, resulting in mechanical subsidence and the formation of



159 grabens (Araripe and Feijó, 1994; Fonseca et al., 2024). In this phase, the main
160 structure was the Carnaubais fault system, striking NE-SW and dipping E-W,
161 which resulted from the brittle reactivation of the Portalegre shear zone in the
162 basement (de Castro et al., 2012). The creation of grabens and horsts is related
163 to NE-SW-oriented linear features (Bertani et al., 1990). NW–SE-oriented
164 transfer and accommodation faults controlled the southern edge of the rift,
165 displacing the NE-SW-oriented faults in the Potiguar basin (de Castro et al.,
166 2012), such as the Afonso Bezerra Fault System (ABFS). The sedimentary
167 deposits formed during the rift phase varied from fluvial, lacustrine, and fan-
168 deltaic (from the Pendências Formation) to deltaic and fluvio-deltaic units (from
169 the Alagamar Fm) (Araripe and Feijó, 1994; Pessoa Neto et al., 2007).

170 The post-rift stage occurred in the early Albian, resulting from the breakup
171 and opening of the seafloor (Fonseca et al., 2024). This stage involves thermal
172 subsidence and the deposition of continental and marine sediments from the
173 Alagamar Fm (Pessoa Neto et al., 2007). During the early Albian–Holocene, the
174 drift phase was characterized by reduced subsidence rates driven by thermal and
175 isostatic mechanisms (Bertani et al., 1990). This last stage included transgressive
176 and regressive marine deposits (the Campanian-Maastrichtian Açú Fm), and
177 represents the transition from fluvial-estuarine to marine environments, overlaid
178 by the tidal-dominated carbonate shelf (the Turonian–Campanian Jandaira Fm)
179 (Pessoa Neto et al., 2007). The major unconformity marks the shift to
180 transgressive deposits, which include the Barreiras, Tibau, Guamaré, and
181 Ubarana formations, composed of siliciclastic to carbonate units (Pessoa Neto et
182 al., 2007). These deposits reflect environments ranging from coastal fans,
183 shallow platforms, and slope settings (Araripe and Feijó, 1994). The Afonso



184 Bezerra fault exhibits strike-slip and normal kinematics, affecting the rift and post-
185 rift units, where circulation of Si-rich fluids occurred (Menezes et al., 2019).

186 Three significant magmatic events shaped the basin: Rift-related dikes
187 date back to ~132 Ma (Pessoa Neto et al., 2007), while alkaline basalt spills from
188 the Cuó Volcanism occurred around ~93 Ma (Souza et al., 2004); and during the
189 Eocene/Oligocene the Macau Fm that represents later intrusions striking to N-S
190 (50–6 Ma) (Souza et al., 2019).

191 On the surface of our study area, the top of the pipes ~~structures~~ was
192 described before as a silicified fault zone (ABFS segment) in the lower carbonate
193 unit of the Potiguar Basin. This fault zone is complex and wide (up to 800 m),
194 featuring multiple episodes of silicification and brecciation. The silicified zone
195 includes partially silicified areas (angular fragments in a non-silicified carbonate
196 matrix) and fully silicified zones; the latter are subdivided into low-porosity (no
197 vugs) and high-porosity (with centimeter-scale vugs along fractures) sections.
198 Silicification completely replaced the carbonate mineralogy with quartz,
199 chalcedony, and opal, significantly increasing SiO₂ content (from 3–15% to 94–
200 97%) (Menezes et al., 2019). This study highlighted the heterogeneity of the fault
201 zone, where dynamic (syn-tectonic) and static (non-deformational) silicification
202 processes coexist, influencing reservoir quality.

→ (14) AS EXPECTED...
E.G. CRATERS, MOUNDS
OR PINNACLES

203

204 3. DATA AND METHODS

205 3.1 DATA



206 The study area encompasses 57 km² of the onshore Potiguar Basin (Fig.
207 2B). Subsurface data, including seismic and well logs, were provided by the
208 National Agency for Petroleum, Natural Gas, and Biofuels (ANP). We used
209 seismic reflection data from a 3D seismic survey and two 2D seismic lines. Data
210 from one well were used in this study to perform a seismic-to-well tie for seismic
211 interpretation. The well contains check-shot data and is located near one of the
212 2D seismic lines (Fig. 2B). The 2D seismic line passes through the well data with
213 check-shot information. The 3D survey has 429 inlines and 554 crosslines, where
214 these lines are oriented with NW-SE and NE-SW directions, respectively. The
215 seismic cube extends down to a 3002-ms with a 4ms sampling interval and is
216 prestack time-migrated. The 2D seismic lines were used in the lithostratigraphic
217 interpretation to transfer the well-lithostratigraphic information (Açu Fm and
218 basement tops) to the seismic cube area (Fig. 2).

219 3.2 Attributes analysis

220 To extract more information from the main reflectors, various attribute
221 analyses have been performed (e.g., Chopra and Marfurt, 2007). Three main
222 attributes have been applied: variance, cosine of phase, and dip illumination.

223 The variance attribute is a coherence attribute and is also considered a
224 reverse version of semblance, which has been used in previous applications to
225 indicate seismic breaks (Iacopini et al., 2012; Liao et al., 2019, 2020; Phillips et
226 al., 2019; Oliveira et al., 2023). These attributes calculate the similarity of seismic
227 waveforms between adjacent traces (time-lagged cross-correlation in both inline
228 and crossline directions) by estimating the coherence coefficient (Chopra and
229 Marfurt, 2007). Variance can therefore reveal differences between seismic traces



230 and transform a continuity volume into a discontinuity volume, highlighting
231 structural and stratigraphic boundaries (Brown, 2004; Mituku and Omosanya,
232 2020).

233 The cosine of phase attribute (Taner et al., 1979) is derived from the
234 instantaneous phase of the seismic signal and represents the cosine of the phase
235 angle. Unlike amplitude, the cosine of phase is less sensitive to amplitude
236 variations, rather emphasizing phase-related changes in the seismic signature.
237 The present study utilizes this attribute to reveal the lateral continuity between
238 hydrothermal vents and the surrounding layers. The literature has extensively
239 discussed the use of this attribute in the exploration of subtle discontinuities and
240 mapping reflector continuities (Barnes, 1996; Chopra and Marfurt, 2007), which
241 has been applied to improve the interpretation of various geological features,
242 such as channels (Sarhan and Safa, 2017).

243 We did use the dip illumination attribute (Wu and Chen, 2006), and this
244 seismic attribute simulates an illumination pattern revealing dip structure in the
245 timeslice and can highlight these dip differences, using shine or color variation
246 effect on a seismic map. Dip illumination is often used to detect structural features
247 such as faults, folds, and fractures in the rotated layers of seismic lines (Lisle,
248 1994; Hesthammer and Fossen, 1997). The attribute is very efficient on time
249 slices, and geological features are revealed when this attribute defines a
250 reflective surface on which a discontinuity measure is estimated (Chopra and
251 Marfurt, 2007). We used the dip illumination attribute to support the location and
252 mapping of each fluid pipe previously highlighted by the variance answer, which
253 enhances the scatter and discontinuities. The fluid pipes were then extracted into



254 bodies by isolating the variance answer, allowing the hydrothermal vents to be
255 visualized in a 3D perspective.

256 3.3 Apparent Aspect Ratio (ARA)

257 We used the Apparent Aspect Ratio (ARA), which is a quantitative
258 measure used to assess the plan-view geometry of fluid escape pipes identified
259 in 3D seismic data (Maestrelli et al., 2017). It is defined as the ratio between the
260 lengths of the long and short axes of a pipe's cross-section, measured along
261 seismic inlines and crosslines. Since these directions may not align with the true
262 maximum and minimum dimensions of the structure, the resulting value is only
263 an approximation of the actual elongation. For this reason, it is referred to as
264 "apparent" and cannot be directly used to infer regional stress orientations.
265 Despite this limitation, the ARA is useful for distinguishing between circular and
266 elongated pipe geometries. Values close to 1 indicate pipes with a nearly circular
267 shape, while higher values suggest elliptical or more elongated forms in plan
268 view. This distinction can provide important insights into the morphology and
269 potential development mechanisms of these features.

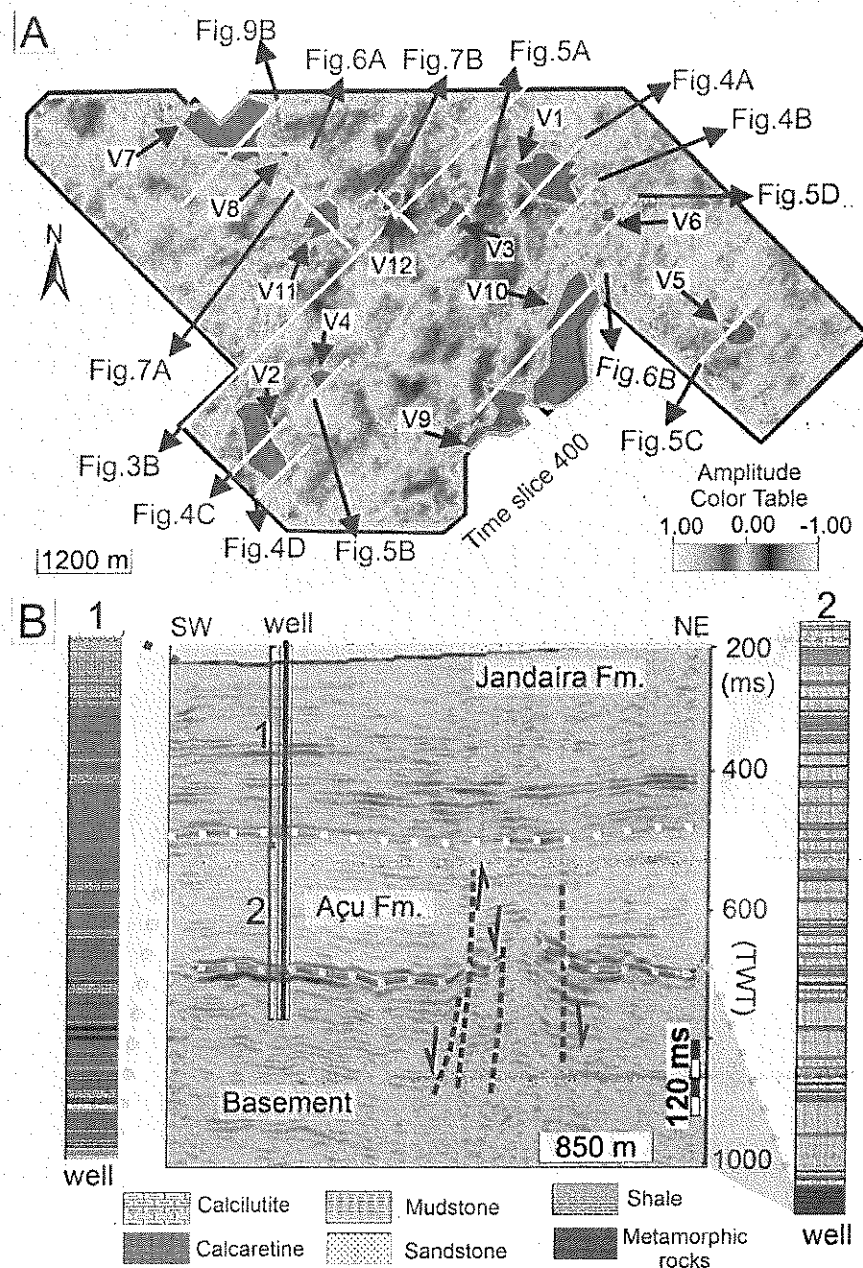
270 To calculate the ARA, measurements are performed on cross-sections
271 extracted from the seismic volume, typically at two different heights along the
272 pipe: one near its base and another closer to its upper termination. The long and
273 short axes are determined using orthogonal seismic slices—inline and crossline
274 directions—intersecting the pipe at those levels. The ratio between these two
275 axes yields the ARA value for that section. Pipes displaying highly irregular,
276 coalescing, or interacting geometries are excluded from analysis due to the
277 difficulty in defining consistent axis lengths along their conduit.



278 **4. RESULTS**

279 *4.1 Mapping by conventional seismic interpretation*

280 The study area comprises part of the onshore Potiguar Basin, featuring
281 a post-rift seismic unit and basement rocks. Two lithostratigraphic formations
282 (Açu and Jandaíra) are identified and described above the basement reflector
283 (Fig. 3B). The basement exhibits discontinuous, scattered reflectors, with its top
284 marked by green dots (Fig. 3b). This seismic facies is characterized by
285 continuous reflectors often disrupted by mound-like or convex structures intruding
286 the overlying unit, displaying strong amplitude anomalies. The Açu Fm, directly
287 overlying the basement, shows a coherent, homogeneous reflection pattern
288 intersected by straight columnar units (Fig. 4b) and diffuse structures with poorly
289 defined boundaries (Fig. 4a). The Jandaíra Fm, above the Açu Fm, displays more
290 continuous and homogeneous facies, interrupted by diffuse low-amplitude
291 anomalies. These amplitude anomalies present patchy disruptions in both
292 horizontal and vertical continuity. In seismic lines, these patches appear as
293 intrusive facies with chaotic reflectors cutting across the primary layering.



294
 295 Figure 3 (A) Vents locations in the normal amplitude at the time slice -400ms. Blue
 296 shapes represent vents shapes. Yellow lines – seismic sections interpreted location in



297 this study. V - Vents . (B) Lithostratigraphic interpretation of a vertical section based on
298 the well data. Vertical exaggeration: 5x.

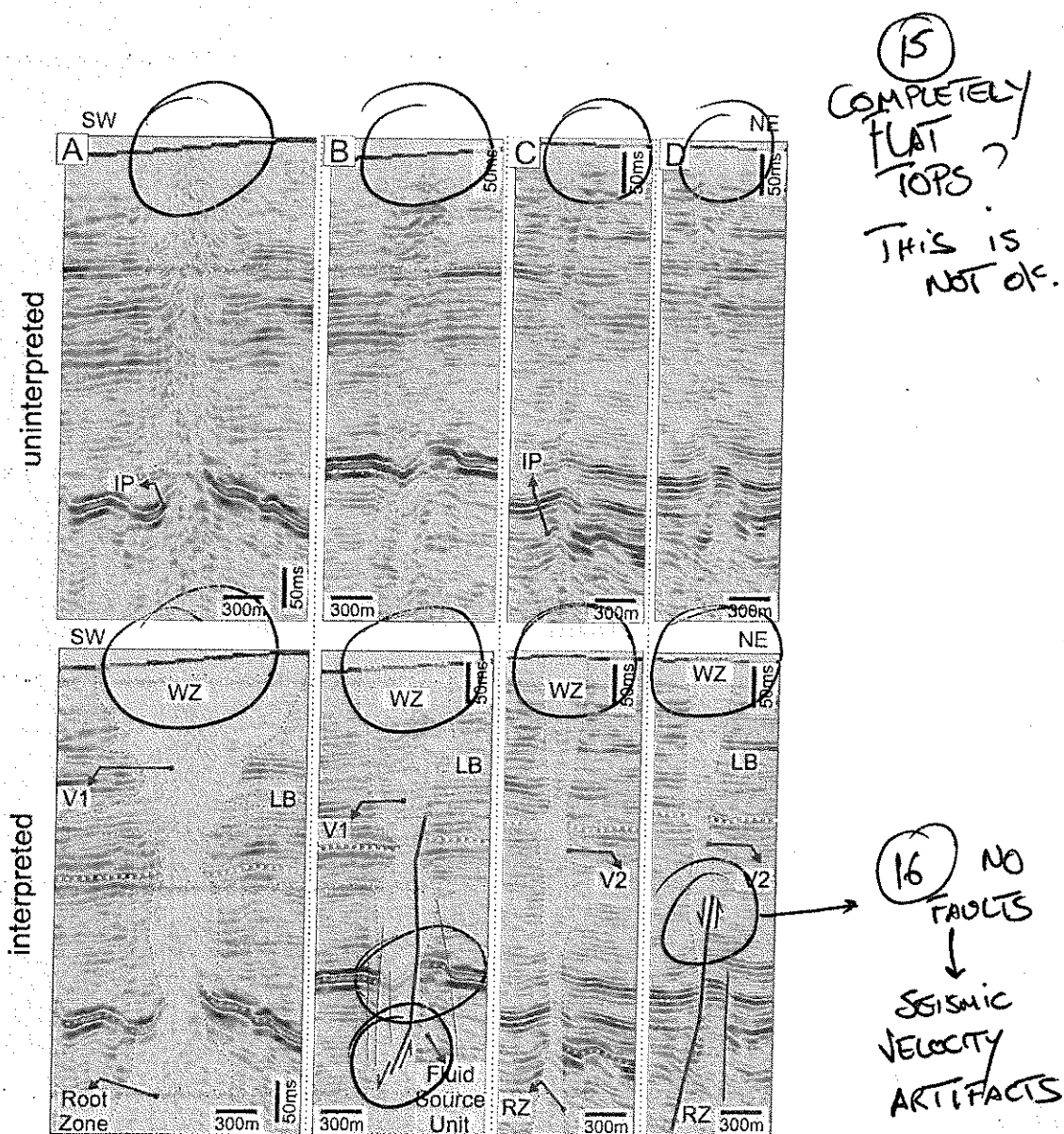
299 The discontinuous basement reflectors suggest a highly fractured or
300 heterogeneous igneous/metamorphic basement. The mound-like intrusions and
301 amplitude anomalies may indicate igneous bodies or fluid migration pathways.
302 The Açu Fm columnar and diffuse structures likely represent sedimentary
303 deposits influenced by syn- or post-depositional intrusions. The chaotic patches
304 in the Jandaíra Fm imply secondary processes such as fluid expulsion or soft-
305 sediment deformation.

306 *4.1.1 Characteristics of the hydrothermal vent complex*

307 We characterized the main columnar vertical seismic facies intruding the
308 main seismic package presenting deteriorated seismic signal, so the primary
309 reflections either are absent or very weak (we will call thereafter those zones as
310 wipe out zone, sensu Loseth et al., 2004) showing also edge discontinuities and
311 attenuation of the reflectors (Figs. 4, 5, 6, and 7). Both along inlines or crosslines,
312 some of these structures are represented by wipe out zones rimmed by an inner
313 zone of high amplitude anomalies and an outer zone of dim amplitude anomalies.
314 The various wipe out zones probably reflect various types of leakage processes
315 through the low-permeable zone, contrasting with the surrounding reflector
316 packages, where the disturbed zones stand out from the surrounding horizontal
317 reflectors (Fig. 4a,b, and 6a,b). Therefore, other seismic sections show instead a
318 more localized signal disturbance (Fig. 4c,d, and Fig. 5a,b), related to the leaking
319 from fault structures. In Figures 7a and b, we observe a large disturbance zone
320 broadening upward, making the signal interpretation near the surface difficult.
321 Interestingly almost all figures show within all columnar areas of the disturbance



322 zone upward convex deflection of the main reflectors (Figs. 4, 5, 6, 7). This
323 horizon deflection has been observed, except in some rare cases, with a different
324 degree of development. In some of the largest examples with large wipe out zone,
325 a chaotic expression of the seismic signal is visible: the reflection terminations of
326 the deflected horizons show a clear loss of amplitude and a disruption of the
327 internal architecture of the pipe.



328

329 Figure 4 - Characterization of the vents 1 and 2 (V1 and V2) with their elements: Wipe
 330 out Zone (WZ), Dead Mixed Zone (DMZ), Inflection Point (IP), and Lateral Brightness
 331 (LB). When the vertical disturber zone is surrounded by bright reflectors, we refer to wipe
 332 out zone. Yellow dotted lines - Açu Fm top, green dotted lines - Basement top. Vertical
 333 exaggeration: 5x.

334

The root zone indicates the fluid source unit, which is below the basement

335

top, and shows that those columnar wipe out zones are connected below the

336

basement top. In the more localized condition the wipe out zone is exploiting



individual normal faults (Figs. 4, 5, 6, and 7). In our study case, all those columnar
 seismic facies are often connected to faults showing a normal fault kinematic.

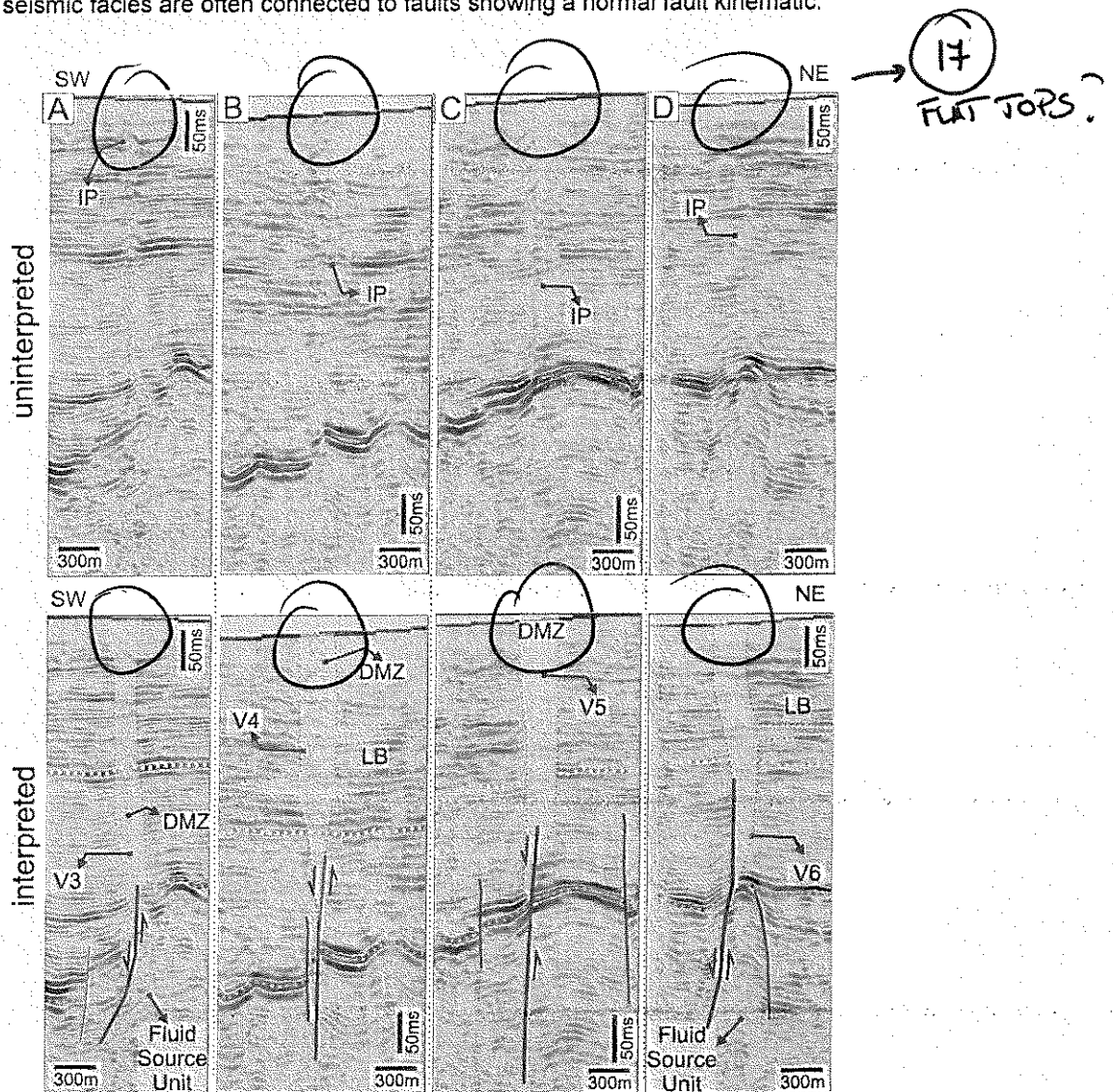
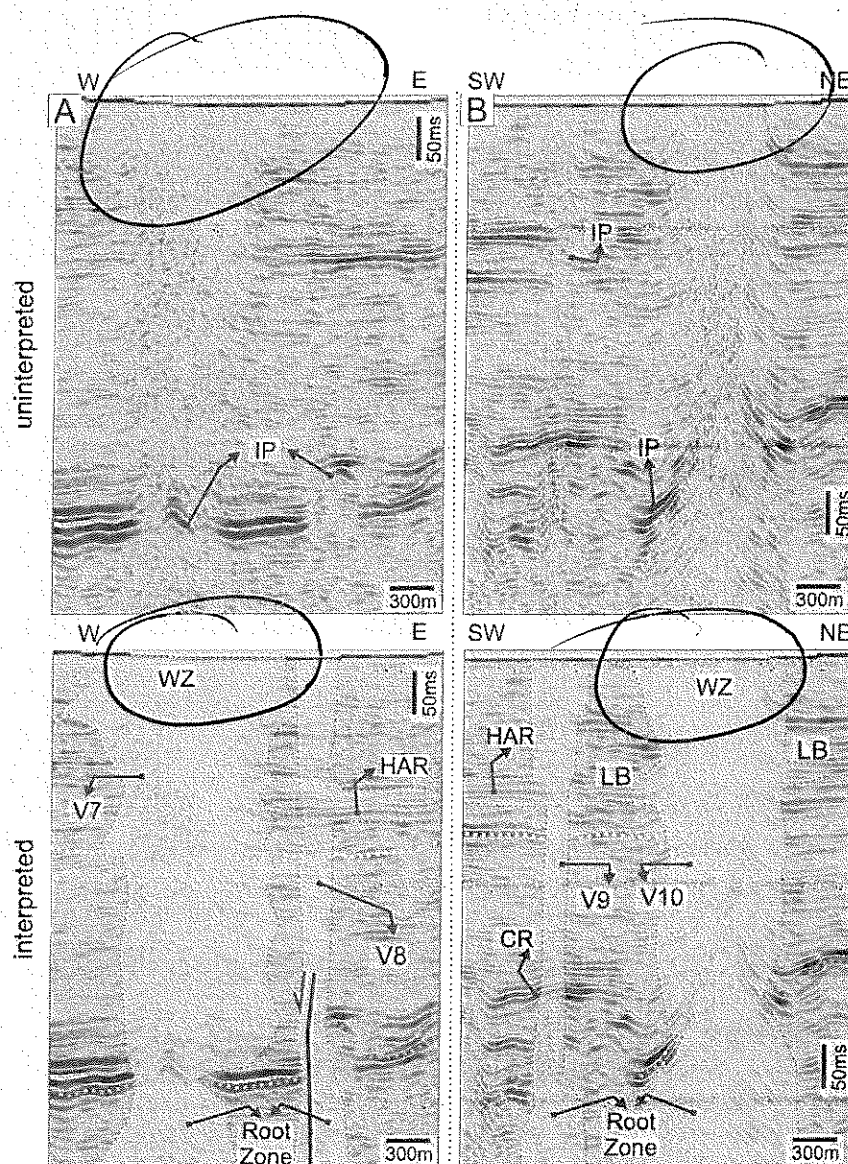


Figure 5 - Characterization of the vents (A) 3, (B) 4, (C) 5, and (D) 6 (V3, V4, V5, and V6) with their elements: Dead Mixed Zone (DMZ), Inflection Point (IP), and Lateral Brightness (LB). Yellow dotted lines - Açú Fm top, green dotted lines - Basement top. Vertical exaggeration: 5x.



344 Inside the main columnar wipe out zones, we can characterize some
345 further seismic details (V1, V7, V10). The WZ, which are disturbed and chaotic
346 zone, creates a zone of amplitude points or semi-continuous reflectors (Figs. 4,
347 6, and 7). The presence of inflection point (IP) of the seismic reflectors affecting
348 the beddings, producing reflectors with dome-shaped, suggesting push-ups,
349 which suggests a clear velocity changes in the seismic signal (Figs 4,5,6).



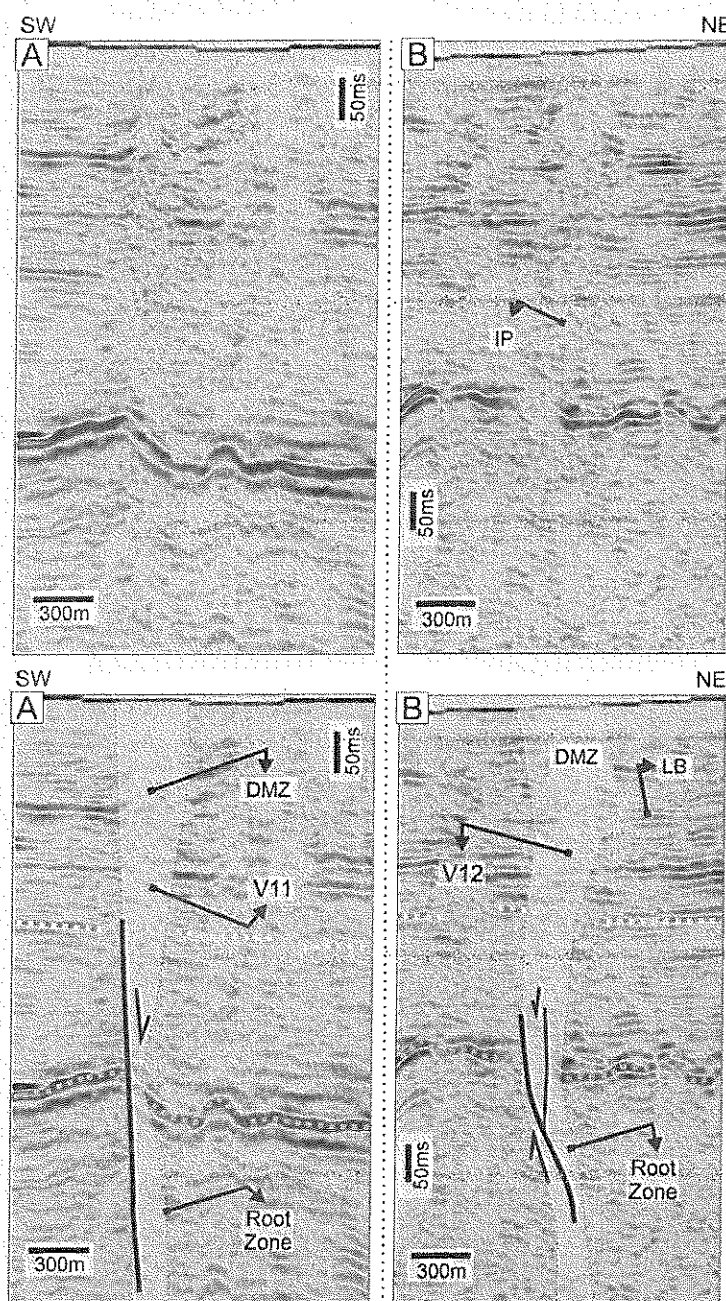
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351 Figure 6 - Characterization of the (A) vents 7 and 8 (V7 and V8) and
 352 10 (V10) with their elements: Wipe out Zone (WZ), Inflection Point (IP), Lateral
 353 Brightness (LB), High Amplitude Reflectors (HAR), and Coherent Reflector (CR). Yellow
 354 dotted lines - Açú Fm top, green dotted lines - Basement top. Vertical exaggeration: 5x.

355 The columnar wipe out zones with a 'downward tapering cone' (V1, V7,
 356 and V10) increase their width through the top, crossing all the formations of the
 357 basin up to the surface (Figs 4, 5, and 6), making it impossible to characterize



358 the vents terminus in our study area. Close to all pipes, we do recognize high
359 amplitude reflectors (HAR) and increasing their lateral brightness (LB) (Figs. 4,
360 5, 6, and 7).



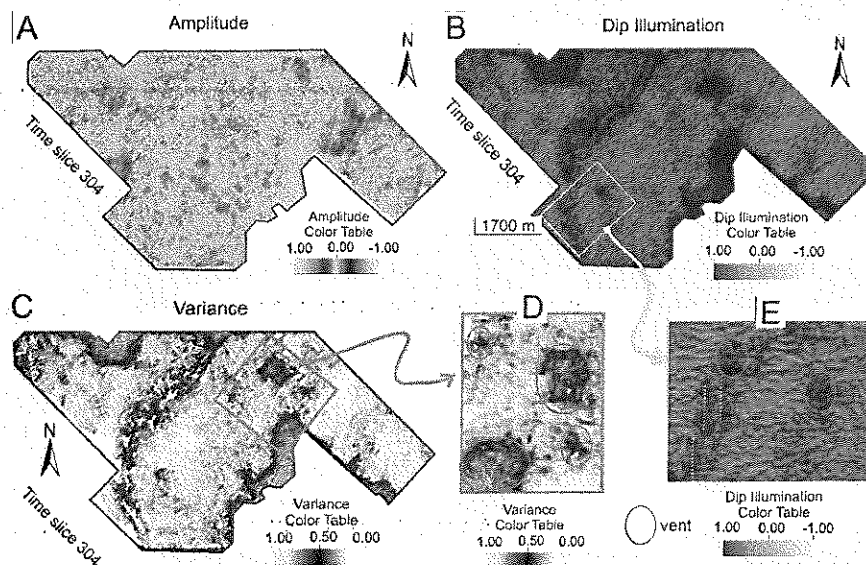
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362 Figure 7 - Characterization of the fluid pipes 8 and 9 (P8 and P9) with their elements:
 363 Dead Mixed Zone (DMZ), Inflection Point (IP), and Lateral Brightness (LB). Yellow dotted
 364 lines - Açu Fm top, green dotted lines - Basement top. Vertical exaggeration: 5x.
 365



366 4.2 Seismic Attributes

367 The application of seismic attributes such as dip illumination (Fig. 8B) and
 368 variance (Fig. 8C) confirms and enhances the signal anomalies corresponding to
 369 the wipe out zones, correlated to the vents, and to structures such as faults and
 370 fractures in their zones (Fig. 8D and E).



371
 372 Figure 8 - Comparison of the seismic answers between (A) amplitude, (B) dip
 373 illumination, and (C) variance, revealing (D) the vents or fluid pipes and (E) the
 374 surrounding structures at the time slice 304ms. White dotted line – fault traces.

375 In vertical sections, the variance answer cover a large area of the wipe
 376 out zone related to the vent structures and cover entirely the dead mixed zones
 377 from the fluid pipes (Fig. 9). The variance attribute completely covers the fluid
 378 pipe shapes with low width variation (Fig. 9) and loses some areas for the vents
 379 with a conical shape (Fig. 9B). This correspondence between the variance
 380 attribute and the dead mixed zones provides an automatic vertical
 381 characterization of the pipes. The variance attribute reveals areas related to the



vents and fluid pipes, showing a great correspondence compared with the manual interpretation of the vents, which is observed by combining the variance answer with the normal amplitude for the pipes.

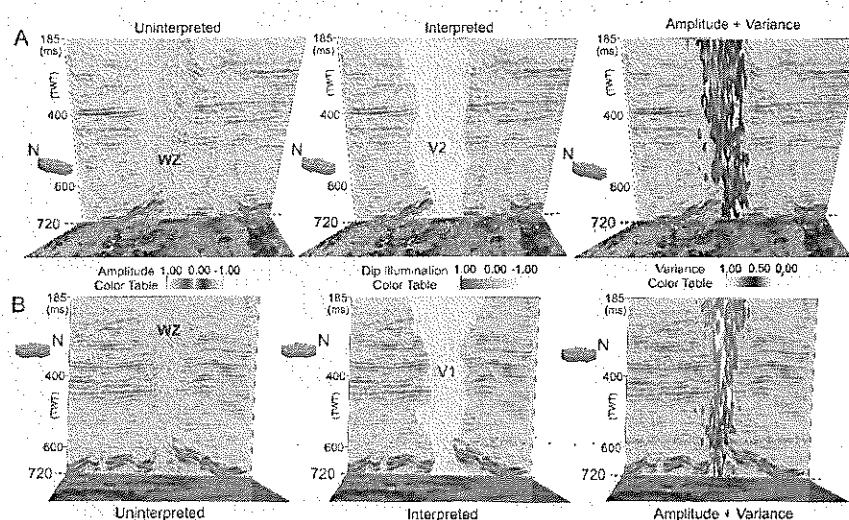
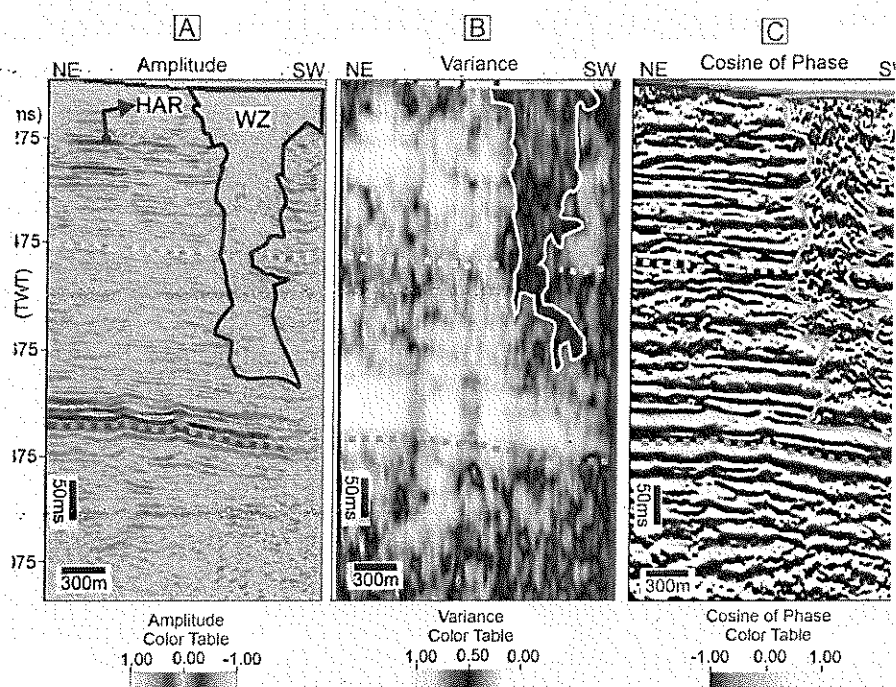


Figure 9 - External shape comparison between normal amplitude uninterpreted, interpreted, and variance attribute applied for the pipes V2 (A) and V1 (B). See Figure 3A for the location of the vents. Vertical exaggeration: 5x.

Even though applying the variance attribute is very effective in recognizing and characterizing hydrothermal vents, the vertical continuity of some fluid pipes can not be delimited (Fig. 10A and B). With the application of the cosine of phase attribute, the vertical and lateral continuity of the pipe anomalies caused by the seismic signal becomes more visible due to the contrast between the seismic facies pattern of the hydrothermal vents and the host rock. For some pipes, the shape of a 'christmas tree' becomes evident with the application of the cosine of phase (Fig. 10C), highlighting the variation in the lateral distribution of the fluid into the sedimentary formations.



398
 399 Figure 10 - Comparison of the pipe (V2) external shape between the normal amplitude
 400 (A), Variance (B), and Cosine of Phase (C) interpretation in a vertical section. See Figure
 401 3A for the location of the vents. Vertical exaggeration: 5x.
 402

403 Applying the cosine of phase attribute highlights the reflectors affected
 404 by the fluid, where the wipe out zone connect or penetrate the sedimentary
 405 formations of the basin (Fig. 11). The application of the cosine of phase attribute
 406 shows a new geometry of these structures, which are much more complex fluid
 407 bodies in a 3D perspective than previously highlighted by manual interpretations
 408 or compared to the variance attribute application.

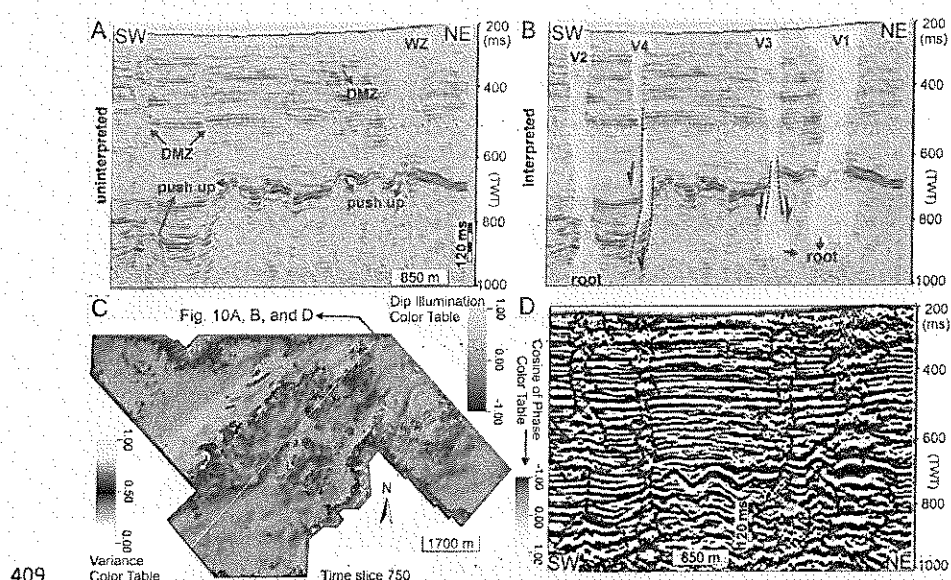


Figure 11 – Comparison between the fluid bodies geometry in (A) an uninterpreted vertical section, (B) with a manual interpretation of the vents and fluid pipes. (C) Time slice 750 ms applied Dip Illumination and Variance. (D) The cosine of phase attribute applied in the same seismic section. Vertical exaggeration: 5x.

4.3 Structural and geometric analysis of the wipe out zones

DIM ZONES?

We chose two wipe out zones to analyze the geometric parameters of the external shape. The graph of the pipes' geometrical parameters consisted of the values of the wipe out zones axes 1 and 2, in the direction of the inlines and crosslines (Fig 12B), as well as the apparent aspect ratio by measuring the maximum and minimum fluid structures axes (Fig. 12C). All the values were measured at different depth levels from the fluid structures geobodies based on the variance attribute (Fig. 12A). We choose to show the values in a graphs with a fixed horizontal axis due the comparison between wipe out zones results.

The values measured above the inlines are higher for both fluid structures (V1 and V2), which are, therefore, more elongated in the NW-SE direction. For V1, the values of the axes in the inline and crossline directions are close to each



other (from 120m to 820m) in the inline direction, thus showing more dispersion
of the data on the graph (Fig. 12B). The smaller axis of the V2 pipe is in the
direction of the crossline (NE-SW) where its values vary from 120 to 450 m.

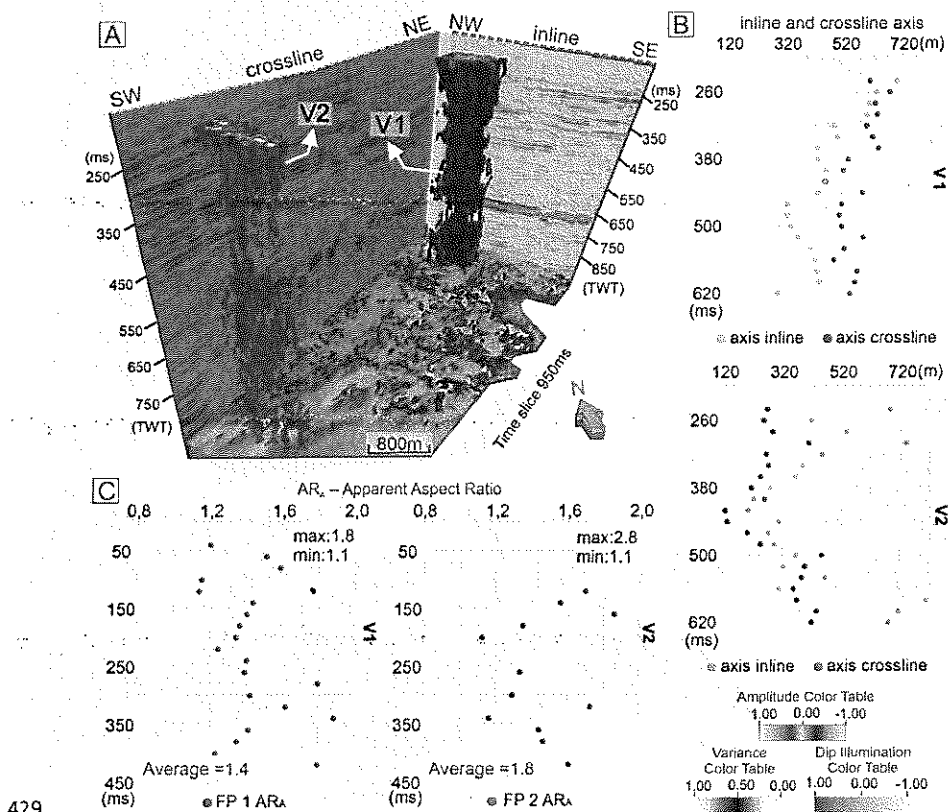


Figure 12 - (A) Geobodies of the vents 1 and 2 extracted based on the variance attribute. The graphs display the fluid pipe axis in inline and crossline directions (B) and their Apparent Aspect Ratio (ARA) to understand the fluid structures ellipticity in different levels. Vertical exaggeration: 5x.

We used the ARA to verify the ellipticity of the fluid structures. Based on Maestrelli et al. (2017), the apparent aspect ratio (ARA) was calculated as the ratio of the long axis to the short axis, approximating the pipe's elongation in plan view (circular if $ARA \approx 1$, elliptical if $ARA > 1$). The values calculated from the maximum and minimum axes for the apparent aspect ratio exhibit greater



440 dispersion for the V2 pipe, with the opposite behavior observed in the V1 graph
441 (Fig. 12C). The maximum radius values for V2 reach 2.8, which is 2 times the
442 length of V1, with values of 1.8. This demonstrates a strongly elliptical
443 classification of both pipes, with an ARA average of 1.4 and 1.8 for V1 and V1,
444 respectively. With this, the axis elongation striking to NW-SE for both pipes shows
445 a greater directional control in the V2 values.

446 5. DISCUSSION

447 5.1 Geometry of the hydrothermal vents complex and fault systems

448 Previous studies associate hydrothermal vent complexes with faults,
449 describing them as *pipe fault-related* (Planke et al., 2005) or fluid conduits
450 (Magee et al., 2014; Rovere et al., 2014), often linked to structures above and
451 around vents (Hansen, 2006; Kjoberg et al., 2017) or gas ascent within polygonal
452 fault systems (Rovere et al., 2022). Our seismic analysis identifies "wipe-out
453 zones" and "dead mixed zones" (Figs. 4–7), characterized by reflectors
454 attenuation and internal chaotic pattern, and revealing that all analyzed pipes are
455 associated with fault activity. This suggests their formation cannot be attributed
456 solely to hydraulic fracturing or igneous intrusion-related pressure (Skogseid et
457 al., 1992; Davies et al., 2002, 2012; Aarnes et al., 2010). Our description shows
458 these vents are structurally controlled by regional faults, with root zones
459 extending below the basement, indicating a fluid source within the crystalline
460 basement. Surface studies by Menezes et al. (2019) corroborate this, showing
461 the NW-SE Afonso Bezerra Fault System (active from rift to post-rift phases)
462 cutting through the basin and basement. Seismic interpretation further reveals
463 fluid conduits elongated along fault trends (Figs 12), with "inflection points" (IP)

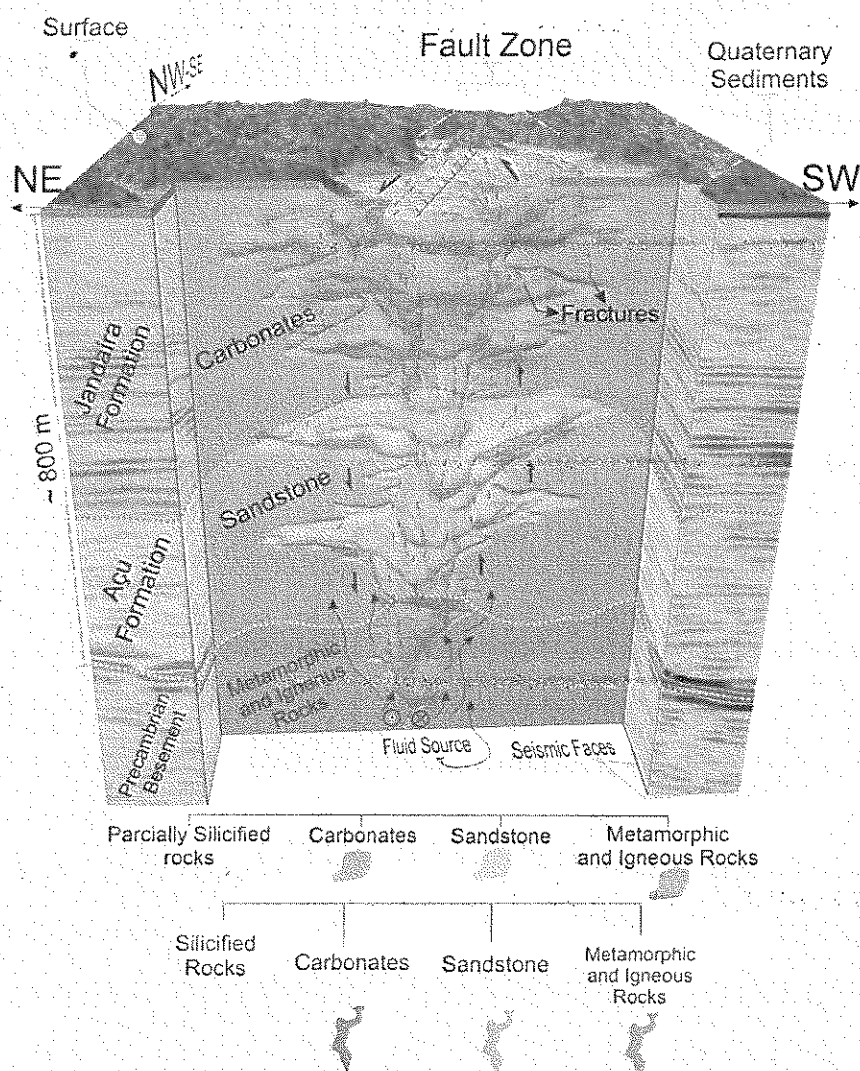


464 forming dome-shaped geometries (Figs. 4–7), indicative of fluid ascent altering
465 sedimentary layers. The internal signal and edge reflectors related to the vents
466 show a push-up geometry, mostly dragging upward the main reflector (Figs. 4, 6,
467 and 11), which suggests a denser intrusive unit, distinguishing it from a simple
468 gas intrusion. Therefore, this is typical of hydrothermal rock or intrusion, which
469 produces mineralization often re-fractured but the various intrusions. These
470 conduits align with surface silicified breccias (Menezes et al., 2019), confirming
471 their hydrothermal origin. Additionally, magmatic activity in the Potiguar Basin
472 (e.g., Macau and Serra do Cuó events; Mizusaki et al., 2002; de Castro et al.,
473 2012; Souza et al., 2019) likely contributed to thermal anomalies and sedimentary
474 alteration, facilitating vent genesis.

475 The application of the cosine of phase attribute with the lateral brightness
476 recognition (see LB in Figs. 4A, B, C, 5B, D, 6B, and 7B) reveals the vent fluids
477 entering laterally in the sedimentary layers, changing the vents geometry (Fig.
478 13). The interaction between hydraulic fracturing, overpressure, and faults must
479 be considered for a more comprehensive understanding of the genesis of the
480 pipe systems, since structures as faults change the permeability influencing fluid
481 flow (Caine et al., 1996; Faulkner et al., 2010; Palhano et al., 2023), acting as
482 seals or conduits (Fisher et al., 1998; Bense et al., 2013; Torabi et al., 2021;
483 Medici et al., 2021; Labry et al., 2025). Although previous studies suggest that
484 hydraulic fracturing is a fundamental mechanism for the initiation and control of
485 vent formation (Svensen et al., 2006; Alvarenga et al., 2016), we highlight that
486 the development of brittle structures such as faults plays a crucial role in this
487 process (Fig. 13). This implies that the evolution of the vents should be



488 interpreted in a broader tectonic context, where faults act as preferential
 489 pathways for fluid migration and control their ascent and escape.



490

491 Figure 13 - The schematic model of fluid pipes ascending through the sedimentary basin
 492 controlled by a fault. Red traces - fractures.

493 Sedimentary basins that feature fluid pipes or hydrothermal vents, such
 494 as those in the Gulf of Mexico (Roberts and Carney, 1997; Aharon, 1994), the



495 North Sea (Cartwright et al., 2007; Løseth et al., 2009), the Santos Basin
496 (Camboa and Rabinowitz, 1981; Mohriak et al., 2008), and the Campos Basin
497 (Guardado et al., 1989; Bruhn and Walker, 2006), are characterized by dynamic
498 geological systems where the circulation of thermal fluids plays a crucial role in
499 rock modification and the generation of petroleum systems (Palhano et al., 2023;
500 Maciel et al., 2024). In these basins, fluid pipes are often associated with tectonic
501 and magmatic processes, creating migration pathways for hydrocarbons and
502 contributing to the formation of structures such as sandstone dykes and
503 hydrothermal alteration zones.

504 *5.2 Seismic data limitation in the vents characterization*

505 The hydrothermal vents are described in their parts as inner and outer
506 zones based on the composition and structures of the vent outcropping, and how
507 they affect the host rock (Jamtveit et al., 2004; Svensen et al., 2006). These vent
508 zone descriptions allow the characterization of the fluid zones in terms of origin,
509 host rock permeability, fluid pressure, and pipe complexity (Planke et al., 2005),
510 where these zones were measured and analyzed using field data in previous
511 studies. In the literature, major hydrothermal vent complex characterization has
512 been conducted using seismic data by applying coherence attributes to reveal
513 these structures (Svensen et al., 2003; Hansen, 2006; Kjøberg et al., 2017; Wang
514 et al., 2019). In our case, we used seismic attributes such as variance, dip
515 illumination, and cosine of phase to distinguish the disturbed zones from the fluid
516 pipes and the host rock in the seismic data (Figs. 8, 9, 10, and 11), but even with
517 this, it is impossible to define the internal vent zones as other previous studies
518 (McDonnell et al., 2007; Magee et al., 2016; Mituku and Omosanya, 2020; Chen



519 et al., 2021). Therefore, the data resolution still limits the characterization of fluid
520 pipe zones in the seismic data.

521 Coherence attributes alone can highlight other geological features
522 besides faults (e.g., channel edges) or artifacts, and therefore need to be
523 geologically validated. In our fluid pipes interpretation, it is evident that the fluid
524 pipe detection in seismic data and the seismic attributes applied, such as
525 variance and dip illumination, are particularly sensitive to these discontinuities
526 (Figs. 8, 9, 10, and 11). We used seismic data from a shallow sedimentary
527 package of the Potiguar Basin onshore portion, which presents noise or NR areas
528 close to the surface or inside the basement, making the geometric
529 characterization of the vents difficult. Among various seismic attributes, those that
530 emphasize discontinuities between seismic reflectors or geological horizons are
531 the most suitable ones for imaging faults (Chopra and Marfurt, 2005; Di et al.,
532 2019; Libak et al., 2017; Oliveira et al., 2023) and vent complex areas as
533 disturbed zones. However, the presence of noise poses a significant challenge
534 and is very impacted to noise and no disturbance of the reflectors, as it can
535 adversely affect the accuracy and reliability of seismic attribute results (Cohen et
536 al., 2006; Hale, 2013; Wu et al., 2019).

537 6. CONCLUSIONS

538 Our results demonstrate that hydrothermal vent development in the
539 Potiguar Basin is fundamentally controlled by fault activity, particularly the Afonso
540 Bezerra Fault System. The strongly elliptical and elongated vent geometries
541 aligned with fault trends contribute to the previous models that attribute vent
542 formation solely to hydraulic fracturing from igneous intrusions. Instead, we
543 propose a hybrid model where faults act to guide the fluid pathways, modify



544 permeability, and change the vent morphology. Fault zones not only localize
545 vents but also enhance reservoir-scale permeability, with implications for
546 hydrocarbon migration and hydrothermal mineralization.

547 The association of vents with regional fault systems suggests their
548 formation is intrinsically linked to the basin's rift-related tectonic framework. This
549 aligns with global analogs (e.g., Gulf of Mexico, North Sea), where vents develop
550 along fault zones in magmatically active basins. The Potiguar Basin's silicified
551 breccias and magmatic events (e.g., Macau and Serra do Cuó) further support a
552 tectonic-magmatic interplay in the vent development.

553 While seismic attributes (variance, dip illumination, and cosine of phase)
554 effectively delineate vent boundaries and disturbed zones, they cannot resolve
555 internal vent zonation (e.g., inner/outer zones) observed in the field studies.
556 Discontinuity-based attributes (e.g., coherence) are sensitive to vent structures
557 but require geological validation to distinguish vents from other features. Variance
558 and dip illumination proved most robust for mapping fault-vent relationships,
559 though noise in shallow sedimentary sections limits geometric precision. Data
560 resolution and near-surface noise remain key challenges, emphasizing the need
561 for integrated approaches combining seismic, well, and outcrop data.

562 **Author Contribution**

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566 Roles/Writing - original draft; and Writing - review & editing

567 **D.I.:** Conceptualization; Investigation; Methodology; Formal analysis; Validation;
568 Visualization; Roles/Writing - original draft; and Writing - review & editing

569 **F. B.:** Conceptualization; Investigation; Methodology; Supervision; Validation;
570 Visualization; Roles/Writing - original draft; and Writing - review & editing



571 **A. T.:** Conceptualization; Formal analysis; Investigation; Methodology;
 572 Supervision; Validation; Visualization; Roles/Writing - original draft; and Writing
 573 - review & editing

574 **B. A.:** Conceptualization; Formal analysis; Investigation; Methodology;
 575 Supervision; Validation; Visualization; Writing - review & editing

576 **J.F. de S.N.:** Investigation; Methodology; Validation; Visualization;

577 **P. E. F. M.:** Visualization; Writing - review & editing

578 **D. L. V.:** Writing - review & editing;

579 **V. La B.:** Writing - review & editing;

580 **F. H. R. B.:** Conceptualization; Investigation; Methodology; Resources; Project
 581 administration; Supervision; Validation; Visualization; Roles/Writing - original
 582 draft; and Writing - review & editing.

583 **The authors declare that they have no conflict of interest**

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 588 Porocarste Fase II" (UFRN/UNB/UFPE/UFC/UFRA/IFRN/IFPB/Shell Brasil/ANP)
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593

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