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Citation for final published version:

Qin, Yongpeng, Alves, Tiago M. , Constantine, Jose Antonio, Gamboa, Davide and Wu, Shiguo 2020. The effect of channel tributaries on the evolution of submarine channel confluences (Espírito Santo Basin, SE Brazil). GSA Bulletin 132 (1-2) , pp. 263-272. 10.1130/B35082.1

Publishers page: <https://doi.org/10.1130/B35082.1>

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The effect of channel tributaries on the evolution of submarine channel confluences (Espírito Santo Basin, SE Brazil)

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ABSTRACT

Confluences are geomorphologic features fed by distinct channel tributaries and record the contribution of multiple sediment sources. They are key features of both fluvial and submarine channels in geomorphologic and sedimentologic terms. Here, we use high-quality 3D seismic data from SE Brazil to document the response of a submarine channel confluence to turbidity currents sourced from a tributary. The studied channel system consists of a west tributary, an east tributary and a post-confluence channel, with the last two comprising the main channel at present. Downstream

from the confluence, a series of changes in planform morphology and architecture were found due to the effect of turbidity currents sourced from the west tributary channel. A channel bend in the main channel curved toward the west when it was first formed but later curved toward the east, and so remained until the present day. This process led to the migration of the confluence point ~500 m to the east, and changed its bed morphology from discordant (the beds of tributaries and main channels meet at an unequal depth) to concordant (the beds of tributaries and main channels meet at approximately the same depth). In addition to the channel bend near the confluence, two other bends further downstream record significant changes with time, increasing channel sinuosity from 1.11 to 1.72. These three channel bends near the confluence accumulated a large volume of sediment at their inner banks, generating depositional bars. Multiple channel forms within the depositional bars indicate the occurrence of large-scale lateral migration near the confluence. Hence, turbidity currents from the west tributary are shown to influence submarine channels by promoting lateral channel migration, confluence migration, increases in channel sinuosity, and the formation of large depositional bars. The above variations near the confluence reveal a change in tributary activity and a shift in sediment sources from east to west on the continental shelf. Such a shift suggests variations in sedimentary processes on the continental shelf but with unclear causes.

Keywords: SE Brazil; Submarine channel; Confluence; Tributary; Lateral migration; Sediment supply

INTRODUCTION

Confluences mark the locations where two channels meet to accommodate water and sediment

47 flows from distinct tributaries (e.g. Best, 1987; Ferguson and Hoy, 2008; Ismail, 2017). In fluvial
48 channels, the varied depositional records upstream and downstream of confluences reflect the
49 contribution and provenance evolution of their tributaries (e.g. Constantine et al., 2014; Munack et
50 al., 2014; Jonell et al., 2017). On the Tibetan plateau and Himalayas, for instance, geochemical and
51 sediment-composition analyses of fluvial channel confluences were used to demonstrate variations in
52 the denudation rates of mountain ranges due to climatic, glacial and tectonic events (Munack et al.,
53 2014; Jonell et al., 2017; Munoz et al., 2019). In submarine settings, channels are conduits that
54 transport sediment from land sources to the deep sea (e.g. Kolla et al., 2007; Jobe et al., 2015).
55 Sedimentary records from submarine-channel tributaries and associated confluences reflect variations
56 in the hydrodynamics of turbidity currents sourced from different parts of continental margins. In
57 tectonically active regions such as the Cascadia Margin, North America, turbidite sequences cored
58 upstream and downstream of channel confluences are key for recognising the main triggers of
59 turbidity currents (Goldfinger, 2011; Atwater et al., 2014). Some submarine confluences indicate
60 variations in sedimentary processes on the continental shelf (Jobe et al., 2015; Hansen et al., 2017).
61 Offshore the Niger Delta, the occurrence of a submarine channel tributary and a new confluence may
62 have caused by an avulsion of rivers on Niger Delta (Jobe et al., 2015).

63 Submarine channel confluences are well documented on continental margins such as West Africa
64 (e.g. Pirmez et al., 2000; Hansen et al., 2017), in North and South America (e.g. Greene et al., 2002;
65 Mitchell, 2004; Paull et al., 2011; Gamboa et al., 2012), offshore Japan (Noda et al., 2008), and in
66 New Zealand (Micallef et al., 2014). On the Atlantic continental slope off New Jersey, Mitchell (2004)
67 observed that tributary canyons tend to be steeper near their confluences than main slope canyons.
68 Similar patterns have been documented in other parts of the USA (Greene et al., 2002), offshore Japan
69 (Noda et al., 2008), in New Zealand (Micallef et al., 2014) and Nigeria (Hansen et al., 2017). In SE

70 Brazil, the gradients of tributaries and main channels are nearly the same for the Miocene-Quaternary
71 Rio Doce Canyon System (Gamboa et al., 2012). However, channel width and height increase
72 downstream of an Early Miocene channel confluence in the same area considered in this paper (Fig.
73 1). In Nigeria, a decrease in channel size is recorded downstream of a channel confluence (Jobe et al.,
74 2015), contrasting with the information in Gamboa et al. (2012). Further data from offshore Nigeria
75 recorded changes in channel pathways, and associated sinuosity, near submarine confluences: a) Jobe
76 et al. (2015) described the straightening of a submarine channel downstream of a confluence and
77 attributed it to ‘underfit’ flows sourced from a tributary, b) Hansen et al. (2017) documented a marked
78 difference in channel sinuosity between a relatively straight tributary (Upper Avon channel) and a
79 sinuous post-confluence channel (Lower Avon channel). This increase in sinuosity relates to the
80 presence of an inherited, but presently inactive, main channel (Hansen et al., 2017).

81 Morphologic changes in submarine confluences reflect the complex hydrodynamics of
82 submarine channels. Variation in flow dynamics at confluences is probably one main cause for such
83 complexity. For example, there are three possible scenarios when considering flow dynamics at
84 submarine channel confluences (Gamboa et al., 2012): a) confluences showing an active tributary and
85 an active main channel (e.g. Gamboa et al., 2012), b) confluences between an active tributary and an
86 inactive main channel (e.g. Jobe et al., 2015), and c) confluences dominated by an active main channel
87 and an inactive tributary (e.g. Pirmez et al., 2000). Furthermore, tributary flows are able to reactivate
88 abandoned or inactive submarine channels, in which case pattern b) above can be inferred (Jobe et
89 al., 2015; Hansen et al., 2017). Numerical simulations and experimental studies show that junction
90 angles are critical to flow hydrodynamics in submarine confluences (Ismail, 2017). Increases in
91 junction angle from 30° to 90° lead to an increase in the peak front velocity and front thickness of
92 turbidity currents (Ismail, 2017).

Although the morphology and architecture of submarine channel confluences have been extensively documented (Mitchell et al., 2004; Gamboa et al., 2012; Jobe et al., 2015; Hansen et al., 2017), little attention has been paid to: a) confluence evolution through time, and b) the responses of confluences to turbidity currents sourced from channel tributaries.

This work reconstructs the temporal variations in submarine channel morphology around a Pliocene-Quaternary confluence offshore Espírito Santo Basin, SE Brazil (Fig. 1). The studied channel system is commonly named *Rio Doce Canyon, or Channel System*, in the literature (Qin et al., 2016). It is only partly filled by sediment and comprises two tributaries upstream, and a post-confluence channel downstream (Fig. 1B). The continuity of sedimentary infill patterns between the east tributary and the post-confluence channel, as well as their continuous channel thalwegs, indicate that these two channel segments are the main flow pathway at present (Gamboa et al., 2012). There has been a detailed description of spatial changes in morphologic characters of this channel system (Gamboa et al., 2012, Qin et al., 2016), however, the architecture and the temporal evolution of the channel system and the confluence region were not fully addressed in previous work.

We aim at analyzing how submarine channels adjust their morphology and architectures in response to turbidity currents sourced from tributaries. Hence, this paper provides a case study documenting: 1) temporal variations in submarine channel morphology near confluences, and 2) the depositional architecture of a submarine channel system around its confluence region.

DATA AND METHODS

The interpreted 3D seismic volume covers 1600 km² of the northern Espírito Santo Basin, SE Brazil (Fig. 1A; Alves et al., 2009), and has a bin spacing of 12.5 m by 12.5 m, with a 2 ms vertical

116 sampling interval. The vertical resolution of the seismic data is ~10 m at the depth of analysis in this
117 study, based on a dominant frequency of 40 Hz and a P-wave velocity of 1600 m/s for near-seafloor
118 strata. This vertical resolution improves to ~ 5 m on the sea floor. A water-column velocity of 1480
119 m/s is used for time-depth conversions of seafloor features.

120 Channel depth was measured at intervals of 125 m at the channel thalweg (i.e. the deepest point
121 of channels) along the west tributary and the main channel. The cross-sectional area of the channel
122 system (CSA_E), and cross-sectional area of deposits within the channel system (CSA_D), were
123 calculated at intervals of 1 km along the main channel (i.e. east tributary and post-confluence channel)
124 and exclude overbank deposits (Fig. 2), which may have similar seismic facies to deposits that are
125 not related to channels, and induce errors in geomorphologic calculations. The parameter CSA_E
126 indicates the size of the channel system generated by erosional processes. In turn, CSA_D concerns the
127 sediment volumes accumulated by depositional processes within the channel system. Sediment
128 volume is calculated as CSA_D multiplied by distance along the channel, and is proportional to CSA_D .

129 The depositional ratio, defined as CSA_D/CSA_E , is used here to quantify sediment dispersal
130 patterns in the studied channel system. This ratio quantifies the percentage of the area filled by
131 deposits at pre-selected sections across the channel system. As flows may deposit more sediment in
132 locations where erosion has produced more accommodation, CSA_D is normalized by CSA_E in order
133 to eliminate the influence of CSA_E on deposition.

134

135 **GEOLOGIC SETTING**

136

137 **Tectono-sedimentary evolution of the Espírito Santo Basin**

138

139 The Espírito Santo Basin is located on the continental margin of SE Brazil, between the Abrolhos
140 Bank and the Campos Basin (Fig. 1A). The development of the Espírito Santo Basin is related to the
141 breakup of the Gondwana supercontinent (Ojeda, 1982; Mohriak, 2008), with three main tectono-
142 stratigraphic megasequences filling the basin: syn-rift, transition and drift (França et al., 2007). The
143 ‘syn-rift’ megasequence spans the Late Berriasian to Early Aptian and comprises fluvial-lacustrine
144 sediments (Ojeda, 1982). The transitional megasequence spans the Middle Aptian to Late
145 Aptian/Early Albian and is composed of thick evaporites and marine carbonates (Ojeda, 1982). Thick
146 salt was deposited at this time to be later deformed into various salt structures (e.g. salt rollers, salt
147 diapirs and salt canopies) by gravitational gliding and differential loading (Fiduk et al., 2004). Salt
148 structures controlled deposition in great part of the Espírito Santo Basin, deforming carbonates
149 accumulated in the transitional megasequence and marine strata of Late Aptian/Early Albian to
150 Holocene age (Ojeda, 1982).

151 In the study area, two salt ridges bound a NW-SE salt-withdrawal basin containing large-scale
152 depositional elements such as mass-transport deposits (MTDs), turbidite lobes, submarine canyons
153 and channels (Gamboa and Alves, 2015). The distribution and geometry of these depositional
154 elements are closely related to the location of seven (7) distinct salt diapirs that grew close to the
155 modern sea floor (Alves et al., 2009; Gamboa et al., 2012; Gamboa and Alves, 2015).

156

157 **Sources of sediment to submarine channels**

158

159 In the Espírito Santo Basin, one possible terrestrial sediment source for the interpreted submarine
160 channels is the Rio Doce (Fig. 1A). This river has an annual suspended-sediment flux of 11×10^6
161 ton/year (Lima et al., 2005), and an annual average discharge of $900 \text{ m}^3/\text{s}$ (Oliveira et al., 2012). The

162 present-day distance between the mouth of the Rio Doce and the shelf edge is ~ 70 km (Fig. 1A).
163 Turbid river water has been observed 40 km off the Rio Doce after prolonged rainfall, suggesting that
164 hyperpycnal flow events are able to deliver sediment to the continental slope during river floods
165 (Summerhayes et al., 1976).

166 On the continental shelf, seismic data shows a series of incised valleys connected to the Rio
167 Doce Channel System (Bischoff and Lipski, 2008). However, it seems that these valleys are no longer
168 active conduits of terrestrial sediment from the Rio Doce to the continental slope, as they are nearly
169 completely filled.

170

171 **RESULTS**

172

173 **Morphology of the Rio Doce Channel System**

174

175 ***West tributary***

176

177 The west tributary is 15 km-long as measured from a lower-order confluence upslope to the
178 confluence analysed in this work (Fig. 3A). The west tributary shows an NNW–SSE course on the
179 upper continental slope, shifting to NW–SE at a water depth of ~ 1100 m (Fig. 3A). There is an 80
180 m-high morphologic step (i.e. a sudden change in thalweg slope) approximately 500 m to the west of
181 the studied confluence (Figs. 3B and 4). At the foot of the step in thalweg slope, a 6 m-depth scour
182 was identified (Fig. 4B). Downstream of the step, the orientation of the tributary pathway changes
183 from NW-SE to E-W (Fig. 3B). The tributary joins the main channel at a water depth of 1405 m (Fig.
184 4B), with a confluence angle of 75° (Fig. 3B).

185 The width of the west tributary ranges from 500 to 1800 m. The tributary height changes from
186 20 m to 200 m. Tributary depth ranges from 950 m to 1405 m (Fig. 4A). Its gradient decreases from
187 2.9° in its shallowest portion, to 0.7° downstream until the step near the confluence is reached (Fig.
188 4A).

189

190 ***Main channel (east tributary and post-confluence channel)***

191

192 The main channel is 42 km-long in the interpreted seismic volume (Fig. 3A). Its orientation is
193 NNE-SSW in its shallowest portion, and changes to NE–SW at a water depth of ~ 1300 m due to the
194 presence of a growing salt diapir (Fig. 3A). At a water depth of 1330 m, the general orientation of the
195 channel system changes to nearly N–S and is maintained toward the southern limit of the seismic
196 volume (Fig. 3A). Its width changes from 200 to 1000 m, whereas its height ranges between 10 and
197 150 m (Qin et al., 2016). The depth of the main channel varies from 1000 to 1700 m (Fig. 4A) and
198 the channel gradient ranges from 1.5° in its shallowest part, to 0.5° downstream (Fig. 4A).

199

200 **Depositional patterns near the confluence**

201

202 The depositional ratio (CSA_D/CSA_E) of the main channel (east tributary and post-confluence
203 channel) increases by 14% downstream of the confluence and is the largest for 4 km, between 18 km
204 and 22 km (Fig. 5A). It varies between 72% and 85%, with an average value of 78% from 18 km to
205 22 km (Fig. 5A). It is less than ~60% on average in the first 18 km, and approximately 50% on average
206 between 22 km and 34 km. In addition, CSA_E and CSA_D are both larger downstream of the confluence
207 when compared to other parts of the channel system, suggesting that the largest sediment volumes

208 occur immediately downstream of the confluence (Fig. 5B).

209 Three large depositional bars are observed where the largest depositional ratios are recorded -
210 from 18 km to 22 km along the main channel (Figure 5C). Seismic data show these deposits to be
211 associated with lateral channel migration (Fig. 6). Channel-form erosional truncations at the base of
212 the channel system represent the positions of previous channel banks (Fig. 6).

213 Lateral channel migration, demonstrated by the trajectories of shifts in bank positions (Fig. 6),
214 resulted in large CSA_E and CSA_D values from 18 to 22 km (Fig. 5B). These large values in CSA_E and
215 CSA_D are associated with cut-bank erosion and inner-bank deposition caused by lateral migration,
216 respectively. We interpret that the enhanced sediment volumes in the channel system, downstream of
217 the confluence, result from large sediment inputs from the west tributary (Fig. 5). We also interpret
218 that flows from the east tributary contributed to deposition near the confluence, but they were not as
219 important as the flows sourced from the west tributary. If flows from the east tributary were the main
220 source of sediment downstream of the confluence, we would expect a reduction in channel gradient
221 immediately downstream of the east tributary, as sediment tends to deposit in places where channel
222 slope decreases (e.g. Friedmann et al., 2000; Mulder and Alexander, 2001; Wynn et al., 2012). Such
223 a reduction in channel gradient, however, is not observed in association with the east tributary (Fig.
224 4).

225 The depositional ratio (CSA_D/CSA_E) decreases from 85% to 32% at a down-channel distance of
226 23 km (Fig. 5A), indicating that some of the sediment sourced from the west tributary was deposited
227 directly downstream of the confluence, with only a small volume of sediment reaching the lower part
228 of the channel system.

229

230 **Temporal variations in confluence morphology**

231

232 ***Variations in the pathway of the west tributary and the main channel***

233

234 Temporal variations in channel pathways were reconstructed in Figure 7. The map of the original
235 and present-day channels in the Rio Doce Channel System reveals significant variations in the
236 pathway of the main channel immediately downstream of the confluence (Fig. 7A). At the confluence,
237 a channel bend curved initially toward the west but subsequently changed its curvature to the east
238 until the present day (Figs. 7B and 7C). In addition, sharp variations in the pathway(s) of the main
239 channel are observed in two bends further downstream (Fig. 7). These variations increased channel
240 sinuosity from 1.11 for the original channel pathway, to 1.72 for the present-day pathway (Figs. 7B
241 and 7C). Seismic data show that such a significant change in channel sinuosity resulted from lateral
242 channel migration near the confluence (Fig. 6).

243 The west tributary shows small changes in its pathway with time. This tributary migrated laterally
244 for ~500 m toward the east, accompanying confluence migration (Fig. 8).

245

246 ***Confluence migration***

247

248 In the west tributary, a step in thalweg slope and a scour are observed the west of the present-day
249 confluence (Figs. 3B and 4B). These two features are commonly found at confluences where
250 tributaries join the main channels (Best, 2008). Considering that the step in thalweg slope is located
251 at the intersection of the west tributary and original pathway of the main channel (Fig. 8A), we
252 interpret it as marking the original position of the confluence between the west and east tributaries
253 (Fig. 8B). The different positions between the original and the present location of the confluence

254 suggests confluence migration toward the east in the order of ~500 m.

255 At the original location of the confluence, the confluence bed is discordant because the west
256 tributary is much higher than the east tributary (Fig. 8A). In contrast, the confluence bed is concordant
257 at its present-day location, as shown by the same depth between the beds of the west and east
258 tributaries (Fig. 4B).

259 Confluence bed morphology changed from discordant to concordant during confluence
260 migration. When the west tributary started to move eastward, its bed changed from the top of the step
261 to its foot, where its depth is similar to the bed of the east tributary. This resulted in the formation of
262 a concordant confluence.

263

264 **DISCUSSION**

265

266 This work shows that the main channel bend curved toward the west at the original location of
267 the confluence (Figs. 8 and 9). After the west tributary joined the main channel, sediment flows from
268 the west tributary pushed the bend toward the east due to flow inertia, resulting in confluence
269 migration and a series of morphologic and sedimentologic changes. These include changes in channel
270 pathways, the formation of depositional bars and relative increases in sediment volume downstream
271 of the confluence (Figs. 8 and 9).

272

273 **Confluence morphology**

274

275 Similarly to the confluence morphology documented in this work, Paull et al (2011) observed a
276 step in the thalweg slope of the Soquel channel (offshore California) upstream of its confluence with

277 the Monterey channel. A 500 m-long, smooth tributary segment was mapped between the step and
278 the confluence, and later defined as an “embayment” at the mouth of tributary (see Fig. 8 in Paull et
279 al., 2011). We suggest that this embayment was formed by the upstream migration of the step by
280 means of retrogressive (headwall) erosion, contrasting with the downstream migration recorded in
281 the study area due to the absence of features such as the original channel pathways and attached
282 depositional bars near the confluence analyzed in the Rio Doce Channel System. An arcuate feature
283 at the tributary mouth of the Soquel Canyon also indicates sediment failure (Paull et al., 2011). Such
284 types of feature are not observed in the study area.

285 Confluence migration is also common in both meandering and braided rivers (Dixon et al., 2018).
286 In meandering rivers of Argentina and USA, confluence migration was promoted by the migration
287 and cut-off of tributaries, with the planform of the main channel recording minor changes (Dixon et
288 al., 2018). In the Pliocene-Quaternary Rio Doce Channel System, confluence migration was also
289 associated with lateral migration of the main channel, but considered to have resulted from turbidity
290 currents flowing from the west tributary toward the east.

291

292 **Generation of depositional bars**

293

294 In the study area, depositional bars are identified both upstream and downstream of the
295 confluence (Fig. 5C). Similar bars have been documented in fluvial channel confluences due to flow
296 stagnation upstream of the confluence and flow separation downstream (Best, 1988). Flow stagnation
297 results from mutual flow deflections away from the upstream confluence corner when flows join
298 together (Best, 1987). Flow separation occurs when tributary flows detach from tributary banks as
299 they enter the main channel, resulting in a zone of low velocity favouring sediment deposition (Best

300 and Reid, 1984). Despite the different flow properties of turbidity currents (sediment gravity flows)
301 and river currents (fluid gravity flows) (Kolla et al., 2007), flow stagnation and separation can also
302 occur in submarine confluences and contribute to the formation of depositional bars. This is suggested
303 by the similar locations of depositional bars in both submarine and river confluences.

304 Flow deflection and reflection probably occurred near the confluence in this study. A possible
305 scenario is that the basal, denser part of turbidity currents were deflected against the inner bend of the
306 main channel, resulting in bank erosion, whereas the upper, less dense part of the flows was reflected
307 back to the outer bend of the main channel, leading to bank deposition and the formation of
308 depositional bars (Fig. 9). After these bars were formed, subsequent tributary flows were deflected to
309 promote bank erosion and deposition, leading to further growth of the bars. Finally, channel gradient
310 decreased as the channel became longer and more sinuous, leading to enhanced deposition near the
311 confluence.

313 **Flows within the channel system**

314
315 The lack of core data and age constraints make it difficult to evaluate flow dynamics within the
316 Rio Doce Channel System. Nevertheless, variations in the continuity and amplitude of seismic
317 reflections in submarine channels have been widely used to assess flow dynamics in a qualitative way.
318 For example, active channels are characterised by high-amplitude near-seafloor strata, whereas
319 inactive channels are commonly of relative low amplitude (Pirmez et al., 2000; Gamboa et al., 2012;
320 Jobe et al., 2015; Hansen et al., 2017). In the study area, the west tributary and main channel are likely
321 active at present based on the presence of high-amplitude strata inside them (Gamboa et al., 2012).
322 Therefore, flows downstream of the confluence could be either sourced from the west tributary or the

323 east tributary, or from both at the same time.

324 We interpret that the west tributary contributed with larger volumes of sediment to the post-
325 confluence channel than the east tributary due to the presence of large depositional bars downstream
326 of the confluence. In addition, there are abrupt decreases in channel width and height (Qin et al., 2016)
327 and a temporal change in the channel pathway immediately downstream of the confluence (Fig. 7A).
328 All these changes suggest a marked effect of the west tributary on post-confluence channel
329 morphology during the main stages of confluence migration (Fig. 9). However, based on the smooth
330 transition at the confluence between the east tributary and the post-confluence channel, the east
331 tributary is currently active (Fig. 4B).

332 The west tributary contributed more sediments than the east tributary to the confluence region,
333 suggesting an eastern ward shift in major sediment sources on the continental shelf (Figs. 9A and B).
334 Such a shift is interpreted to be a result of variations in sedimentary processes on the continental shelf.
335 Similar variations in tributary activities have also been documented offshore Niger delta (Jobe et al.,
336 2015; Hansen et al., 2017). These variations have been linked to river avulsions on the Niger delta
337 (Jobe et al., 2015) and the capture of sediment supply by different canyons along the Niger shelf edge
338 (Hansen et al., 2017). In this work, both of scenarios mentioned above could have occurred as the
339 sediment delivery processes from the Rio Doce delta to the submarine channels is still unclear.

340

341 **Lateral migration as a response to turbidity currents from the west tributary**

342

343 We suggest that the west tributary provided significant volumes of sediment into the post-
344 confluence channel, as indicated by large depositional bars immediately downstream of the
345 confluence. Lateral channel migration was a major response to greater sediment discharge and

346 resulted in confluence migration, as shown by: a) the multiple channel forms in depositional bars
347 downstream of the confluence, and b) the higher magnitude of lateral migration at the three meander
348 bends downstream of the confluence (Fig. 6).

349 In a channel system offshore Nigeria, Jobe et al., (2015) found a transition from large-scale
350 lateral migration at the early incision stage, to aggradation soon after, and attributed this transition to
351 a decrease in sediment discharge. Unfortunately, it is difficult to evaluate the role of extrinsic controls
352 (e.g. climate change, tectonic activity, and the proximity of a shelf-edge delta) in sediment delivery
353 to the channel system due to the lack of chronostratigraphic constraints (Jobe et al., 2015). In subaerial
354 settings, close relationships between sediment supply and lateral channel migration have also been
355 documented. For example, downstream of tributaries a relative increase in channel migration rate is
356 observed in rivers such as the Amazon (e.g. at the confluence between the Rio Mamoré and Rio
357 Grande) due to high sediment load from tributaries and associated point-bar growth (Constantine et
358 al., 2014).

359 Other flow properties such as flow velocity could have also contributed to lateral channel
360 migration in the study area. Numerical models by Das et al. (2004) show that lateral migration is
361 more likely to be driven by erosional currents with a relatively high current velocity and a steep
362 channel bed slope. Ismail (2017) further found that higher junction angles result in higher peak front
363 velocity in channel flows. In this work, the junction angle is 75°, which is a higher angle than that
364 reported by Ismail (2017). Therefore, a relatively high flow velocity likely promoted out-bank erosion
365 during lateral channel migration.

366 Hubbard et al. (2009) suggest a link between the grain size of turbidity currents and the
367 magnitude of lateral channel migration in the Molasse foreland basin of Austria. They considered
368 relative pauses in channel sedimentation (Puchkirchen Formation, represented by 1–20 m thick shale

369 beds), and associated slow channel migration rates, as reflecting the cessation of coarse-grained
370 sediment supply. Similarly, Nelson and Dubé (2016) found a close relationship between river bed
371 sediment flux and lateral channel mobility in the Chehalis River in Washington State, Northeast USA.
372 The influx of coarse-grained sand may have also contributed to lateral migration in the Rio Doce
373 Channel System, but it is hard to confirm such an assumption without sediment cores and in-situ
374 current monitoring equipment.

375

376 **CONCLUSIONS**

377

378 This work documents a series of morphologic and sedimentologic features downstream of a
379 confluence of a Pliocene-Quaternary submarine channel system, SE Brazil. Such variations are
380 interpreted as resulting from the effect of turbidity currents sourced from tributaries, which have
381 impacted on the hydrodynamic processes sculpting a submarine confluence. The results of this work
382 can be summarized as follows:

383

384 (1) High-quality 3D seismic data reveal confluence migration approaching 500 m during the
385 development of the Pliocene-Quaternary Rio Doce Channel System. The original location of the
386 confluence is discordant, and marked by an 80 m-high morphologic step. At present, the
387 confluence is concordant, i.e., characterized by a similar bed depth between the tributary and the
388 main submarine channel.

389

390 (2) Significant temporal changes are recorded in the pathway of the main channel and associated
391 sinuosity values. At the confluence, a channel bend in the main channel curved toward the west

when the bend was formed in the Pliocene. However, this same channel bend curves toward the east at present. We interpret the changes in the geometry of this bend as resulting from the effect of turbidity currents sourced from the west tributary. Turbidity currents deviated the channel bend and curved it toward the east. Two other bends downstream of the confluence also show significant variations in channel pathway, increasing the sinuosity of the main channel from 1.11 to 1.72.

(3) Lateral channel migration is therefore proposed as an important process responding to sediment supply from channel tributaries. Lateral channel migration led, in the study area, to the accumulation of large depositional bars fed by sediment discharged from tributaries.

(4) Confluence evolution in this study reflects an eastward shift in sediment sources at the continental shelf. The cause of such a shift is interpreted as reflecting variations in sedimentary processes on the continental shelf. Further numerical and physical models addressing the hydrodynamic processes at submarine confluences are needed to further understand how these latter evolve. Both numerical and physical models are important to understand flow properties (e.g. sediment discharge, grain size, flow velocity) and associated variations in morphology and architecture (e.g. depositional bars formed during lateral channel migration) of submarine channel systems.

ACKNOWLEDGEMENTS

The authors thank CGG for the permission to use the 3D seismic data in this article. Luke Pettinga, an anonymous reviewer and associated editor Ganqing Jiang are acknowledged for their constructive comments. Yongpeng Qin thanks the financial support from 'The National Major Science and Technology Program (2017ZX05026006)' and NSFC-Guangdong Joint Foundation (U1701245). Davide Gamboa thanks the Sêr Cymru National

415 Research Network for Low Carbon Energy and the Environment and publishes with the permission of the Executive Director, British Geological Survey.

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505

506 **FIGURE CAPTIONS**

507

508 **Fig. 1.** (A) Bathymetric and topographic map of the SE Brazilian margin showing the location of the study area in
509 the Espírito Santo Basin. (B) Contoured seafloor map of the study area generated from the interpreted seismic
510 volume. Bathymetric data in (A) was taken from GeoMapApp (<http://www.geomapapp.org>; Amante and Eakins,
511 2009).

512

513 **Fig. 2.** Uninterpreted and interpreted seismic profiles highlighting the areas of the Pliocene-Quaternary Rio Doce
514 Channel System used to calculate CSA_E (cross-sectional area of the channel system formed by erosional processes)
515 and CSA_D (cross-sectional area of the deposits within the channel system). (modified from Qin et al., 2016).
516 Overbank deposits were not considered in the calculation because they may have similar seismic facies to deposits
517 unrelated to the channel system, causing errors in calculations. The location of the seismic profile is shown in Fig.
518 1B. The polarity of data is SEG normal i.e., positive amplitude reflections (red) on the seismic profiles represent an
519 increase in acoustic impedance in seismic sections.

520

521 **Fig. 3.** (A) Dip map of the seafloor showing that the modern Rio Doce Canyon System is composed of west and
522 east tributaries upslope of a confluence and a post-confluence channel downslope. The east tributary and the post-
523 confluence channel comprise the main channel. (B) Dip map showing the seafloor morphology near the confluence.
524 In the west tributary a step in thalweg slope, with a height of 80 m, is located ~500 m to the west of the confluence,
525 as shown in dark color.

526

527 **Fig. 4.** (A) Depth profiles of the west tributary and main channel. Values next to the profiles show the average
528 channel gradient of a specific channel segment. (B) Enlarged view of depth profiles near the confluence. This graph
529 shows a morphologic step in thalweg slope and a scour in the west tributary, near the confluence.

530

531 **Fig. 5.** (A) Depositional ratio (CSA_D/CSA_E) along the channel system, which comprises the east tributary and the
532 post-confluence channel. The depositional ratio was not calculated at the confluence because here CSA_D and CSA_E
533 are also affected by the west tributary, instead of the east tributary and main channel alone. (B) Variations of cross-
534 sectional area of the channel system (CSA_E) and cross-sectional area of deposits within the channel system (CSA_D).
535 These two parameters were not calculated at the confluence because they are also affected by the west tributary. (C)
536 Thickness map of deposits within the channel system. The upper and lower surfaces used in the calculation of
537 thickness are the sea floor and the base of the channel system, respectively.

538

539 **Fig. 6.** Seismic profiles across three depositional bars near the confluence. The profiles reveal lateral channel
540 migration and suggest that depositional bars were formed by this same process. The shift in bank positions show
541 the trajectories of lateral channel migration.

542

543 **Fig. 7.** (A) Schematic diagram showing significant variations in the pathway of the channel immediately
544 downstream of the confluence. Small variations in the pathway of other parts of the main channel are also observed.
545 (B) and (C) show that channel sinuosity increases from 1.11 to 1.17 due to pathway changes in the post-confluence
546 channel.

547

548 **Fig. 8.** Schematic diagram highlighting the observed variations in the geometry of channel pathways and confluence,
549 overlain on a seafloor dip map. (A) The step in thalweg slope at the west tributary is shown by a high dip value and
550 dark color. The foot of the step marks the original position of the confluence. (B) Original position of the confluence
551 at the intersection between the west tributary and the post-confluence channel. (C) Present-day position of the
552 confluence at the intersection between the east tributary and post-confluence channel. (D) The confluence migrated

553 ~500 m toward the east until it reached its present location.

554

555 **Fig. 9.** Schematic diagram summarizing the influence of the west tributary on the evolution of the Pliocene-
556 Quaternary Rio Doce Channel System. Turbidity currents from the west tributary promoted a series of morphologic
557 and architectural variations via lateral channel migration. These included confluence migration, the formation of
558 three large depositional bars downstream of the confluence, changes in channel pathway, and variations in channel
559 sinuosity. T2 and T4 correspond to Figs. 8B and 8C, respectively.

















