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Seismic evidence of gas hydrates, multiple BSRs and fluid flow offshore Tumbes Basin – Peru.

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ABSTRACT (247 words)

Identification of a previously undocumented hydrate system in the Tumbes Basin, localized off the north Peruvian margin at latitude of 3°20' – 4°10'S, allows us to better understand gas hydrates of convergent margins, and complement the 36 hydrate sites already identified around the Pacific Ocean. Using a combined 2D-3D seismic dataset, we present a detailed analysis of seismic amplitude anomalies related to the presence of gas hydrates and/or free gas in sediments. Our observations identify the occurrence of a widespread Bottom Simulating Reflector (BSR), under which we observed, at several sites, the succession of one or two BSR-type reflections of variable amplitude, and vertical acoustic discontinuities associated with fluid flow and gas chimneys. We conclude that the uppermost BSR marks the current base of the hydrate stability field, for a gas composition comprised between 96% methane and 4% of ethane, propane and pure methane. Three hypotheses are developed to explain the nature of the multiple BSRs. They may refer to the base of hydrates of different gas composition, a remnant of an older BSR in the process of dispersion/dissociation or a diagenetically induced permeability barrier formed when the active BSR existed stably at that level for an extended period. The multiple BSRs have been interpreted as three events of steady state in the pressure and temperature conditions. They might be produced by climatic episodes since the last glaciation associated with tectonic activity, essentially tectonic subsidence, one of the main parameters that control the evolution of the Tumbes Basin.

Keywords

Gas hydrates, Bottom Simulating Reflector, multiple BSRs, seismic chimneys, Tumbes, Peru.

28 **Introduction**

29 Natural gas hydrates have gained international attention over the last few decades for energy, safety
30 and environmental reasons (Kvenvolden, 1993; Milkov, 2004; Sultan *et al.*, 2004). Because they are
31 thermodynamic products, they can be extremely useful to indirectly estimate heat flow of continental
32 margins (Yamamoto *et al.*, 1982), and can provide valuable information on environmental and/or tectonic
33 evolution of a sedimentary basin.

34 Gas hydrates are formed by a lattice of water molecules held together by hydrogen bonding, and
35 stabilized by the inclusion of a guest molecule, typically low molecular weight gas (Ballard and Sloan,
36 2002). Natural gas molecules trapped in hydrate consist mainly of methane, but other higher and non-
37 hydrocarbons, such as nitrogen, hydrogen sulfide or carbon dioxide, can also form hydrates. To form, gas
38 hydrates need high pressure, low temperature, and the right amount of water and gas (Kvenvolden, 1993),
39 conditions commonly found in oceanic sediments along continental margins, at water depths greater than
40 400 m. The field of hydrate stability, called the Gas Hydrate Stability Zone (GHSZ), comprises the first few
41 hundred meters of the sedimentary section. It is largely controlled by pressure and temperature
42 conditions, and is limited in depth due to increasing temperature from the local geothermal gradient.

43 In seismic reflection section, a common indicator of submarine gas hydrates is a Bottom-Simulating
44 Reflector (BSR) (Shipley *et al.*, 1979), although its absence does not necessarily mean absence of
45 hydrates in sediments (Vanneste *et al.*, 2001). A hydrate-related BSR mimics the seafloor topography and
46 crosscuts the sedimentary strata as it follows the GHSZ. It is characterized by a strong negative
47 impedance contrast due to high-velocity sediments containing hydrates above the base of the hydrate
48 stability field and lower-velocity sediments containing free gas beneath it (Field and Kvenvolden, 1985). If
49 the gas composition is known, the in situ temperature at the BSR can be estimated from the depth of this
50 reflector.

51 When a hydrate system is not in thermodynamic equilibrium, the position of the BSR is expected to
52 change. Multiple BSR-type reflections, subparallel to the seafloor but at different sub-bottom depths, have
53 been observed in both active and passive margins, as the Storegga Slide area on the Norwegian margin
54 (Posewang and Mienert, 1999; Andreassen *et al.*, 2000), the upper slope of the SE Nankai margin (Foucher
55 *et al.*, 2002), in the Yaquina and Trujillo Basins off Peru (Hübscher and Kukowski, 2003; Herbozo *et al.*,

56 2013), at Hydrate Ridge on Cascadia margin (Bangs *et al.*, 2005), in the Danube deep-sea fan on the NW
57 Black Sea margin (Popescu *et al.*, 2006), or in the Mohican Channel area on the central Scotian Slope
58 (Mosher, 2008). The origin of these multiple reflectors is not well understood, and several interpretations
59 have been suggested, i.e. residual BSR in the process of dispersing, layers of hydrates of different gas
60 composition, or diagenetic reaction.

61 Along South American continental margins, numerous accumulations of gas hydrates are known and
62 have been described (Kvenvolden and Kastner, 1990; Brown *et al.*, 1996; Pecher *et al.*, 2001; Hubscher
63 and Kukowski, 2003; Rodrigo *et al.*, 2009). Off Peru, during Ocean Drilling Program (ODP) Leg 112, gas
64 hydrates were identified in water depth greater than 3000 m, within core drillings, and on seismic profiles
65 crossing the Yaquina and Lima forearc Basins (sites 682, 685, and 688) (von Huene *et al.*, 1987) (Figure
66 1A). The occurrence of BSRs in these basins was interpreted to reflect a history of vertical tectonism,
67 sedimentation, and carbon concentrations in sediments (von Huene and Pecher, 1999). Off margin north
68 of Peru, no data were available until recent 2D-3D seismic reflection data acquisition in the Tumbes Basin,
69 which allowed the identification of a new hydrate province (Figure 1B).

70 The purpose of this study is to (1) document the hydrates in the Tumbes Basin (2) describe associated
71 fluid seeps (3) estimate the thermal regime and (4) discuss the influence of climatic changes and tectonic
72 factors related to the evolution of the margin that help generate multiple BSRs.

73 **2. Geological framework**

74 The Tumbes Basin is a particular type of forearc basin which evolves in response to subduction
75 dynamics of the Nazca plate beneath the South America plate. The study area, located offshore northern
76 Peru between 3°20 and 4°10S, consists of a several-kilometer-thick accumulation of Oligocene to
77 Quaternary sediment characterized by normal faulting (Figure 1C). It is delineated by three major N-S-
78 trending normal and low-angle gravity-driven fault systems. These gravitational tectonic features have
79 generated rollover anticlines and rotated fault blocks during Pliocene-Pleistocene times. To the west, an
80 east-dipping normal fault bounds the eastern flank of Banco Peru, a flat shallow-depth seafloor high
81 located 30-50 km seaward from the coast, which bounds the extension of the basin to the west. The
82 southern limit of the basin occurs near 4°S as the triple junction between these two major fault systems
83 and a south-dipping listric normal fault branched onto the Talara detachment, which extends to the Peru-

84 Chile trench axis at $\sim 5^{\circ}\text{S}$ (Bourgeois *et al.*, 2007). The presence of multiple reservoirs, giant oil
85 accumulation in the onshore fields of the Talara Basin and different hydrocarbon occurrences in the
86 eastern shallow-depth Tumbes Basin (Deckelman *et al.*, 2005), makes the study area a promising region
87 for hydrocarbon exploration.

88 **3. Data and methods**

89 The seismic reflection dataset was acquired over exploration block Z-38, in water depths ranging from
90 110 m to 2765 m, offshore Tumbes Basin (Figure 1B). The 2D multi-channel seismic data acquired in
91 2009 has a total survey length of about 2393 km. The dataset has a sampling rate of 2 ms. The frequency
92 content ranges between 10–70 Hz and the 2D grid spacing ranges from 1 to 6 km. Dominant frequencies
93 around 45 Hz for the shallow subsurface provide a theoretical vertical resolution ($\lambda/4$) of ~ 10 m (P-wave
94 velocity in sediments of 1800 m/s). The 3D seismic dataset, acquired in 2010, covers an area of 1500
95 km^2 . It has a sampling rate of 4 ms. The 3D grid is subdivided into inline and crossline directions, spaced
96 at 25 m and 12.5 m respectively. The frequency of the seismic signal in the shallow subsurface ranges
97 between 5 and 90 Hz with a dominant frequency around 45–55 Hz. Assuming a velocity of 1800 m/s, the
98 theoretical vertical resolution ($\lambda/4$) is ~ 9 m.

99 The seismic data have been interpreted using standard seismic stratigraphic techniques (Mitchum *et al.*,
100 1977), based on reflection terminations and seismic facies reflection characteristics. Geometric seismic
101 attributes, such as similarity, have been used to enhance recognition of coherent events and emphasize
102 discontinuities such as faults and stratigraphic surfaces. Using these techniques, a framework of four
103 interpreted seismic horizons (seafloor, H1, H2 and H3; Figure 2A) has been used in the Mancora Basin, a
104 sub-basin of the Tumbes Basin (red dashed box Figure 1B), in order to obtain accurate and detailed
105 information on amplitude anomalies, depositional elements, structural patterns, direct hydrocarbon
106 indicators (DHI), and sediment remobilization or fluid flow features (Calvès *et al.*, 2008).

107 As hydrates are only stable in a very limited range of temperatures and pressures (Yamano *et al.*, 1982;
108 Sloan, 1998), the occurrence of BSRs related to methane hydrates in the shallow subsurface allows us to
109 estimate the thermal regime. This estimation is based on the assumption that the BSR is related to the
110 base of the GHSZ. We have used information from seismic reflection surveys, seabed temperature from
111 World Ocean Database (http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html–2009) and Sloan's

112 (1998) phase boundary diagram for pure methane and 3.5 wt% seawater. The workflow consists of the
113 following steps (e.g. Calvès *et al.*, 2010): (1) picking of seabed and regional BSR horizons, (2) conversion
114 from two-way time (TWT) to depth, based on a P-wave velocity of 1475 m/s in seawater and 1800 m/s in
115 sediments, (3) conversion from BSR depth to temperature using a phase boundary diagram, (4)
116 determination of the thermal gradient computed by dividing the temperature difference between the
117 seabed and the BSR by the subbottom depth.

118 **4. Results**

119 **4.1. Seismic evidence of multiple BSRs: characteristics and distribution**

120 Analysis of seismic reflection profiles revealed the presence of numerous BSRs in water depths of 470-
121 2410 m. We identified an extensive BSR (Figure 1D and upper BSR, Figure 3) under which we observed,
122 at several sites, the succession of one or two BSR-type reflections at different depths (intermediate and
123 lower BSRs, Figure 3). All of them mimic the seafloor topography, cross-cutting stratigraphic horizons, and
124 display reversed polarity relative to the seafloor reflection. Below these multiple BSRs, enhanced
125 reflections are commonly observed (e.g. HAA: Calvès *et al.*, 2008; Figure 3A). This association of BSRs
126 with reversed apparent polarity and the abrupt termination of enhanced reflections against them indicate
127 the occurrence of gas hydrates overlying free gas accumulations. Other anomalous amplitude reflections
128 are observed in the shallow subsurface, and identified as Direct Hydrocarbon Indicators (DHIs) (Figure
129 2B). DHIs are particularly present in the SW part of the 3D seismic block in the intra-slope Mancora Basin
130 (Figure 2A), where they occur as local increases or decreases in reflection amplitudes (called bright
131 spots/flat spots or dim outs respectively), phase reversals along particular sedimentary reflections and
132 BSRs, and columnar disturbances linked to fluid seeps, which are interpreted as seismic chimneys.

133 Among the multiple BSRs identified, the upper one (Figure 1D and upper BSR, Figure 3) is the longest
134 and can be followed over distances of up to 15 km without interruption. The isochore of the interval from
135 the seabed to the upper BSR (Figure 4A) shows a variation in thickness from 170 to 560 m, and increases
136 with increasing water depth, i.e. with pressure; it is controlled by the gas hydrate stability conditions. As
137 observed in other hydrate provinces, the upper BSR undergoes important amplitude variations depending
138 on which structural features or geological elements it intersects (Ashi *et al.*, 2002; Lin *et al.*, 2008).
139 Contrary to observations done in the Yaquina Basin further south by Hübscher and Kukowski (2003), the

140 upper BSR is most easily recognized where it cross-cuts sedimentary strata. It displays strong amplitude
141 in anticline structures, or cross-cutting inclined stratal reflections on structural ridges, and is weaker in
142 synclinal structures, slope basins, or sub-marine canyons. In the intra-slope Mancora Basin, the upper
143 BSR cross-cuts parallel stratified sediments with a small angle (Figure 2A). Its reflection is superimposed
144 on the underlying sedimentary reflections, which makes it difficult to follow. On some seismic profiles, that
145 intersection can be seen and is characterized by local decreases in amplitude and polarity changes of the
146 strong sedimentary reflections intersected (dim out and phase reversal – Figures 2A and 2B).

147 Intermediate BSRs are observed at depths ranging from 36 to 72 m (40 to 80 ms TWT) below the upper
148 BSR. They appear as negative polarity reflections or an upper limit of enhanced reflections, mimicking the
149 seafloor topography (Figures 3A and 3B). As with the upper BSR, they have a water-depth dependence
150 (Figure 4B), but are much more discontinuous. They occur locally as patches of high amplitude reflections
151 of 50 to 250 m (Figure 4C), or as reflection segments of 1000 to 2600 m (Figure 4D), and are generally
152 located in zones strongly affected by normal faults.

153 Lower BSRs are observed at depths ranging from 115 to 190 m (130 to 210 ms TWT) below the upper
154 BSR. They appear as discontinuous reflection segments of 200 to 2800 m long, display reversed polarity
155 and are, in most seismic profiles where they occur, the BSRs showing the strongest amplitude values.
156 They are present within different structural and sedimentological settings, from a buried structural high
157 with near-vertical stratal reflections (Figures 3A and 4C), to stratigraphic layers sub-parallel to the seabed
158 and affected by normal faults (Figure 3B).

159 A particular type of HAA, which have the same negative polarity as a hydrate-related BSR but are
160 affected by a fault system that shifts them downward, are observed in the Mancora Basin (Figures 2A and
161 3C). Approximately parallel to the seabed, they extend semi-continuously over the intra-slope basin,
162 cross-cutting the background inclined sedimentary reflections. Their depth below seafloor varies from 480
163 to 810 m (530 ms to 810 ms TWT) for water depths of 950–1030 m respectively. In seismic profiles
164 oriented NW-SE, they appear as flat spot of over 2000 m long (yellow triangle, Figure 2A), while in seismic
165 profiles oriented perpendicularly (SW-NE), they appear as high reflectivity segments shifted down
166 between sub-parallel normal faults (right profile, Figure 3C). The extension of these HAA is difficult to

167 visualize due to their location at the boundary between the 3D block and the 2D seismic data, but they
168 seem to fit with the lower BSR observed in the 2D seismic profile (NW-SE section– Figure 3C).

169 **4.2. Distribution of fluid seeps**

170 In the Mancora Basin, within ~100 km² imaged by the 3D seismic reflection (Figure 5), we have identified
171 a series of pockmarks/mounds that consist of patches of HAA on the seabed and 10-15 m deep/high on
172 seismic profiles. These features are the expressions of focused fluid flow activity on the seabed (Judd and
173 Hovland, 2009; Hustoft *et al.*, 2009). Depending on their morphology, we defined two categories of
174 pockmarks: the circular or elliptic ones, typically measuring from 40 to 350 m in diameter, and the
175 elongated ones, which have one axis that is much longer than the other, up to 500 m (e.g. chimney α : 85
176 m wide, and 515 m long, Figures 5 and 6). Underlying the pockmarks/mounds field lies a corresponding
177 series of vertical seismic chimneys, i.e. the acoustic imprint of fluid migration. Time-structure/similarity
178 attribute maps of three paleo-surfaces illustrates the subsurface expression of the fluid-escape chimneys
179 in plan form (H1, H2, H3, Figures 2A and 6). The maps show that chimneys are represented by circular
180 and elongated well-exposed anomalies, and reveal a preferred direction of the elongated chimneys, with
181 the longest axis perpendicular to the faulting. This preferred direction remains commonly constant with
182 depth (Figure 6). In seismic reflection sections, the chimneys appear as columnar zones of low coherence
183 and reduced reflectivity, where surrounding strata can be both truncated or flexed upward at their flanks.
184 Of 48 seismic chimneys identified, one fifth are buried chimneys ending at different stratigraphic levels,
185 generally with a patch of high amplitude reflections or intra-sedimentary doming, i.e. deflected upward
186 reflections stopped into the sediment column (e.g. chimneys γ and δ , Figure 5). A typical chimney has a
187 root zone that in the seismic data appears to originate below the strong stratigraphic clustering that occurs
188 throughout the intra-slope basin, between 315 to 540 m (350 to 600 ms TWT) subsurface depths (Figure
189 2A). In some areas attenuation and scattering of the seismic signal suggest the presence of free gas
190 accumulation.

191 **4.3. Estimated geothermal gradient from BSR depth**

192 Variations in the thermal regime of sedimentary basins can be a good indicator of tectonic features
193 and/or fluid migration through the sedimentary column. In the undrilled part of the Tumbes Basin, the
194 geothermal gradient is computed using the inferred temperature at the BSR (Yamano *et al.*, 1982;

195 Hyndman *et al.*, 1992), assuming hydrostatic pressure, and a gas composition of pure methane, which
196 seems a good approximation for the Peru margin (Pecher *et al.*, 2001). As temperature is available only at
197 the seabed (World Ocean Database, 2009), the estimated thermal gradient values are used only for
198 qualitative assessments. Using the methodology described above, the seafloor (water depth ranging from
199 110 to 2765 m), and the BSR (depth below seafloor ranging from 171 to 558 m) are mapped in detail from
200 the 2D and 3D seismic dataset (Figures 7A and 7B). Temperature at the BSR is estimated from pressure-
201 temperature curves for seawater-methane hydrate stability based on experimental data, and the derived
202 geothermal gradient is mapped and extrapolated across the mapped BSR (Figure 7C). The average value
203 obtained, 26°C/km, is consistent with the regional thermal regime trend. In the Yaquina and Lima Basins,
204 Kvenvolden and Kastner (1990) obtained values of 40-50°C/km at water depths greater than 3000 m,
205 which fit with our estimation of a thermal gradient close to 40°C/km at a water depth of ~3000 m.

206 In order to assess potential uncertainties due to gas composition, we use the seawater approximation
207 with variable mixtures of methane, ethane, and propane, i.e. 100% methane, mixte (96% methane, 3%
208 ethane, 1% propane), and thermogenic (90% methane, 7% ethane, 3% propane). We then use an
209 average geothermal gradient of 25-40°C/km for the study area (Figure 8), to estimate the approximate
210 expected depth of the hydrate stability zone, and therefore the potential depth of the BSR below the
211 seafloor. Hydrates are predicted to be stable in sediment from 125 to 780 m below seafloor, based on a
212 hydrate stability field for a three variable mixture of gas and assuming a 25-40°C/km geothermal gradient
213 and water depths of 765, 950, 1115 and 1330 m. Our results are summarized in Table 1.

214 **5. Discussion**

215 **5.1. Nature of the BSRs**

216 Although direct analyses of hydrate composition are not available in the Tumbes and Mancora Basins,
217 we interpret the upper BSR as the active BSR, in part because it is the BSR that shows the greatest
218 continuity and that is not affected by faults. Moreover, the data presented reveal that the upper BSR
219 corresponds to the present-day position of the base of the hydrate stability field, estimated from pressure-
220 temperature conditions exerted at seafloor and in sediment, and a gas composition comprised between
221 96% methane and 4% of ethane, propane and pure methane. Locally, CO₂ may be present as well as
222 thermogenic gases, according to the seawater-hydrate stability curves. These results seem consistent

223 with previous reported analyses done in the Piedra Redonda and Corvina gas wells, located eastward of
224 block Z-38 in the shallow depth Tumbes Basin, which show a gas composition with near 98% methane
225 and 2% of ethane, propane and CO₂ (Basin Evaluations Group Exploration Department, 2005).

226 For the other deeper BSR-type reflectors, which we interpret as possible hydrate-related BSRs, we have
227 three hypotheses:

228 (1) Intermediate and lower BSRs could represent the base of hydrates formed from a mixture of gases.
229 Hydrates with mixed compositions of methane and heavier natural gas components such as ethane,
230 propane or carbon dioxide, will cause an increase in depth of the base of the GHSZ, due to the
231 displacement of the phase boundary to higher temperature-pressure values (Sloan, 1998). In the Tumbes
232 Basin, we calculated that intermediate and lower BSRs are all within the stability range of hydrates for
233 variable mixtures of methane, ethane and propane (with less than 10% of the heavier hydrocarbon gases)
234 (Table 1). Conversely, in the intra-slope Mancora Basin, although both fluid-flow features and gas hydrate
235 accumulations may indicate the presence of a deep thermogenic gas source (Heggland, 1998), the HAA
236 occur at depths where the ambient temperature is too high for the hydrate to be stable, even in the
237 presence of more complex gas/fluid components (section SW-NE – Figure 3C). Our results may support
238 the hypothesis that intermediate and lower BSRs mark the base of hydrates of different gas compositions,
239 although no current data allows us to confirm this hypothesis.

240 (2) In response to variations in pressure and temperature conditions exerted on the GHSZ, vertical
241 displacement of the BSR is expected. Intermediate and lower BSRs could be interpreted as a remnant of
242 an older BSR that is in the process of dispersing, after a pressure drop and/or a temperature increase
243 (e.g. von Huene and Pecher, 1999; Foucher *et al.*, 2002, Bangs *et al.*, 2005). This hypothesis supposes
244 that the amount of free gas is still high enough that the reflectivity of the old BSR persists. Foucher *et al.*
245 (2002) estimated the duration of persistence of a diffusing gas layer at several thousand years, with a
246 maximum of the order of 10 000 yr. We suggest three thermodynamic stability periods to form the lower,
247 intermediate, and upper BSRs, during the last 10 000 yr as required by the estimated short duration of the
248 BSR's reflectivity.

249 (3) We suggest that multiple BSRs may represent a permeability barrier (e.g. diagenetically induced)
250 formed when the active BSR existed stably at that level for an extended period. The permeability barrier

251 would allow the trapping and accumulation of free gas, which would be expressed in seismic data as a
252 negative reflection, and as a level at which enhanced reflections would terminate. We excluded here the
253 possibility of a diagenesis-related BSR resulting from the phase transitions between opal-A, opal-CT/C,
254 and microcrystalline quartz, which displays the same polarity as the seafloor reflection, opposite to that of
255 a hydrate-related BSR (Berndt *et al.*, 2004).

256 **5.2. Mechanisms at the origin of BSR migration**

257 Multiple BSRs that would correspond to a previously deeper phase boundary BSR, either in the process
258 of dispersing or diagenetically induced, have to readjust their position to current pressure and temperature
259 conditions. We will discuss the main mechanisms that could generate vertical movement of the base of
260 the GHSZ to explain their origin. In the Tumbes basin, these mechanisms are associated with eustatic,
261 tectonics and sedimentary processes, the main parameters that control the evolution of the basin through
262 time. We will not further develop the hypothesis of hydrates formed from a gas mixture, which would need
263 borehole data to be substantiated.

264 Since the last glacial maximum, the eustatic sea level increased by 125 +/- 5 m from ~15 to 7 ka and
265 stayed roughly constant from 7 ka until present time (Fleming *et al.*, 1998), and bottom water temperature
266 was estimated 1.5°C cooler than today (data from deep-sea core V 19–30; 3091 m water depth,
267 Koutavas, *et al.*, 2006) in the Equatorial Pacific Ocean (Chappell and Shackleton, 1986; Waelbroeck *et al.*,
268 2002). Pressure and temperature changes affect the BSR with different timing. The pressure, which
269 increased nearly uniformly during 10 ka, is transferred immediately to the depth of the BSR. Conversely,
270 the thermal pulse associated with rising bottom-water temperatures propagates gradually, from the
271 seafloor down to the BSR depth, following the laws of thermal conduction (e.g. on the upper slope of the
272 eastern Nankai margin, Foucher *et al.* (2002) estimated a time delay of 4700 yr before the thermal pulse
273 would affect local temperature conditions at 200 m sub-bottom depth, for a thermal diffusivity of the
274 sediments of $3 \times 10^{-7} \text{ m}^2/\text{s}$). In order to determine the possible depth of the paleo-BSR that could
275 correspond to the last glacial pressure-temperature conditions, we computed the depth of the BSR for a
276 seafloor temperature 1.5°C lower than today, assuming sea-level lowstand of ~120 m for pure methane
277 hydrates and a geothermal gradient of ~30°C/km (Figure 9). Our results show that multiple BSRs can be
278 locally interpreted as the result of different stable climatic episodes, with temperature between glacial

279 values and the present-day conditions (for a mixture or thermogenic gas composition, the interval between
280 the two theoretical BSRs increases and includes the lower BSRs, see Table 1).. Nevertheless, the
281 importance of faulting and associated shift of the multiple BSRs lead us to suspect that tectonic
282 subsidence/uplift could play a major role in addition to sea level rise and thermal pulse.

283 In the Tumbes Basin, and more widely along the Peru margin, the presence or absence of a BSR is
284 largely controlled by tectonism and sedimentation (e.g. von Huene and Pecher, 1999). The Tumbes Basin
285 is defined as a complex forearc basin. It is controlled by detachment tectonics, the Tumbes and Zorritos
286 detachments, which accommodate the main subsidence phase that has been occurring since the late
287 Pliocene-Pleistocene until present time (Witt and Bourgois, 2010). We hypothesize that tectonic
288 subsidence is the main controlling factor for multiple BSRs generation. The intra-slope Mancora Basin
289 shows a nice example of such activity. Indeed, we suggest that the HAA shifted down observed in this
290 sub-basin are related to a paleo BSR, probably the same as that called 'lower BSR' observed in profile 3C.
291 The intra-slope Mancora Basin is located at the complex triple junction between the Tumbes detachment,
292 the normal fault bounding the eastern flank of Banco Peru, and the Talara detachment. It is controlled by a
293 major seaward-dipping listric fault (i.e., the Talara detachment, Witt and Bourgois, 2010), which controls
294 the subsidence of the intra-slope basin, and displaced the seafloor producing a 220 m-high scarp. The
295 listric fault and the growth of antithetic faults are at the origin of the shift of the paleo-BSR (Figures 10A
296 and 10B). Thereafter, sediment deposition thickens towards the listric fault, increasing pressure and
297 temperature, causing the dissociation of the deepest segments of the BSR. This step probably coincides
298 with the first chimneys' appearance in the intra-slope basin and the reactivation of antithetic faults which
299 facilitated fluid migration (Figure 10C). The last sediment depositions are flat lying and are not cut by the
300 antithetic faults, which suggests a reduced activity of the listric fault, and a period of relatively stable P-T
301 conditions allowing the formation of the upper BSR (Figure 10D). The preservation of the reflectivity of the
302 old BSR supposes that amount of free gas remains stable enough to prevent it from dispersing quickly by
303 diffusion (Bangs et al., 2005). Little or no fluid advection is required to explain the retention of the lower
304 BSRs. The areas where intermediate BSRs occur have in common a structural architecture characterized
305 by high concentration of normal faults. We suggest that the fracture pathways may contribute to disperse
306 BSRs faster due to upward migration of warm fluid migration which partially destroys the multiple BSRs

307 (Tréhu *et al.*, 2006). Moreover, lower BSRs in these zones are usually very faint or absent, which is
308 consistent with this hypothesis.

309 **5.3. Plumbing system and BSR**

310 The plumbing system of the Tumbes-Mancora Basin for its shallow portion is complex with faults
311 outcropping at the seafloor surface and buried to outcropping gas chimneys/pipes and pockmarks
312 (Figures 1B, 2, 5 and 6). The inferred evidence from the BSRs for hydrate bearing sediments means that
313 the fluids that circulate/migrates within these basins can be trapped due to high pressure and low
314 temperature at seafloor. The buried features such as gas chimneys show vertical migration rather than
315 stratal migration from deeper sourced fluids to the shallow subsurface. This is well depicted by the faults
316 mapped within the 3D area covered of the Mancora Basin (Figures 5 and 6). Figures 5 and 6 illustrate the
317 location of vertical discontinuities such as gas chimneys that originates from various depth levels. They
318 are not all spatially linked to the presence of the BSR. They illustrate various levels of source/root zones
319 such as compiled by Cartwright and Santamarina (2015), with the source being above, at and below the
320 BSR in various hydrates provinces. The relation between pipes/gas chimneys and hydrate is not yet fully
321 understood (e.g. Paull *et al.*, 2008). The highly heterogeneous occurrence of the root zones of pipes/gas
322 chimneys around the GHSZ and BSR might express the complex variations of mechanism related to
323 fracture induced processes due to upward migration of free gas and hydrate nucleation and/or dissociation
324 related to physical/chemical processes.

325 **6. Conclusions**

326 Seismic data acquired in the Tumbes Basin have revealed the occurrence of an extended active
327 hydrate-related BSR, and multiple BSRs observed at different sub-bottom depths below, comprising a
328 lower BSR of high reflectivity and several soft intermediate BSRs localized within the interval between the
329 active and lower BSR. We have focused our attention on the multiple BSRs which may represent
330 segments of residual BSRs in the process of dispersing, or related to a permeability barrier left behind
331 after an upward displacement of the base of the GHSZ. They have been interpreted as three events of
332 steady state in the pressure and temperature conditions, produced by climatic episodes since the last
333 glaciation associated with tectonic activities, essentially tectonic subsidence regarding the Tumbes-
334 Mancora Basins. This paper document hydrates using seismic data only. Further investigations must be

335 conducted by developing geophysical tools, and drilling cores in hydrate zones, to better understand the
336 distribution of gas hydrates in sediment and the nature of the multiple BSRs in the area.

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342 **Conflict of Interest**

343 The authors declare that they have no conflict of interest.

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471 **Figure captions and tables**

472 Figure 1: (A) Location map of the main sedimentary basins along the Peruvian margin. The red box is the
473 study area covered by seismic reflection data. The red dots mark the scientific boreholes from ODP Leg
474 112. The black dot marks the location of core V19-30 (Koutavas, *et al.*, 2006). (B) Bathymetric map of
475 the study area in the Tumbes Basin. Banco Peru, a flat shallow-depth bathymetric high, marks the NW
476 limit of the basin. The 3D seismic survey is represented by the black dashed line; the similarity attribute
477 at seafloor reflection is highlighting discontinuities such as faults. The location of seismic figures
478 illustrating bottom-simulating reflectors (BSRs) is represented by black straight lines. The red dashed
479 box shows the Mancora Basin sub area in the 3D seismic block (Figures 5 and 6). (C) SW-ENE transect
480 of the basin using 2D and 3D seismic profiles showing the main tectonic features. (D) 2D seismic profile
481 illustrating the BSR in the SW of the Mancora Basin.

482 Figure 2: (A) Uninterpreted and interpreted line showing examples of DHIs in the intra-slope Mancora
483 Basin. Seismic reflections of high amplitudes are present close to the depth of the BSR. Three horizons
484 (H1, H2, H3) have been picked at different depths in order to intersect the BSR, and differentiate high
485 amplitude anomalies (HAA) due to sedimentary or structural elements from those due to the BSR. The
486 profile shows a singular HAA located beneath the BSR (yellow triangle) identified as a flat spot in NW-
487 SE oriented profiles. (B) Example of DHIs revealing the presence of a BSR indicated by black triangles,
488 dim out and phase reversal on a sedimentary layer of high amplitude intersected by a BSR, free gas
489 bearing sedimentary layer of high amplitude ending onto a BSR, and seismic chimney rooted at the BSR
490 depth. See Figure 1B for location.

491 Figure 3: Reflection seismic lines from the combined 2D and 3D seismic dataset showing evidence of
492 BSRs, and multiple BSRs (intermediate and lower BSRs). See Figure 1B for location.

493 Figure 4: (A) Time structure map below seafloor of the distribution of the BSR, and (B) multiple BSRs.
494 Seafloor time contours are labelled for reference. (C and D) Multiple BSRs stacking details, see Figure
495 3A.

496 Figure 5: Similarity attribute map of the seafloor highlighting the location of chimneys at the seafloor (red),
 497 and buried chimneys (yellow). Seismic chimneys ending with mounds or pockmarks at the present day
 498 seafloor (α and β), and buried chimneys ending with an intra-sedimentary doming (γ) or a patch of HAA
 499 (δ).

500 Figure 6: Blended TWT-structure and similarity maps of the seafloor (A) and three horizons (H1, H2, H3)
 501 (B, C, D) showing the relationship between faults azimuth and chimneys, the rose diagrams indicating
 502 the normal fault trend. The deepest horizon evidenced the highest fault density of the Mancora Basin.

503 Figure 7: Results from a detailed analysis of the base of the gas hydrate stability zone (GHSZ) within the
 504 2D seismic dataset. (A) Water depth map assuming 1500 m/s seawater velocity; (B) Gas hydrate
 505 stability zone thickness assuming 1800 m/s sediment velocity; (C) Geothermal gradient computed
 506 across the mapped BSR. Contours interval is 200 m.

507 Figure 8: Stability conditions for gas hydrate from depth-temperature readings within the study area.
 508 Seawater temperature data compiled from World Ocean Database 2009. The theoretical curves are
 509 calculated for seawater-methane approximation with different gas compositions using the program
 510 CSMHYD of Sloan (1998).

511 Figure 9: Plots of observed upper BSR (black line), intermediate BSR (blue line), and lower BSR (yellow
 512 line), and computed positions of the upper BSR for present and glacial temperature and pressure
 513 conditions. See Figure 3 for original seismic observation of the BSRs.

514 Figure 10: Diagram showing how tectonic subsidence and sedimentation influence the depth and shape of
 515 the BSR in Figure 2A. (A) Initial state; (B) Listric normal fault developement and downward shift of the
 516 BSR; (C) Sedimentation and fault reactivation. Dissociation of hydrates (BSR) near the contact with the
 517 foot wall; (D) Sedimentation without faults reactivation. Free gas accumulation near the listric fault plane.

518 Table 1: Scenario of base of hydrate stability zone below seafloor for given water depths, different gas
 519 composition, and geothermal gradient. Observed BSRs depth is from the Tumbes Basin.

Water depth (m)		765			950			1115			1330		
Seafloor temperature (°C)		5.8			4.8			4.2			3.4		
Gas composition		100% CH4	96% CH4	90% CH4	100% CH4	96% CH4	90% CH4	100% CH4	96% CH4	90% CH4	100% CH4	96% CH4	90% CH4
Predicted GHSZ thickness (m)	geotherm 25°C/km	245	425	615	390	530	680	475	585	725	550	645	780
	geotherm 40°C/km	125	235	245	215	300	410	250	325	420	300	360	445
Observed BSR depth (mbsf)	upper BSR	225			306			432			441		
	lower BSR	351			414			567			540		

520

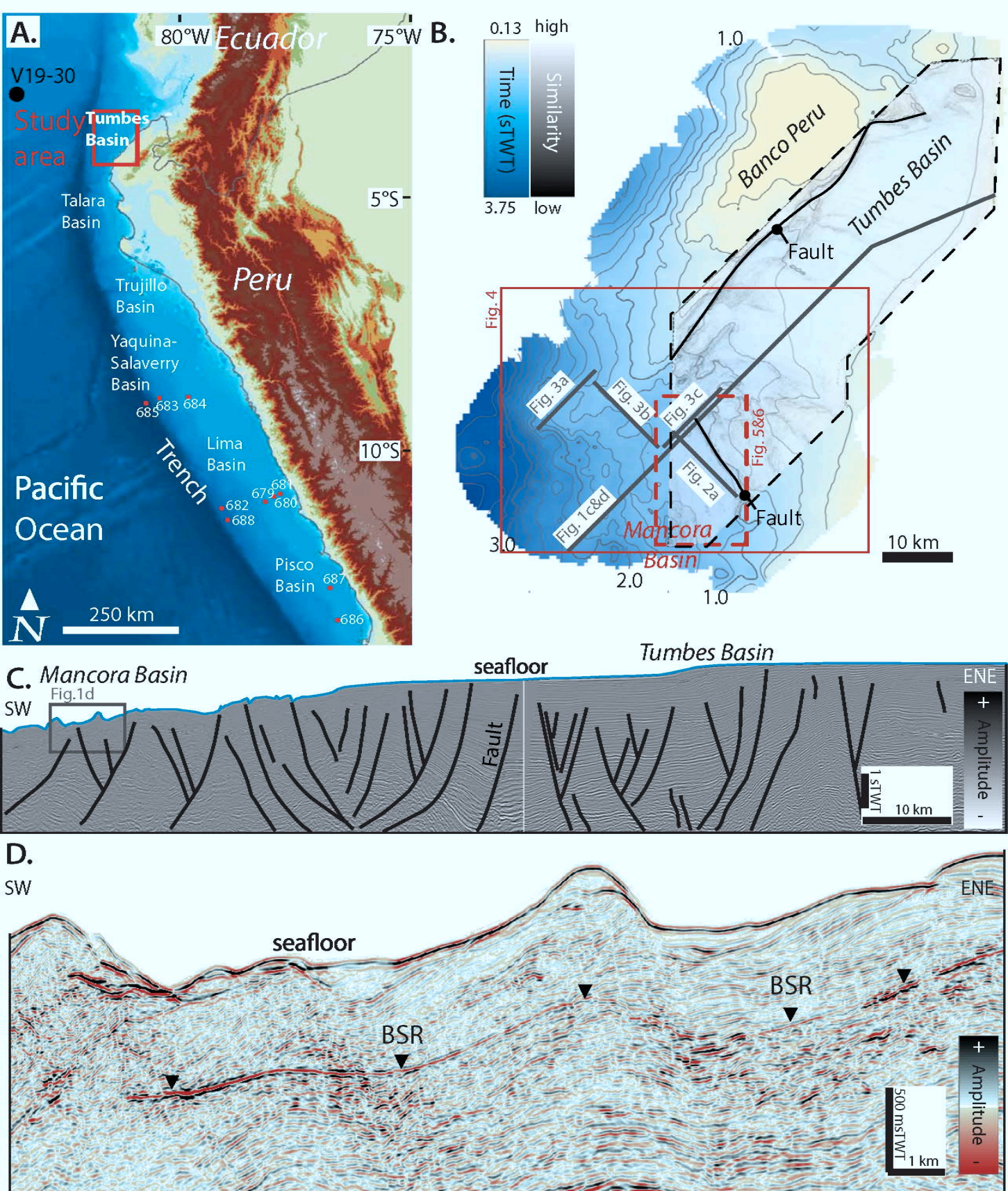


Figure 1

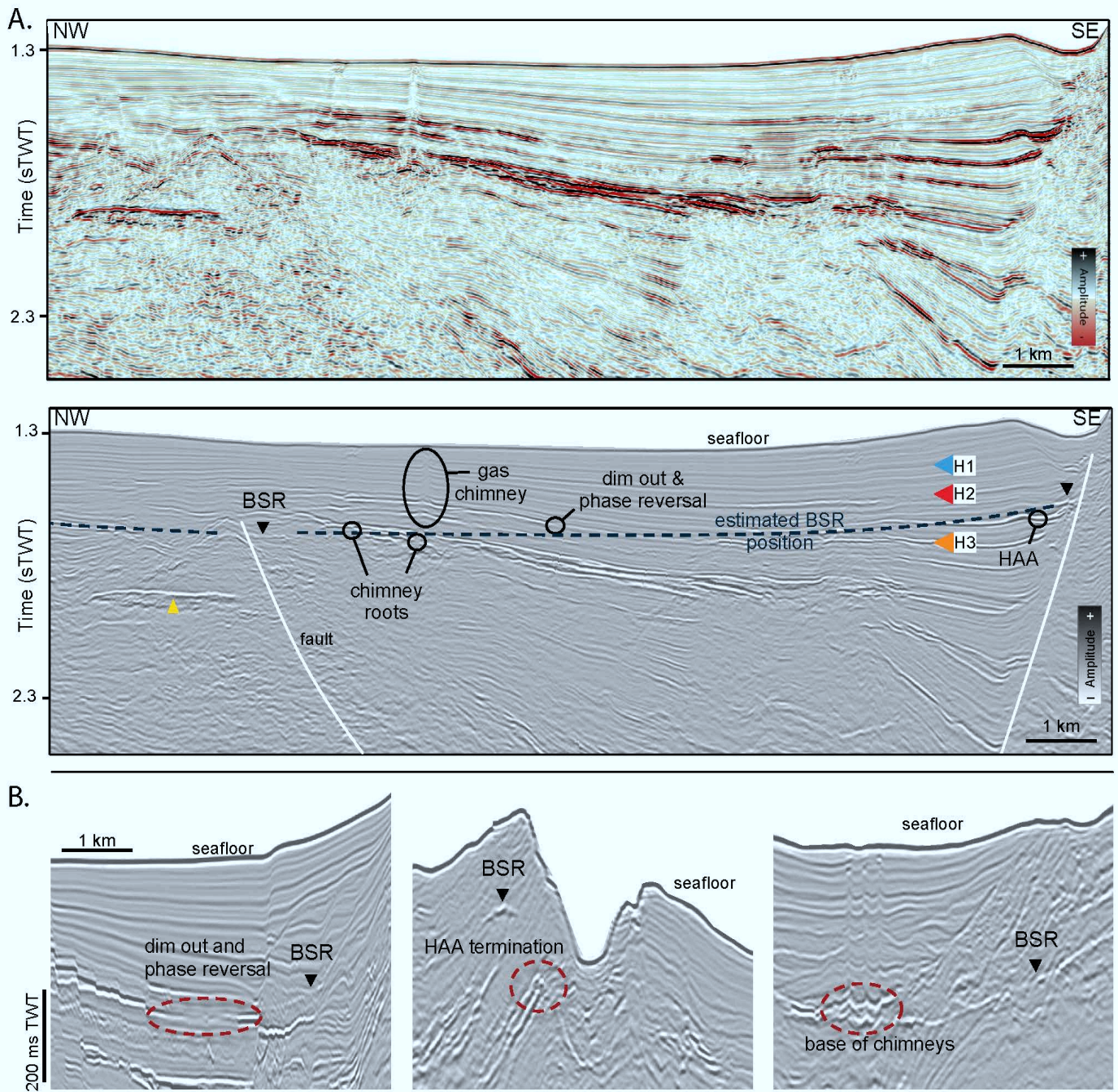


Figure 2

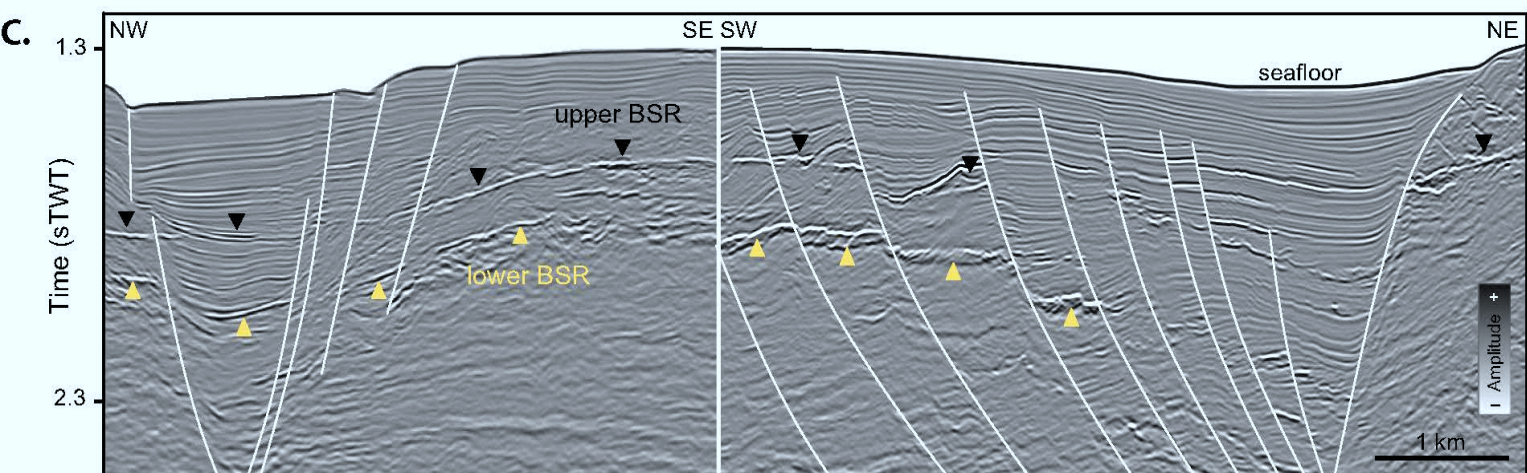
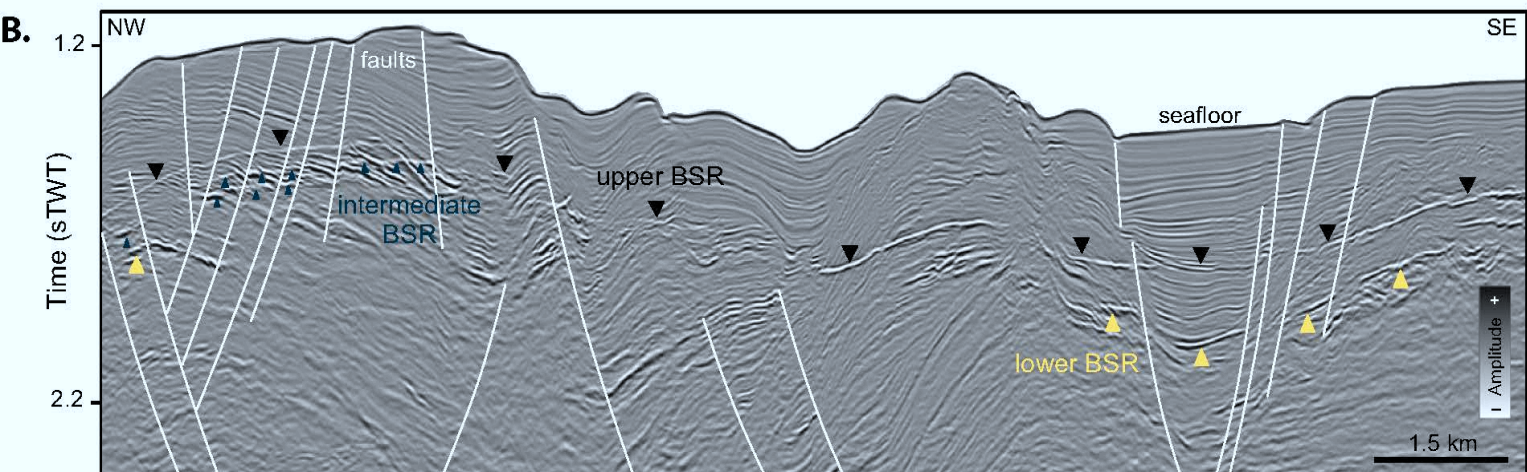
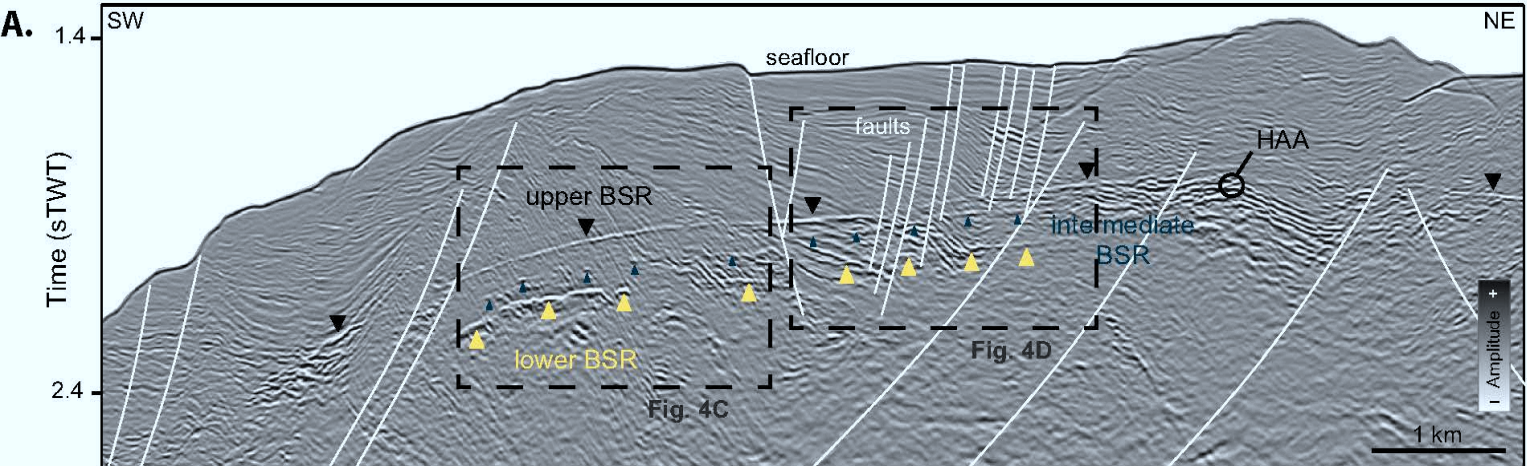


Figure 3

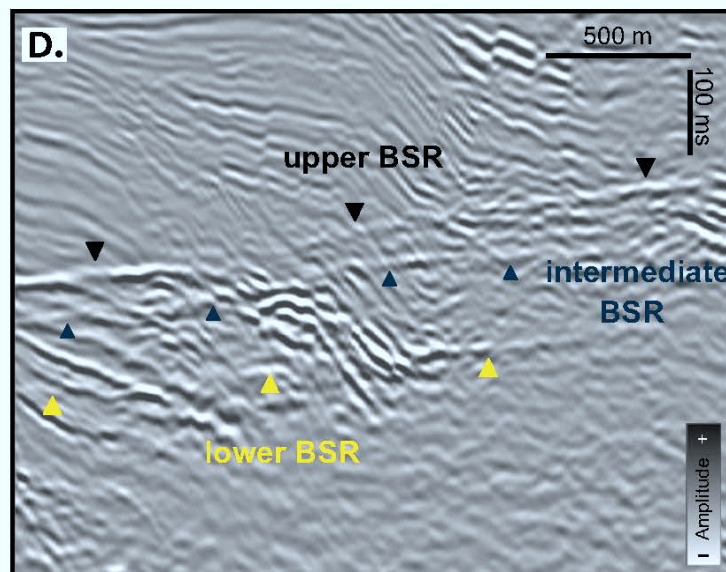
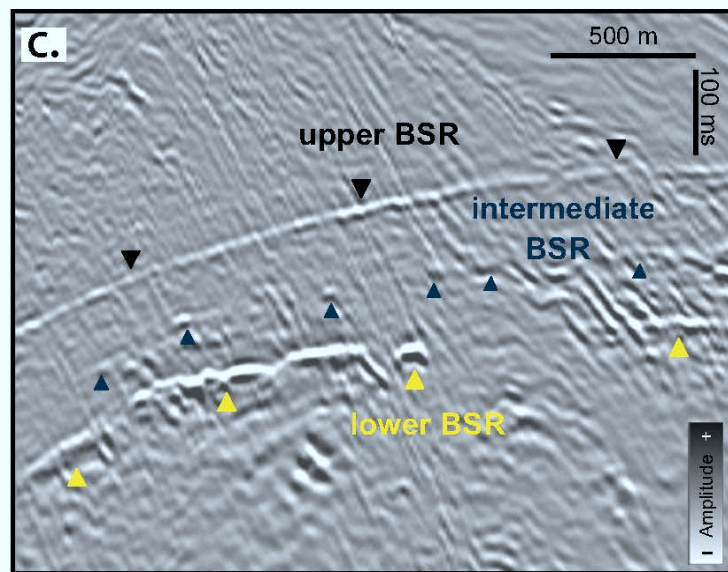
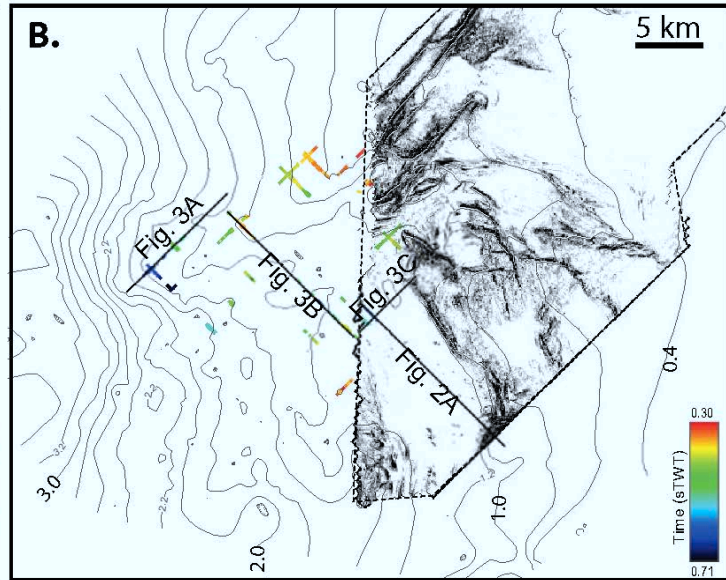
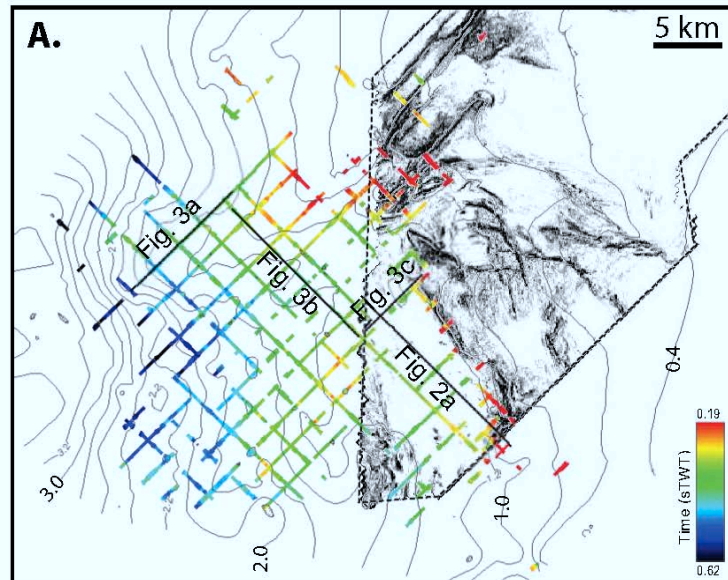


Figure 4

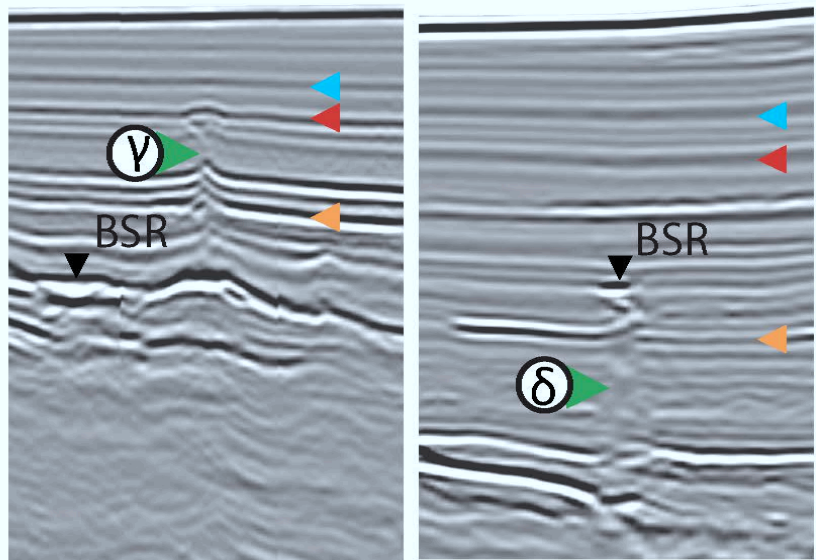
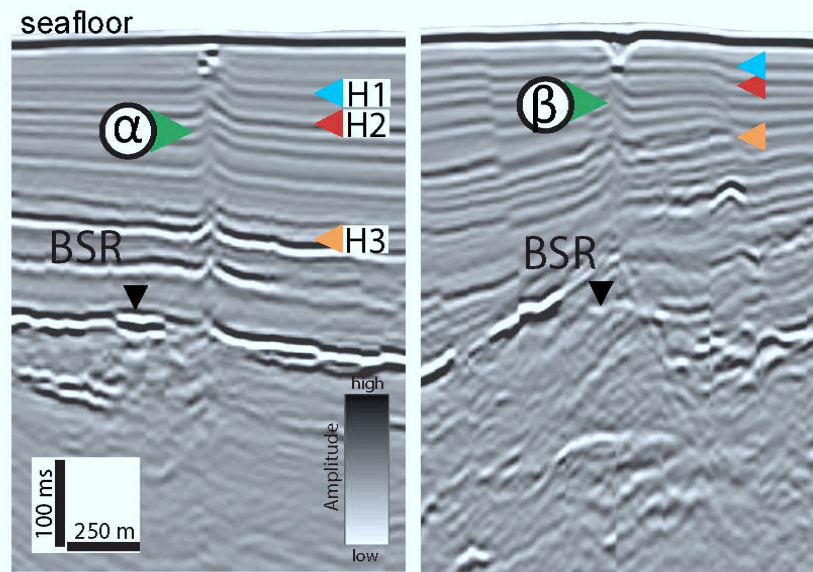
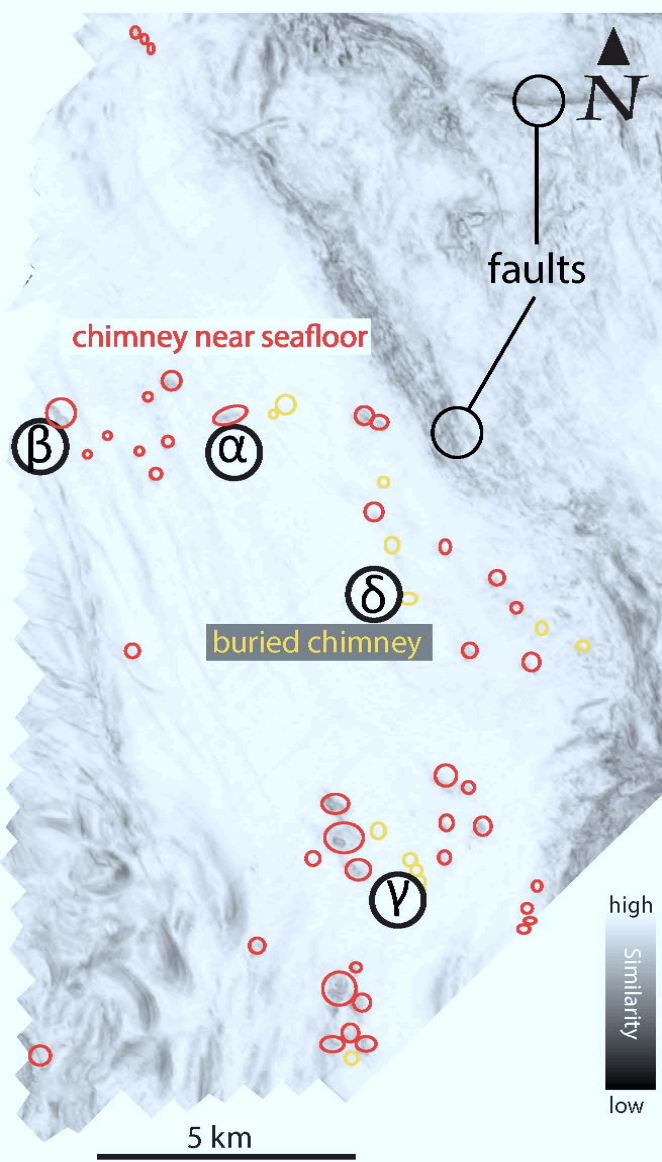


Figure 5

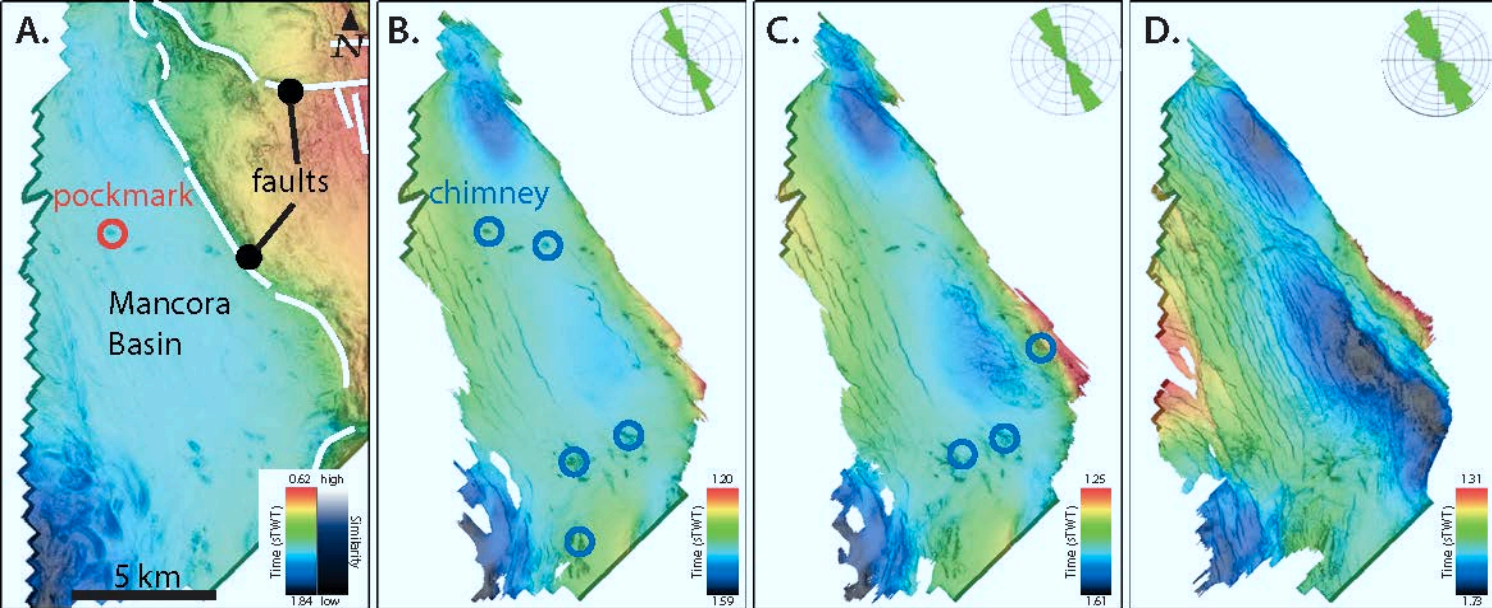


Figure 6

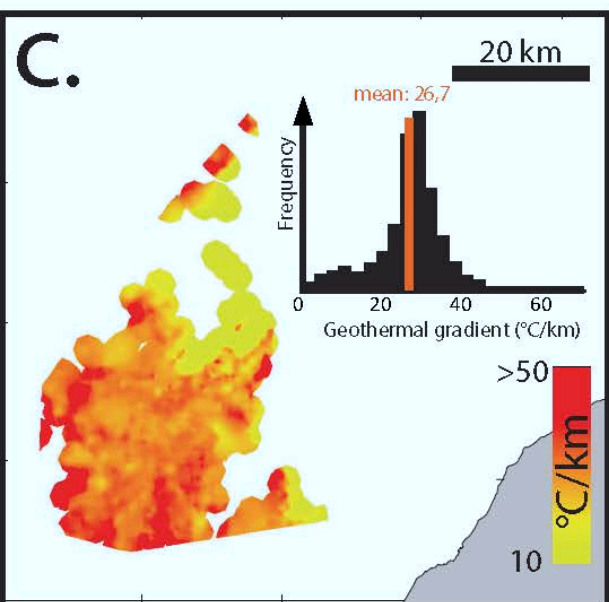
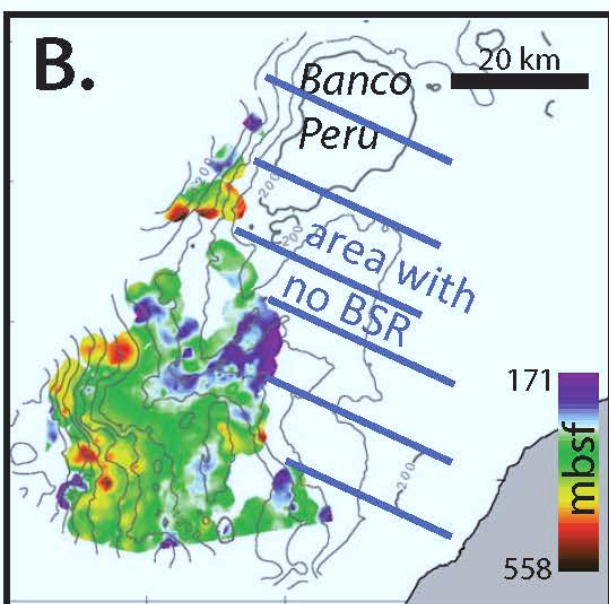
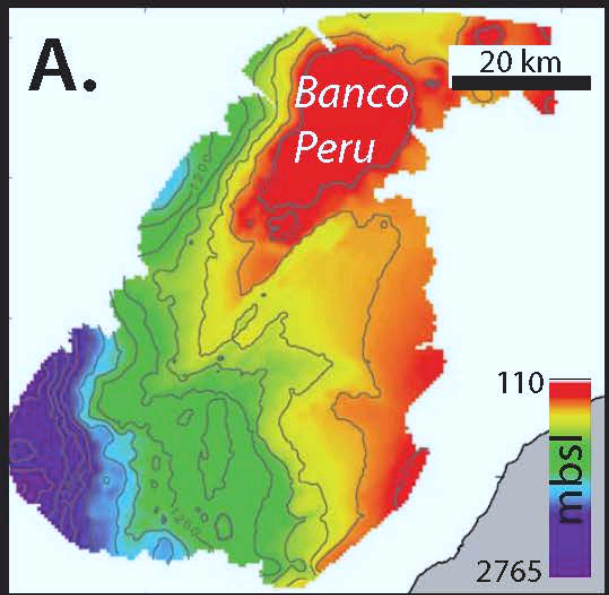


Figure 7

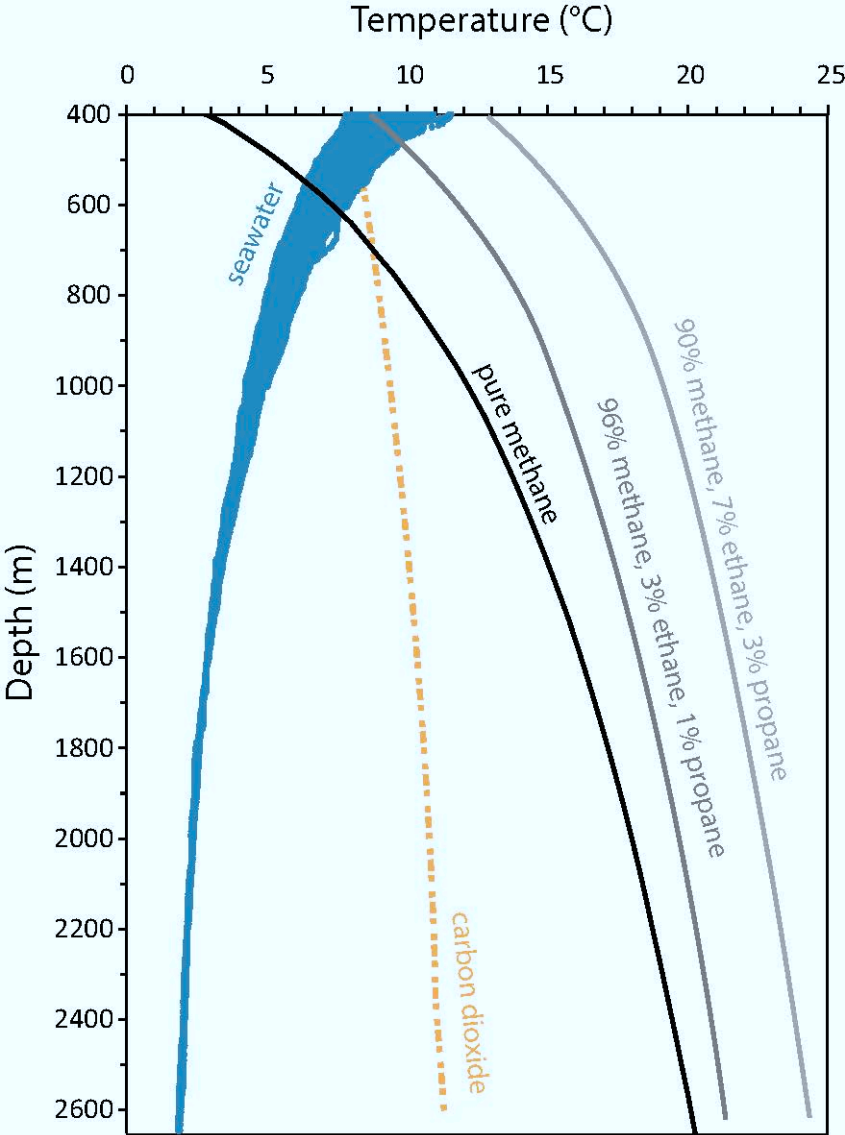


Figure 8

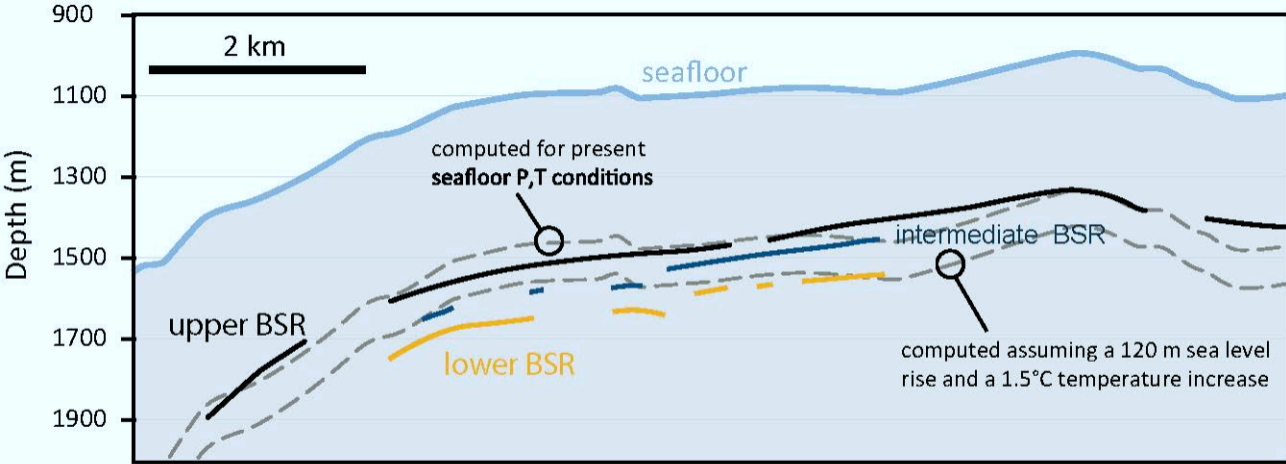


Figure 9

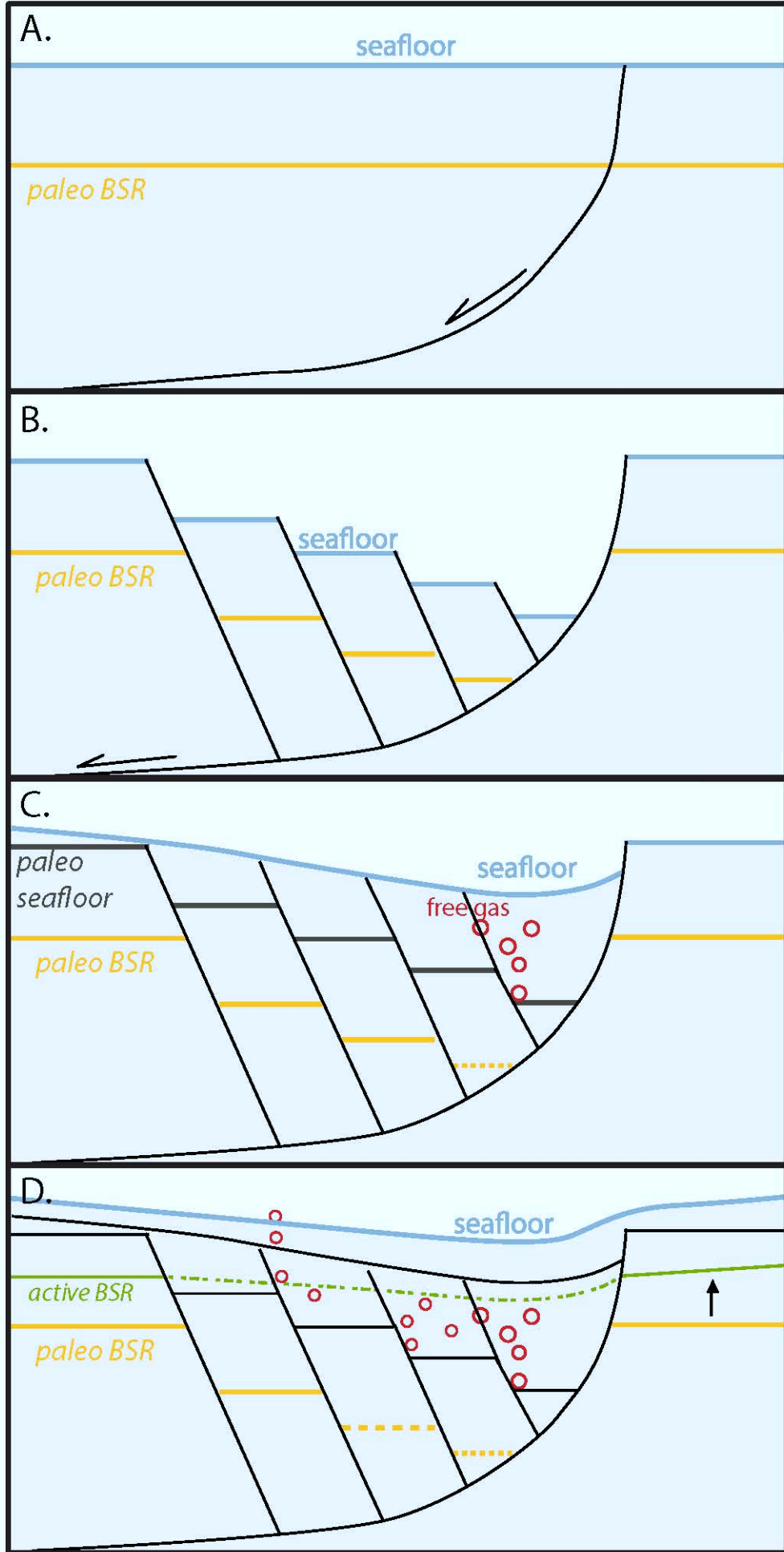


Figure 10