

Submarine salt dissolution in the Santos Basin, offshore Brazil

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Abstract

Salt dissolution occurs when evaporite-dominated rocks come into contact with NaCl-undersaturated fluids. Salt dissolution can positively and negatively impact hydrocarbon and mineral exploration, seismic imaging, drilling, and structural restorations in salt-bearing sedimentary basins. However, due to typically poor seismic imaging and a lack of borehole data, few studies have analysed the detailed morphology of salt dissolution-related features (i.e., salt karst) and how this relates to intrasalt stratigraphic heterogeneity, and associated deformation within post-salt overburden. Here we integrate high-quality 3D seismic reflection data, a regional 2D seismic reflection line, and borehole data from the Santos Basin, offshore Brazil to characterise salt dissolution-related features at the crest of buried salt diapirs.

24 We recognise: (i) flat (<10°), halite-dominated crests mainly characterised by up to 100
25 m tall, sub-circular mounds, likely comprising insoluble evaporite; (ii) rugose, evaporite-
26 interbedded crests mainly characterised by up to 100 m deep, oval-to-circular sinkholes
27 above more soluble evaporite units; and (iii) up to 60 m tall breccia pipes, capped by
28 collapse-related sinkholes within the overburden above the flat and rugose crests.
29 Reverse-basin modelling suggests salt dissolution occurred in a fully submarine
30 environment in water depths of 1900 m (\pm 100 m), which, in combination with seismic-
31 stratigraphic-relationships in post-salt strata, suggests dissolution occurred due to (i)
32 superjacent NaCl-undersaturated seawater which penetrated exposed, thin (up to 60 m)
33 overburden; and (ii) lateral updip migration of formation fluids from flanking submarine
34 channels and lobes. We are therefore able to demonstrate a direct link between the
35 intrasalt stratigraphic heterogeneity, and the style of salt karst, and related deformation
36 in post-salt sedimentary overburden, providing evidence for widespread dissolution of
37 salt in a fully submarine environment.

38

39 **1. Introduction**

40 Salt (i.e. rocks comprised of soluble minerals that precipitate from the evaporation of
41 brines) is typically dissolved when it comes into contact with NaCl-undersaturated
42 waters. Salt composition varies hence its solubility; i.e., the most soluble and weaker
43 evaporite minerals are the bittern salts (K and Mg salts, e.g., carnallite, tachyhydrite)
44 followed by halite (NaCl), whereas the least soluble are anhydrite and gypsum (e.g.;
45 Warren, 2006). Hence, when salt dissolution occurs, the more-soluble evaporites

46 (bitterns and halite) are dissolved first, resulting in the body becoming relatively
47 enriched in anhydrite and other insoluble intrasalt residue. Prolonged contact with
48 undersaturated fluids may lead to rehydration of anhydrite and the formation of
49 gypsum, a process particularly common in caprock formed at the top of diapirs (e.g.
50 Jackson et al. 1990; Hovorka, 2000; Warren, 2006). In addition, anaerobic microbial
51 activity within caprocks can lead to the deposition of thick calcium carbonate- and
52 sulphite-rich units (e.g.; Kyle and Posey, 1991; Jackson and Hudec, 2017).

53 Subaerial dissolution of salt has been extensively studied, indicating this process
54 typically results in: (i) discordant geometrical relationships between remaining salt and
55 overburden, (ii) the formation of a residual caprock or diapiric solution breccias, (iii) the
56 development of salt karst features, such as sinkholes, grooves, caves, and residual
57 mounds; and (iv) overburden deformation (e.g.; Jackson et al., 1990; Warren, 1997;
58 Cartwright et al., 2001; Abelson et al., 2006; Warren, 2006; Bruthans et al., 2009; Hudec
59 et al., 2011; Frumkin, 2013; Gutiérrez and Lizaga, 2016; Jackson and Hudec, 2017). Salt
60 karst identified in Iran resemble those related to subterranean karstic dissolution of
61 calcium carbonate, which have been imaged by seismic data and studied due to the
62 importance of carbonate rocks as hydrocarbon reservoirs (e.g. Evans et al., 1994;
63 Vahrenkamp et al., 2004; Sullivan et al. 2006; Zeng et al., 2011; Burberry et al., 2016).
64 However, salt dissolution is not restricted to the subaerial realm, occurring also in
65 submarine settings (e.g., Bertoni and Cartwright, 2005; Talbot and Augustin, 2016). For
66 example, in the Orca Basin, Gulf of Mexico a salt body is currently exposed at the
67 seabed and is currently being dissolved by NaCl-undersaturated seawater, producing
68 brines that flow downslope into an enclosed submarine brine lake (Shokes et al., 1977;

69 Tompkins and Shephard, 1979; Pilcher and Blumstein, 2007). Large-scale, likely
70 submarine dissolution of salt has also been inferred for flat- and rugose-topped diapirs
71 imaged in seismic reflection data in the Barents Sea (e.g. Koyi et al. 1995) and in the
72 Netherlands (e.g. Duin, 2001), although the detailed geometry of salt karst and
73 overburden deformation features in both these examples remain unknown.

74 Identifying salt dissolution and characterising the range of related structural styles has a
75 range of important implications and applications. First, the less-soluble residual
76 evaporite rocks at the crest of dissolved salt structures (i.e. caprock) are the source of
77 economic minerals and have the potential to become reservoir rocks (e.g., Posey and
78 Kyle, 1988; Kyle, 1999). Salt dissolution and related faulting may also generate local
79 accommodation in diapir overburden, potentially promoting reservoir deposition and
80 trap development (e.g., Ge and Jackson, 1998; Cartwright et al., 2001; Hudec et al.,
81 2011; Jackson et al., 2010). In addition, dissolution and related deformation can
82 generate mega-pores and diagenetic alterations, thus reducing the sealing properties of
83 the salt and its overburden, and making it difficult to drill through salt (e.g., Walles,
84 1993; Black, 1997; Vahrenkamp et al., 2004; Willson and Fredrich, 2005; Jackson and
85 Hudec, 2017). Accurate seismic imaging in salt-bearing sedimentary basins requires a
86 good understanding of caprock stratigraphy and associated seismic velocities variations
87 at the crest and lateral margins of salt structures (e.g., Jackson and Lewis, 2012; Jones
88 and Davison, 2014). Finally, the amount of salt dissolved from the geological record is
89 often unknown, thereby challenging our ability to structurally restore salt-bearing
90 sedimentary basins (e.g. Koyi et al. 1995; Cartwright et al., 2001; Rowan and Ratliff,
91 2012).

92 Despite being widespread, and although clearly significant in terms of its impact on
93 resource exploitation, surprisingly few studies have used 3D seismic reflection data to
94 investigate the processes and products of large-scale salt-related dissolution (e.g.;
95 Bertoni and Cartwright, 2005; Pilcher and Blumstein, 2007; Jackson and Lewis, 2012;
96 Burberry et al., 2016; George et al., 2017). This is perhaps surprising given that, despite
97 being unable to resolve sub-decametre structural or stratigraphic details, 3D seismic
98 reflection data do permit relatively detailed characterisation of salt karst-related
99 morphologies and associated overburden deformation over very large areas and for
100 several structures. When coupled with borehole data, seismic expression can be
101 correlated to salt and overburden, which can in turn be related to observed dissolution
102 structural style. A subsurface-based approach, drawing on 3D seismic reflection and
103 borehole data can thus compliment other, principally 1D (e.g. borehole) to quasi-3D (i.e.
104 field) approaches.

105 The aims of our study are to; (i) characterise the style of intra- and supra-salt,
106 dissolution-related deformation; (ii) relate deformation style to intrasalt stratigraphic
107 heterogeneity, (iii) understand the mechanisms driving salt dissolution; and (iv)
108 determine whether dissolution was submarine or subaerial, and to critically discuss
109 what this means for the regional geodynamic evolution of the study area. To achieve
110 these aims we integrate high-quality 3D seismic reflection, 2D seismic and borehole
111 data from the Santos Basin, offshore Brazil, focusing on six, very well-imaged diapirs.
112 This is an ideal location to characterise salt karst and overburden morphology, given the
113 relatively shallow burial depth (<1000 m) of the studied diapirs and resultant excellent

114 seismic reflection imaging. Furthermore, borehole data and highly reflective intra-salt
115 layers allow salt karst style to be related to intrasalt stratigraphic heterogeneity.

116

117 **2. Geological setting**

118 The Santos Basin is located in eastern offshore Brazil and originated as a result of the
119 opening of the South Atlantic Ocean between east South America and West Africa (Fig.
120 1). During the Barremian, non-marine to shallow marine sediments were deposited
121 within rift basins formed due to continental stretching (Fig. 2; e.g., Demercian, 1996;
122 Meisling et al., 2001; Gomes et al., 2002; Moreira et al., 2007). An initially isolated and
123 irregular rift-related valley was intermittently flooded by seawater in the Aptian, with
124 subsequent dessication events leading to deposition of a regionally extensive, up 2.5 km
125 thick, evaporite-dominated sequence (i.e., Ariri Formation; e.g., Szatmari 2000; Dias
126 2004; Davison 2007; Karner and Gambôa, 2007; Davison et al., 2012; Rodriguez et al. (a)
127 in press). Subsequent Albian widening and deepening of the proto-south Atlantic Ocean
128 promoted deposition of a shallow-marine carbonate platform in proximal areas and
129 marls in distal areas (Fig. 2; Moreira et al., 2007). Fully marine conditions became
130 established in the Late Cretaceous, following drowning of the Albian carbonate
131 platform. Subsequent uplift and south-eastwards tilting of this segment of the Brazilian
132 margin drove south-eastwards progradation of a thick, clastic-dominated wedge (Fig. 2,
133 e.g. Modica and Brush, 2004; Moreira et al., 2007).

134 From the Turonian to the Paleocene, deep-water systems were initially deposited within
135 a large, salt-controlled, intra-slope depocenter called the 'Albian Gap', before spilling

136 further south-eastwards into numerous smaller minibasins (e.g. Rodriguez et al.(b) in
137 press). Subsequent onshore uplift and diversion of the Paraiba do Sul river to the NE
138 during the Eocene resulted in relatively limited sediment supply to the Santos Basin,
139 with deposition dominated by suspension settling of very fine-grained clastics and
140 carbonates, and emplacement of shelf- and salt-sourced mass transport complexes
141 (MTCs) (e.g., Cobbold et al., 2001; Modica and Brush, 2004; Guerra and Underhill, 2012;
142 Rodriguez et al.(b) in press). Apart a few, albeit large, shelf-sourced MTCs (e.g., Jackson
143 2011; Rodriguez et al.(b), in press), post-Eocene deposition in the central deepwater
144 Santos Basin dominated by very fine-grained sediment (Fig. 2; Modica and Brush, 2004;
145 Moreira et al., 2007; Guerra and Underhill, 2012).

146

147 **3. Dataset**

148 We use a high-quality 3D time-migrated seismic reflection volume (provided by CGG), a
149 2D post-stack depth-migrated seismic that intersects the 3D volume (provided by
150 WesternGeco), and data from eight publicly available boreholes (Fig. 1b). Borehole data
151 are sparse across the study area, containing only cutting-derived lithology information,
152 and formation markers for the presalt, the intrasalt and postsalt sequences. Two of the
153 boreholes contain a comprehensive set of electrical logs for the intrasalt (eg. GR,
154 Neutron, Density and P-Sonic), and these allow us to tie seismic and borehole data, and
155 to assign lithology information to the mapped intervals (Fig. 2a).

156 The 2D depth seismic profile is c. 350 km long and has a record length of 16 km,
157 providing a good quality regional image along the central deep-water Santos Basin (Fig.

158 2b). The high-quality 3D seismic reflection volume covers an area of 20,122 km² and
159 contains trace data from the sea level down to 5.5 seconds two-way time (TWT). The 3D
160 dataset has a vertical sample rate of 4 ms, inline spacing (east-west) of 18.75 m and
161 crossline spacing (north-south) of 25 m. The stratigraphic units of interest (i.e.; unit 3,
162 unit 4 and the intrasalt within the crests of salt walls; Fig. 2a) lie between 3.2-3.6 s TWT
163 interval of the 3D seismic data. The dominant frequency varies with depth but it is c. 40
164 Hz in unit 3 and unit 4 and c. 37 Hz in the intrasalt units near the crest of the salt walls.
165 The vertical seismic resolution within these units is estimated to be 12 m and 30 m,
166 based on average interval velocities of 1900 m s⁻¹ for the shallowly buried overburden
167 and 4500 m s⁻¹ for the salt. The interval velocities used for the stratigraphic units of
168 interest are averages, based on checkshot data from boreholes 532A, 723C and 709 (Fig.
169 1b). Regional seismic profiles from 2D and 3D data are displayed with SEG normal
170 polarity, where a downward increase in acoustic impedance is represented by a positive
171 reflection event (black) and a downward decrease in acoustic impedance is represented
172 by a negative reflection event (red). Local seismic profiles from 3D data, which illustrate
173 detailed salt karst features, are also displayed with SEG normal polarity although, in
174 these images, a positive reflection event is red and a negative reflection event is blue.

175

176 4. Methods

177 We mapped eight key regional horizons in depth along the 2D seismic profile (Fig. 2b).
178 We mapped these horizons, excluding Basement, but including three additional intrasalt
179 horizons imaged near the diapir crests, in the 3D seismic volume in TWT (top A1, top A2

180 and top A3; Figs. 2a; 3a). A synthetic seismogram provides a tie between lithology and
181 seismic expression for the intrasalt stratigraphy and the Top Salt (boreholes 709 and
182 532A; Figs. 3a, 3b; see also Jackson et al. 2015b and Rodriguez et al.(a) in press). For the
183 post-salt stratigraphy, ages and lithology were assigned to seismic horizons based on
184 regional studies and major lithological breaks or unconformities identified in borehole
185 723C (Fig. 3c; Modica and Brush, 2004; Contreras et al.; 2010; Guerra and Underhill,
186 2012). For the detailed analysis at the crests of salt diapirs, high-resolution (i.e.; seismic
187 grid spacing of 18.75 m x 25 m) structural maps were generated for the Top Salt and
188 overburden horizons.

189 We use several seismic attributes to aid our analysis: (1) *amplitude contrast* – this
190 involves calculation of amplitude derivatives between neighbouring traces
191 (Schlumberger, 2012), and we use it here mainly in map-view to highlight structural
192 discontinuities along top salt; (2) *chaos* – this recognises disorganized seismic traces
193 within a 3D window (Randen and Sønneland, 2005), and we use it here mainly in
194 map/plan-view? to investigate and map intra-salt facies variations subcropping top salt;
195 and (3) *sweetness* - this integrates amplitude strength (envelope) and instantaneous
196 frequency (Hart, 2008), and we use it here mainly to highlight cross-sectional variations
197 in seismic facies along the crest of salt walls, and between and within key intrasalt
198 intervals.

199 We conduct reverse-basin modelling or 'backstripping' of a 2D regional seismic profile
200 to estimate the paleo-water depths at the time of which dissolution likely occurred (i.e.
201 Paleocene; see below) (for general discussion of approach and application in rift basins,
202 see Roberts et al., 2009 and Bell et al., 2014). More specifically, this technique allows us

203 to assess if dissolution occurred in the subaerial or submarine realm. We justify our
204 application of an overburden-focused, reverse-basin modelling technique (rather than a
205 full kinematic restoration of the salt) for the following reasons: (i) salt movement was
206 likely minimal during and after salt dissolution (i.e., Palaeocene); i.e. we are not
207 attempting to reconstruct the main phases of salt-related deformation, which largely
208 occurred prior to dissolution, during the Albian to Maastrichtian (e.g.; Modica and
209 Brush, 2004; Jackson et al., 2014, 2015; Rodriguez et al.(b) in press); and (ii) only very
210 limited thickness variations occur within post-salt sedimentary overburden capping flat-
211 topped diapirs, again suggesting limited large-scale, syn- to post-dissolution salt
212 movement (Fig. 2c). Reverse reverse-basin modelling technique involves removing: (1)
213 the effect of sediment load and (2) the effect of post-rift thermal subsidence of each of
214 the sedimentary layers in the overburden until the horizon of interest is reached. The
215 removal of each sedimentary layer results in the decompaction of the remaining layers
216 allowing the basin geometry at the time at which the horizon of interest was deposited
217 to be resolved.

218 A summary of reverse-basin modelling input parameters is shown in Table 1. Lithology
219 information is mainly based on the final well reports available and based on the
220 integration with seismic stratigraphy and seismic attribute analysis by Rodriguez et
221 al.(b), in press (Figs. 2c, 3c; Table 1). A key input parameter in modelling of this type is
222 the effective elastic thickness (T_e), a parameter expressing the strength of the
223 lithosphere (Watts, 1992). In this study, we use a T_e of 5 km, which is representative of
224 the Santos Basin's thinned and thus relatively weak crust, above which loads are
225 supported only locally, over relatively short wavelengths (i.e. Airy isostasy; e.g., Davison

226 et al.; 2012). Another key input parameter is the beta stretching factor (β), for which we
227 have used a range of values constrained by the 'minimum' and 'maximum' profiles
228 presented by Scotchman et al. (2006). The minimum profile presented by Scotchman et
229 al. (2006) assumes that base salt subsidence from Aptian to the Holocene is due to both
230 syn-rift and post-rift subsidence. Conversely, the maximum profile was calculated
231 assuming that base salt subsidence over the same period occurred due to post-rift
232 thermal subsidence only (Scotchman et al., 2006, 2010).

233

234 **5. Salt-related structural domains**

235 Before we describe the detailed, dissolution-related morphologies at the crests of salt
236 structures, we first describe the broad salt-related structural domains present within
237 the Santos Basin, with a focus on the external shape and internal structure of salt walls.

238 Our 2D seismic profile illustrates how salt-related deformation in the Santos Basin varies
239 from NW to SE. Overall, we identify six structural domains (Fig. 2 b, c), i.e.; (i) an
240 upslope, extensional domain, characterised by salt rollers and landward- and
241 basinward-dipping, thin-skinned listric faults; (ii) the Albian Gap, a large, intraslope
242 depocenter, which is bound on its downdip side by a large diapir, and which trapped
243 large amounts of sediment during the Cretaceous to Eocene (e.g., Jackson et al.
244 2015a); (iii) a minibasin domain, characterised by thick (> 2.5 km deep) minibasins
245 overlying thin or welded salt and bounded by up to 20 km-wide salt walls; (iv) the 'Inner
246 São Paulo Fold Belt' (ISPFB; *sensu* Jackson et al. 2015b), which is defined as a zone of
247 salt-cored folds and predominantly landward-dipping thrusts; (v) the São Paulo Plateau

248 (SPP), which is bound on its eastern margin by the 'Outer High', and which defines a
249 broad structural high characterised by a landward-dipping base salt. The SPP is capped
250 by a highly-reflective, up to 2.5 km thick salt sequence and numerous minibasins; and
251 (vi) a deep basin lying east of the Outer High.

252 The Top Salt structural map generated from our 3D seismic interpretation illustrates the
253 present salt-related deformation occurring in the study area (Fig. 4a). We focus on
254 diapirs in the minibasin domain, the ISPFB and the SPP. Based on distinctly different
255 plan-view trends, external morphologies and sizes, we identify two main types of salt
256 diapir. The first type occurs in the minibasin domain and the ISPFB, trend broadly E or N,
257 and are characterised by broadly rounded but, in detailed, somewhat rugose crests (*R-*
258 *west*; *R-central* or 'Liam'; see Jackson et al. (2015 b); and *R-east*; Figs. 4 a, b). These
259 diapirs are up 10 km wide and 4 km tall. The second type of diapir occurs in the more
260 distal part of the SPP, trend broadly N or NE, and are characterised by strikingly sub-
261 horizontal (<10° dip) crests (*F-west*, *F-central*, and *F-east*; Fig. 4 a, c). Note that *F-central*
262 and *F-east* correspond to *Jimi* and *Freddie* of Jackson et al. (2015b). These diapirs are
263 wider (up to 15 km) but not as tall (up to 2.5 km) as the rounded diapirs (Figs. 4b and
264 4c).

265 Despite their relatively simple external morphologies, many diapirs display considerably
266 greater internal structural complexity (e.g., Davison et al., 2012; Fiduk and Rowan, 2012;
267 Jackson et al., 2014a, 2015b). Of particular interest for this study is the contrast in
268 intrasalt structural style between the flat-topped diapirs, the upper parts of which are
269 invariably dominated by poorly-reflective, intra-salt sheets (Fig. 4c, e.g., Jackson et al.
270 2014a, 2015b), and the rounded salt diapirs, which may locally contain intra-salt sheets

271 (e.g. *R-east* in Fig. 4b), but which may also contain reverse shear zones and internal
272 anticlines (*R-west* and *R-central* in Fig 4b, see also Jackson et al., 2015b). This structural
273 and associated compositional variability is important when we later consider the style
274 of salt dissolution and its relationship with subcropping intrasalt stratigraphy (see
275 below).

276

277 **6. Intrasalt and postsalt stratigraphy**

278 Seismic data show that the top of the Aptian salt is characterised by a high-amplitude
279 and broadly continuous seismic event, reflecting the large acoustic impedance contrast
280 between the relatively high-velocity salt and lower velocity, non-evaporitic overburden
281 (Figs. 3b, 4b, c). Boreholes penetrating the salt indicate Top Salt correlates with a 12-56
282 m thick anhydrite (Fig. 3b). Along the crests of rounded, rugose diapirs, Top Salt exhibits
283 a discordant stratigraphic relationship with highly reflective, anhydrite-halite-carnallite-
284 interbedded, A2 and low-to-moderate-amplitude, relatively halite-rich A3 (Table 2; Fig.
285 4b). Conversely, Top Salt overlies poorly reflective, halite-rich, A1-allochthonous sheets
286 at the crests of flat-topped diapirs (Table 3; Figs. 4c; see also Jackson et al.; 2015b).

287 Seismic data show the postsalt sequence in the distal ISPFB and SPP is characterised by
288 low-to-moderate amplitude, continuous seismic reflections, except for Unit 3, which is
289 defined by unconformity-bound wedges composed of moderate-to-high-amplitude,
290 discontinuous to chaotic seismic facies (i.e., Maastrichtian-to-Palaeocene seismic unit
291 on Fig. 4c; see also Rodriguez et al.(b) in press). Above the crests of diapirs, Unit 3 is
292 dominated by low-to-moderate amplitude reflections, although its seismic expression

293 varies between salt diapirs; i.e., conformable continuous sheets, disrupted sheets with
294 apparent downlap, mounded, rotated and chaotic (SF1-SF7; Tables 2 and 3). Boreholes
295 that penetrate the ISPFB and the SPP indicate that the post-salt succession is mostly
296 dominated by fine-grained lithologies, predominantly mudstones and marls (boreholes
297 532A, 723C, 709, 594, Fig. 1b). However, a notable exception occurs on the eastern
298 flank of a distal minibasin in the SPP, where Unit 1 and Unit 3 are characterised by
299 interbedded mudstone, siltstone and sandstone (borehole 723C, Fig. 4c). The salt diapir
300 crests of interest are not penetrated by boreholes. Rodriguez et al.(b), (in press) show
301 that Unit 3 contains sandstone-rich channel-levee and lobes complexes, some of which
302 are capped by mudstone-dominated Mass Transport Complexes (MTCs). The channels
303 and lobes within Unit 3 onlap onto and dip away from some of the salt walls in the
304 study area (Fig. 4c; Rodriguez et al.(b), in press).

305

306 **7. Seismic expression of salt karst**

307 Having described the external morphology of the diapir crests, and the stratigraphy and
308 seismic expression of the salt and its overburden, we here use high-resolution top salt
309 structural maps and seismic attributes to describe salt karst features. We also describe
310 the spatial relationship between salt karst features and: (i) underlying variations in
311 intra-salt lithology; and (ii) overburden deformation patterns (Tables 2 and 3).

312

313 **7.1 Sinkholes**

314 50 ms TWT deep (c. 100 metres deep) by c. 50 to 500 m diameter, circular to oval-
315 shaped depressions occur along Top Salt (Figs. 5 and 6). The depressions are 'U'- or 'V'-
316 shaped in cross-section, with their margins dipping 60°-90° (Figs. 5 d, e). The bases of
317 the depressions are characterised by lower sweetness attribute values (Fig. 5e) and
318 higher chaos attribute values (Fig. 6e) than otherwise observed along Top Salt,
319 suggesting lateral variations in the composition and structure. Depressions are isolated
320 or clustered (Figs. 5b, 6b). Depressions are best developed along diapirs characterised
321 by rounded crests, typically underlying mounded-to-chaotic overburden (*SF6* and *SF7*),
322 and overlying halite-rich A3 and truncated, dipping, heterogeneous A2 (Table 2; Figs. 5d,
323 6d).

324 Based on their seismic expression, geometry, scale and occurrence atop a salt-rich unit,
325 we interpret these features as sinkholes or dolines that formed due to dissolution at the
326 diapir crests (cf. Spain; Elorza and Santolalla, 1998; Gutiérrez et al., 2008; Galve et al.,
327 2009; United States; Ege, 1984; Johnson, 2005, 2008). Furthermore, our analysis
328 suggests that variability in top salt subcrop, related to intrasalt structural and
329 stratigraphic variability (*R-west*, *R-central* and *R-east*), led to preferential dissolution
330 and development of sinkholes above the more soluble, halite-rich A3, and dipping, more
331 heterogeneous layers of A2 (Figs. 5d-e, 6d-e). We speculate that sinkholes preferentially
332 develop within the more soluble, halite- and carnallite-rich layers within A2. Irrespective
333 of the precise underlying lithological control on sinkhole formation, it is clear that their
334 development led to deformation of immediately overlying overburden strata (e.g., *SF6*
335 and *SF7*; Table 2).

336

337 7.2 Residual mounds

338 50 ms, TWT (c. 100 metres deep) by 50 m to 500 m in diameter, sub-circular, elongate
339 and irregular mounds occur along the Top Salt (Figs. 7-9). The local positive-relief
340 features are defined by steeply-dipping (c. 70°- 90°) walls and smooth or rugose tops
341 (Figs. 7d, 8c and 9e). We note that, in contrast to the negative-relief sinkholes described
342 above, these features are characterised by high sweetness attribute values along the
343 top salt (Figs. 7e, 8d). In addition, these mounds are bounded by high chaos attribute
344 values, representing discontinuities along the top salt and in the overburden (Fig. 8d).
345 These mounds are most evident where they appear in clusters below semi-continuous
346 to disrupted strata (*SF1*, *SF2* and *SF4*) and above poorly-reflective, A1-allocthonous-
347 sheets (e.g., *F-east*, *F-west* and *F-central*; Table 3; Figs. 7b, 8b). In addition, some
348 isolated mounds are also found along the rugose crests, overlying poorly-reflective A3
349 and highly-reflective A2 and underlying mounded-to-chaotic overburden strata (e.g,
350 *SF5*, *R-central*; Fig. 9b, e).

351 Based on their seismic expression, geometry, scale and occurrence atop a salt-rich unit,
352 we interpret these features as salt dissolution-related karst mounds formed by the
353 insoluble residuum left after dissolution of halite-rich, A1 sheets (e.g., Posey and Kyle,
354 1988; Warren, 1997; Kyle and Posey, 1991; Hovorka, 2000; Jaworska and Novak, 2013;
355 Jackson and Hudec, 2017). Geometrically similar, gypsum-dominated karst hills or
356 mounds, formed due to near-surface dissolution in the subaerial realm, have been
357 described from other sedimentary basins (e.g., Stafford et al., 2008, Chiesi et al., 2010).
358 We also suggest that the more isolated mounds rising above the crests of rounded-

359 topped diapirs represent the remains of A4 and A3 evaporites dissolved from the cores
360 of intrasalt anticlines (Fig. 9).

361

362 **7.3 Breccia pipes**

363 60 ms (TWT) (c. 60 metres) tall by c. 30 metres wide, parallel to sub-parallel, linear pipes
364 cross-cut the overburden strata (Fig. 10). The pipes are defined by downward-deflected
365 v-shaped depressions which die-out upwards (Fig. 10b). The lowest downward flexure
366 of the pipes defines apparent downlaps on the Top Salt (SF2, Table 3). The uppermost
367 downward flexure capping the pipes define subcircular to oval-shaped (up to 200 m
368 long, 100 m wide) sinkholes contained within linear (up to 2 km long, 200 m wide)
369 depressions (Fig. 11c). The edges of the linear depressions are defined by high
370 amplitude contrast attribute in plan-form (Fig. 10a). The pipes are characterised by high
371 chaos and relatively low sweetness attribute values across the overburden strata (Figs.
372 10 c, d). These vertical discontinuities are best developed in the strata above *F-central*
373 and in less extent above *F-east*, *F-west* and *R-west* (e.g., Figs. 8d, 10 and 11). The
374 sinkholes capping the pipes are locally onlapped by a relatively more continuous seismic
375 event of Paleocene-age (Fig. 11 d). Furthermore, we note that the pipes within the
376 overburden are aligned at depth with steps and seismic facies variations along the Top
377 Salt (e.g., Figs. 8c-e, 10d).

378 Based on their seismic expression, geometry, scale and occurrence in strata overlying
379 salt-rich units, we infer these features are breccia pipes or chimneys formed due to
380 collapse above dissolving diapirs. Geometrically and seismically similar, pipe-like

381 features, also flanked by downward deflected reflections, are documented in seismic
382 reflection data from other carbonate- and evaporite-bearing basins (e.g. Hardage et al.,
383 1996; Bertoni and Cartwright, 2005; Burberry et al., 2016). We infer pipes in the Santos
384 Basin are likely filled with insoluble, likely non-evaporitic sedimentary material that
385 caved in from the overburden. We can approximately constrain the timing of pipe
386 collapse based on the stratigraphic level at which related deformation terminates, with
387 this approaching suggesting Late-Maastrichtian-to-Paleocene deformation (Fig. 11d).
388 The approximate timing of dissolution-related collapse is also constrained by the
389 horizon onlapping the uppermost sinkholes, which cap the breccia pipes (e.g. Fig. 11d).

390

391

392 **8. Subaerial or submarine salt dissolution?**

393 We have provided compelling evidence for salt dissolution at the crest of several diapirs
394 in central deep-water Santos Basin. Furthermore, the spatial relationship between
395 overburden deformation (Tables 2 and 3) and underlying salt karst features (section 7)
396 suggest dissolution was subterranean, and occurred in the Paleocene, under an up to c.
397 60 m thick overburden of fine-grained strata (e.g., Figs. 8, 10 and 11). However, it is still
398 uncertain if the entire succession was submerged or exposed when dissolution
399 occurred.

400 Dissolution typically occurs in the subaerial realm (e.g.; the Zechstein salt in the North
401 Sea; Clark et al., 1998; Cartwright et al., 2001 and Texas salt diapirs; Jackson and Seni,
402 1984, Hudec and Jackson, 2011). If this was the case for the Santos Basin, this would

403 have major implications for our understanding of the post-rift subsidence profile of the
404 basin, and eustatic sea-level variations during the early Paleogene. More specifically,
405 this would indicate that the crests of the salt diapirs and a thin (c. 60 m) overburden
406 were subaerially exposed in the Paleocene. However, numerous observations suggest
407 that, in the Santos Basin, dissolution occurred in a fully submarine setting. More
408 specifically, the stratigraphic context and analysis presented by previous studies (e.g.,
409 Modica and Brush, 2004; Moreira et al., 2007; Contreras et al., 2010; de Melo Garcia et
410 al., 2012; Guerra and Underhill, 2012; Rodriguez et al (b)., in press) provide enough
411 evidence that the Santos Basin was characterised by deep waters at least since the
412 Cenomanian. We here attempt to provide a more precise estimate of water depth by
413 reconstructing the basin to the Paleocene.

414 Our backstripped profiles are shown on Figures 12 d-g; these satisfy the crustal and
415 sediment key input parameters for the central deep-water Santos Basin discussed in the
416 Methods section and shown in Table 1. We present two restorations, based on the
417 minimum (Fig. 12b) and maximum (Fig. 12c) β estimate profiles provided by Scotchman
418 et al. (2006, 2010). To estimate the paleowater depths at the top of Unit 3, the effect of
419 sediment load and post-rift thermal subsidence during Unit 4 and Unit 5 deposition are
420 removed (Fig. 12d-g). The removal of Unit 4 and Unit 5 results in the decompaction of
421 the remaining layers and illustrates the basin geometry at the end of deposition of Unit
422 3 (Figs. 12 f, g). The restoration to the top Unit 3 (i.e. Paleocene; Fig. 3c) predicts that,
423 regardless of the β factor, the diapirs were submarine when dissolution occurred, with
424 their crests lying in waters depths of 1800-2000 m (*R-west* and *F-west*, Figs. 12 f, g).

425

426

427 **9. Discussion**

428 We have provided compelling evidence for fully submarine dissolution of salt at the
429 crest of several diapirs in central deep-water Santos Basin, offshore Brazil. Furthermore,
430 we demonstrate that intrasalt stratigraphic heterogeneity along the salt wall crests
431 controlled salt karst morphology and the associated style of deformation developed
432 within the overburden (section 7). We now discuss the mechanisms that may have
433 triggered salt dissolution, and implications of our findings.

434

435 **9.1 Mechanism of salt dissolution**

436 Salt dissolution occurs by: (i) descending NaCl-undersaturated fluids, such as
437 freshwater, coming into contact with salt (superjacent dissolution; e.g., Johnson, 1997;
438 Cartwright et al., 2001; Zarei et al.; 2012); (ii) fluids moving laterally through carrier
439 beds in contact with salt (lateral dissolution; e.g.; Ege, 1984; Johnson, 1997; Warren,
440 1997); or (iii) ascending NaCl-undersaturated fluids, such as connate brines sourced
441 from sub-salt strata, coming into contact with structurally higher salt (subjacent
442 dissolution; e.g., Bertoni and Cartwright. 2005; Jackson and Lewis, 2012; Burberry et al.,
443 2016)

444 Considering these mechanisms in the context of the Santos Basin example, we suggest
445 that subjacent dissolution, with fluids sourced from subsalt stratigraphy, is unlikely
446 considering the likely impermeable nature of the very tall (>1000 ms, TWT; >2000 m),

447 evaporite-dominated diapirs and the fine-grained-dominated, flanking minibasins (Fig. 4
448 b, c). Although clastics and carbonates are present within the salt, it is in only small
449 proportions and they are likely left in welds (e.g.; Jackson et al. 2014b). Therefore, we
450 infer that dissolution of the crests occurred either by superjacent NaCl-undersaturated
451 seawater or by fluids that migrated laterally from carrier beds directly in contact with
452 the salt.

453 We therefore propose that superjacent dissolution is the only feasible mechanism for
454 driving widespread salt dissolution in the central deep-water Santos Basin during the
455 Paleocene, and in a fully submarine setting. Similar to that occurring in the Orca Basin,
456 northern Gulf of Mexico (Pilcher and Blumstein, 2007), NaCl-undersaturated seawater
457 would have penetrated the very fine-grained, but unlithified and thus highly permeable
458 overburden, driving dissolution of diapir crests. We suggest that subsequent
459 overburden deformation via fracturing, driven by underlying salt depletion, increased
460 permeability and facilitated the further ingress of NaCl-undersaturated seawater,
461 driving to more salt dissolution (Fig. 13a).

462 Considering the Paleocene age of salt dissolution, and the composition and geometry of
463 the post-salt sedimentary overburden (section 9; Figs. 13), we suggest that lateral
464 dissolution, by the migration of fluids from sandstone-rich channels directly in contact
465 with the salt, may also have contributed, locally, to salt dissolution (Fig. 13b). More
466 specifically, we infer that formation fluids may have flowed from the minibasin flanks
467 towards the diapirs crests via sandstone-rich, deepwater turbidites (Fig. 13b).
468 Furthermore, we propose that this mechanism likely promoted the dissolution of the *F-*
469 *central* and *F-west* salt walls, which are both flanked by deep-water channels and lobes.

470 For example, we interpret that formation fluids within the sandstone-rich channels
471 onlapping the crest of *F-central* became in contact with the A1-halite-rich crests and led
472 to depletion, subsidence and the formation of salt karst atop the crest. We further
473 propose three likely mechanisms that occur isolated or in conjunction, triggering the
474 dewatering of the submarine channels and lobes and the migration of fluids towards
475 the crest: i) initial compaction of the sand-rich submarine channels and lobes (cf. West
476 Africa, Pilcher and Argent, 2007); (ii) coeval salt movement which caused rotation of the
477 channels and levees during deposition (see Rodriguez et al. (b), in press); or (iii) a
478 regional basin-scale event associated to the deposition of mass transport complexes
479 (MTCs) in the Palaeocene and leading to the escape of overpressure fluids.

480 This dissolution mechanism could also explain the variations in the magnitude and style
481 of dissolution between the crests of flat-topped salt walls. For example, we observe that
482 *F-west* seem to have dissolved more relative to *F-east* given the larger number of
483 thicker and widespread karst mounds forming the highly-reflective caprock (compare
484 Fig.7 with 8). Related to this, we note that submarine channels and lobes within Unit 3
485 occur on both sides of the highly-dissolved crest of *F-west* (Rodriguez et al. b; in press).
486 Moreover, *F-central* shows more depletion of the evaporite-dominated crest adjacent to
487 the flanking submarine channel (Fig. 11). Conversely, submarine channels are not
488 observed at seismic scale next to *F-east*; suggesting that superjacent dissolution by
489 NaCl-undersaturated seawater may have caused the relatively lower magnitude
490 dissolution observed at its crest.

491

492

493 9.2 Implication of salt dissolution for petroleum systems development

494 Salt may represent a seal or a reservoir, and salt-related deformation may generate
495 traps. A key challenge when understanding reservoir compartment into salt is
496 characterising the size, continuity, connectivity of collapse-related features, largely due
497 to poor seismic imaging and sparse wells. We here show that salt dissolution can
498 significantly influence the structure of overburden strata (section 7). In this study, we
499 illustrate a variety of reflection configurations within strata above dissolved salt walls,
500 which are strongly dependent of the underlying intrasalt stratigraphy, the timing of
501 deposition relative to dissolution and the magnitude of underlying salt-related
502 dissolution (Tables 2 and 3). For example, we show that the dissolution of evaporites-
503 interbedded salt crests can result in the truncation of the intrasalt stratigraphy and the
504 formation, above, of residual less-soluble caprock that can sometimes preserve the
505 dipping of underlying intrasalt units (Table 3; Fig. 13). The complex reflection
506 configurations and the composition of the overburden can be highly variable comprising
507 a combination of less-soluble residual evaporites combined with sediments collapse
508 from the overburden during subterranean salt depletion (Fig. 13c).

509 10. Conclusions

510 The integration of 2D and 3D seismic reflection and borehole data has revealed
511 evidence of submarine salt dissolution in the Santos Basin, offshore Brazil:

- 512 1. Seismic stratigraphy and seismic attribute analysis illustrate salt karst features at the
513 crests of salt diapirs consisting of: (i) up to 100 m thick, sub-circular, residual
514 mounds rising above nearly horizontal ($<10^\circ$) Top Salt; (ii) up to 100 m deep, oval-to-

515 circular, dissolution sinkholes below the main level of the Top Salt; and (iii) up to 60
516 m tall breccia pipes capped by collapse sinkholes within the overburden. Styles of
517 dissolution identified suggest a direct link between the salt karst morphologies and
518 the intrasalt stratigraphic heterogeneity along the top salt.

519 2. Seismic-stratigraphic-relationships in post-salt strata indicate several deformation
520 patterns within the overburden; from local disruption of conformable sheets,
521 rotation and apparent downlap, mounds and highly chaotic. The magnitude of
522 deformation within the overburden is controlled by the magnitude of dissolution of
523 the underlying evaporite-dominated crests; thus, indicating subterranean salt
524 dissolution.

525 3. Reverse-basin modelling indicates that salt dissolution occurred in a fully submarine
526 environment in water depths of 1900 m (\pm 100 m).

527 4. Widespread dissolution occurred due to NaCl undersaturated seawater during
528 partial salt diapir exposure (under an up to 60 m thick, fine-grained dominated
529 overburden) at the seabed; and locally, due to (ii) dissolution by formation fluids
530 migrating from Late-Maastrichtian-to-Paleocene submarine channels and lobes
531 directly in contact with the salt-dominated crests.

532 5. Results presented in this study has direct implications for reservoir characterisation
533 and sealing capacity of the crests of salt diapirs and its overburden.

534

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536 We would like to thank CGG for providing access to the 3D seismic data and for granting
537 permission to publish the results of this study. We also thank Statoil and ANP Brazil for

538 providing access to the borehole data. Schlumberger WesternGeco is also gratefully
539 acknowledged for providing 2D seismic regional data, partial funding and support of this
540 work.

541

542 **12. Figure captions**

543 **FIGURE 1:** (a) Eastern Brazil salt-dominated sedimentary basins highlighting the location
544 of the Santos Basin, offshore Brazil; (b) Study area in the central deep-water Santos
545 Basin. Location of 2D seismic profile, 3D seismic reflection and borehole data available
546 for the study.

547 **FIGURE 2:** (a) Seismic stratigraphic framework; key intrasalt stratigraphic intervals A1-
548 A4 for this and previous studies (Jackson et al., 2014, 2015; Rodriguez et al.(a) in press).
549 B1, B2 and B3 refer to competent layers or 'beams' defined by high amplitude
550 continuous reflections. D1, D2 and D3 refer to ductile detachment zones defined by
551 acoustically transparent, poorly continuous reflections (Fiduk and Rowan, 2012). (b) 2D
552 depth seismic profile illustrating salt-related structural domains in the Santos Basin. (c)
553 Geoseismic profile with interpreted seismic units.

554 **FIGURE 3:** (a) Borehole (709) and seismic expression for the intrasalt stratigraphy. A1-
555 A4 intrasalt key stratigraphic intervals are defined by vertical variations in seismic facies
556 and the integration with borehole data. Intrasalt lithology was identified based on the
557 typical well log response for evaporites for a combination of wireline logs; i.e., density
558 (RHOB), sonic (DT), neutron porosity (NPHI) and gamma-ray (GR) (see also. Jackson et
559 al., 2015; Rodriguez et al., in press); (b) Borehole (532A) and seismic expression of the
560 Top Salt in a structurally-low and relatively undeformed area; (c) Borehole (723C) and

561 seismic expression of the post-salt sedimentary overburden. Key post-salt seismic units
562 are defined based on vertical variations in seismic facies and the integration with
563 borehole data.

564 **FIGURE 4:** (a) Top salt structural map with locations of salt walls of interest; (b) Seismic
565 section across salt diapirs with rounded and rugose crests; (c) Seismic section across salt
566 diapirs with flat crests.

567 **FIGURE 5:** Seismic expression of salt dissolution-related sinkholes: (a) R-west top salt
568 structural map; (b) Salt karst along Top Salt and intrasalt stratigraphy subcropping the R-
569 west salt diapir; (c) Amplitude contrast attribute map for R-west Top Salt highlighting
570 the sinkholes along Top Salt, see Figure 5a for location; (d) Seismic section along the
571 crest of R-east illustrating the geometry of sinkholes (indicated by white arrows) and
572 their relationship to halite-rich A3 intrasalt unit. Location is shown on Figure 5c; (e)
573 Sweetness attribute of the seismic section on (d).

574 **FIGURE 6:** Seismic expression of salt dissolution-related sinkholes: (a) R-east top salt
575 structural map; (b) Salt karst along Top Salt and Intrasalt stratigraphy subcropping R-
576 east salt diapir; (c) Amplitude contrast attribute map for R-east Top Salt highlighting the
577 sinkholes along Top Salt, see Figure 6a for location; (d) Seismic section along the crest of
578 R-east illustrating the geometry of sinkholes (indicated by white arrows) and their
579 relationship to dipping-A2 intrasalt stratigraphy. Location is shown on Figure 6c; (e)
580 Chaos attribute of the seismic section on Figure 6d highlighting the sinkholes along the
581 Top Salt.

582 **FIGURE 7:** Seismic expression of residual mounds: (a) F-east top salt structural map; (b)
583 Intrasalt unit subcropping F-east salt diapir; (c) Amplitude contrast attribute map for F-

584 east Top Salt highlighting residual mounds above the nearly-horizontal Top Salt; (d)
585 Seismic section along the crest of F-east illustrating residual mounds above the main top
586 salt level (mounds are indicated by white arrows). See Figure 7c for location; (e)
587 Sweetness attribute for section on Figure 7d highlighting potential facies variations
588 along the Top Salt.

589 **FIGURE 8:** Seismic expression of residual mounds: (a) F-west Top Salt structural map; (b)
590 Salt karst along Top Salt and intrasalt stratigraphy subcropping F-west Top Salt; (c)
591 Seismic section along the crest of F-west illustrating residual mounds defined by highly-
592 reflective packages along the Top Salt (mounds are indicated by white arrows). See
593 location on (a) and (b); (d) Chaos attribute for the seismic section on (c) highlighting the
594 discontinuities along the Top Salt and within the overburden; (e) Sweetness attribute
595 for section on (a) illustrating the facies variations along Top Salt and within the mounds.

596 **FIGURE 9:** Seismic expression of residual mounds: (a) R-central Top Salt structural map;
597 (b) Salt karst morphology and intrasalt stratigraphy subcropping R-central Top Salt; (c)
598 Zoom into Top Salt structural map highlighting the location of the residual mounds; (d)
599 Amplitude contrast map of 8 c; (d) Seismic section across mounds on R-Central salt
600 diapir illustrating remnant mounds after A4 and A3 dissolution. See (c) and (d) for
601 location.

602 **FIGURE 10:** Seismic expression of breccia pipes or chimneys within the overburden: (a)
603 Amplitude contrast seismic attribute time slice highlighting the edges of the breccia
604 pipes. See location on Figure 11a; (b) Seismic section across the crest of F-central and
605 overburden strata. Breccia Pipes are indicated with white arrows; (c) Chaos seismic
606 attribute for the section on Figure 10b highlighting the breccias cross-cutting the

607 overburden strata; (d) Sweetness seismic attribute for the section on Figure 10b. Some
608 of the breccia pipes correlate with facies variations along the Top Salt.

609 **FIGURE 11:** (a) F-central Top Salt structural map; (b) Salt karst morphology and intrasalt
610 stratigraphy along the crest of F-central; (c) Structural map for the seismic horizon
611 within the overburden (blue on (d)) highlighting the collapse associated to dissolution of
612 the underlying halite-rich crest and the top of a channel flanking the salt wall; (d)
613 Seismic section across F-central and the flanking minibasin illustrating the onlap of the
614 channel and discontinuities within the overburden.

615 **FIGURE 12:** (a) Input model used for basin restoration based on the interpretation of 2D
616 depth seismic profile (Figure 2b). See Key on Figure 2a; (b) Minimum Beta Stretching
617 Factor along the 2D seismic profile (after Scotchman et al., 2006); (c) Maximum Beta
618 Stretching Factor along the 2D seismic profile (after Scotchman et al., 2006); (d) Basin
619 restoration to the mid-Oligocene (28 Ma) based on the minimum Beta Stretching Factor
620 profile; (e) Basin restoration to the mid-Oligocene (28 Ma) based on the maximum Beta
621 Stretching Factor profile; (f) Basin restoration to the Paleocene (60 Ma) based on the
622 minimum Beta Stretching Factor profile; (g) Basin restoration to the Paleocene (60 Ma)
623 based on the maximum Beta Stretching Factor profile

624 **FIGURE 13:** Mechanisms and styles of submarine salt dissolution: (a) Superjacent
625 dissolution by NaCl-undersaturated seawater penetrating the very fine-grained,
626 unlithified overburden during exposure at the seafloor; (b) Dissolution due to fluids
627 migrating from carrier beds directly in contact with the salt; (c) Residual Solution breccia
628 formed by the preferential depletion of the evaporite-dominated crests and collapse of
629 the overburden.

630

631

632 **13. Table captions**

633 Table 1: Post-salt sediment key input parameters for the basin restoration based on
634 seismic interpretation and well reports available.

635 Table 2: Overburden seismic expression and thickness variations above dissolved rugose
636 crests.

637 Table 3: Overburden seismic expression and thickness variations above dissolved flat
638 crests.

639

640 **14. References**

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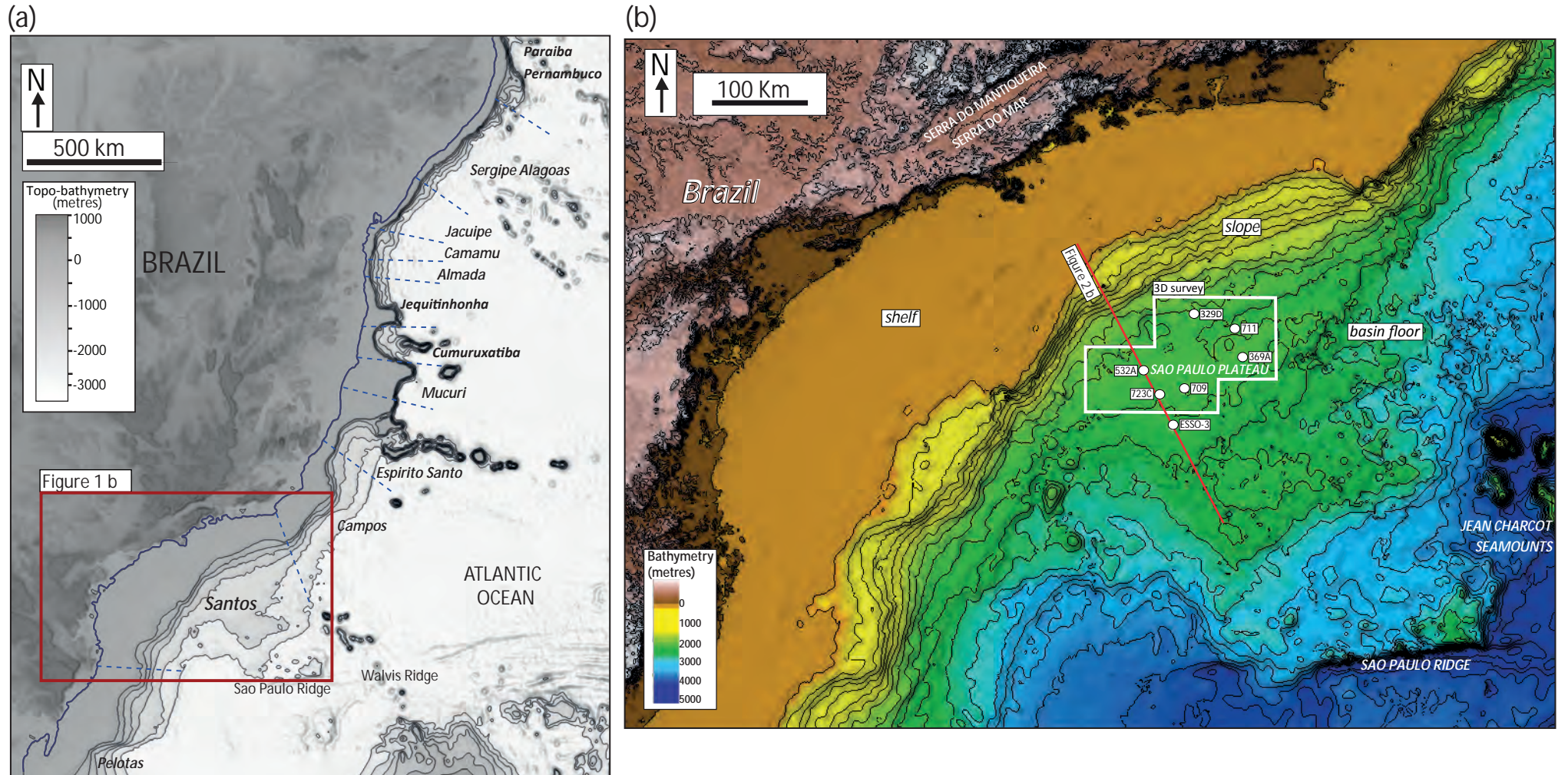


FIGURE 1 (a) Eastern Brazil salt-dominated sedimentary basins highlighting the location of the Santos Basin, offshore Brazil; (b) Study area in the central deep-water Santos Basin. Location of 2D seismic profile, 3D seismic reflection and borehole data available for the study.

(a)

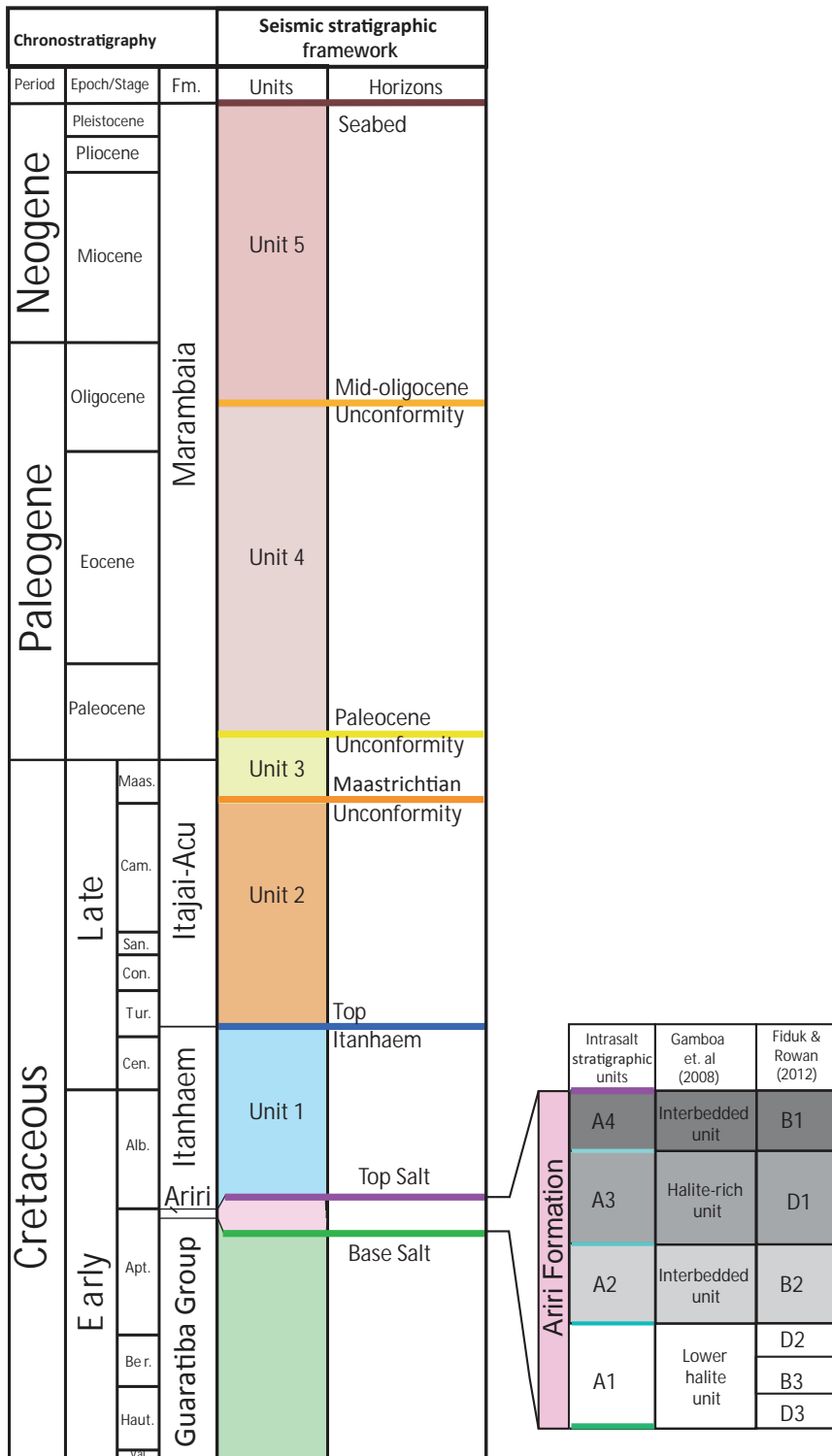


FIGURE 2: (a) Seismic stratigraphic framework; key intrasalt stratigraphic intervals A1-A4 for this and previous studies (Jackson et al., 2014, 2015; Rodriguez et al.(a) in press). B1, B2 and B3 refer to competent layers or ‘beams’ defined by high amplitude continuous reflections. D1, D2 and D3 refer to ductile detachment zones defined by acoustically transparent, poorly continuous reflections (Fiduk and Rowan, 2012). (b) 2D depth seismic profile illustrating salt-related structural domains in the Santos Basin. (c) Geoseismic profile with interpreted seismic units.

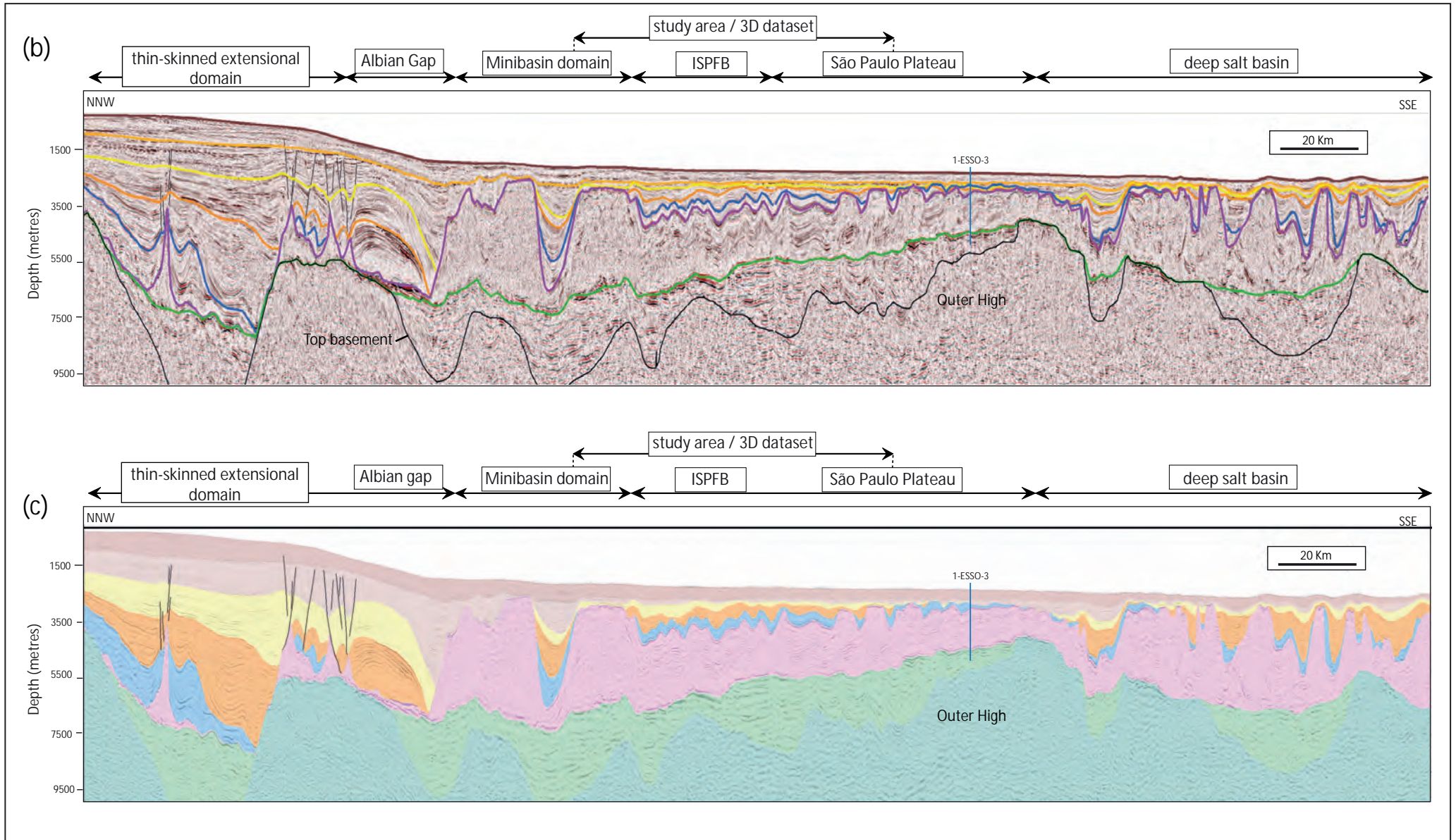


Table 1: Post-salt sediment key input parameters for the basin restoration based on seismic interpretation and well reports available

Horizon age (Ma)	Horizon name	Unit name	Lithology	Near-surface porosity (%)	Decay constant (1/km)	Matrix density (g/cc)
0	Top Marambaia (Seabed)	Unit 5	90% shale 10% sand	61.6	0.49	2.71
~28	Mid Oligocene Unconformity	Unit 4	80% shale 20% sand	60.2	0.46	2.71
~60	Paleocene unconformity	Unit 3	40% shale 60% sand	54.6	0.37	2.68
~67	Maastrichtian unconformity	Unit 2	60% shale 40% sand	57.4	0.41	2.69
~95	Top Itanhaem	Unit 1	70% shale 30% limestone	65.1	0.57	2.72

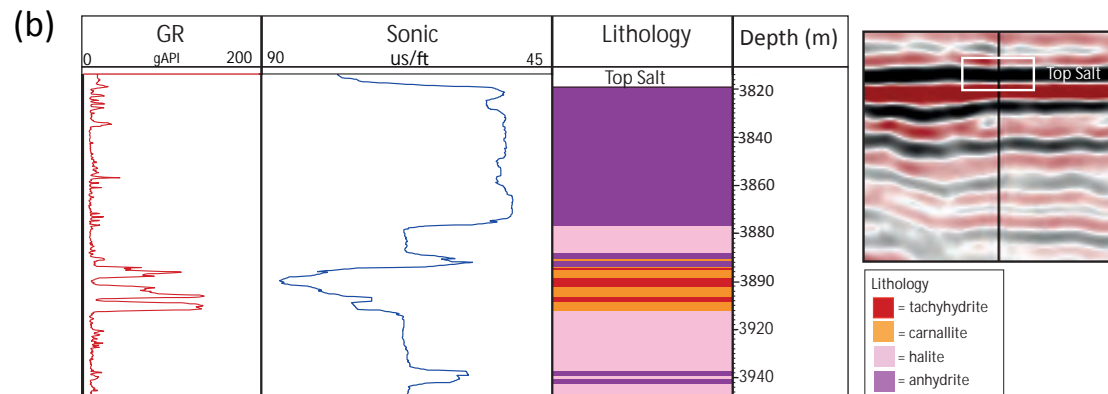
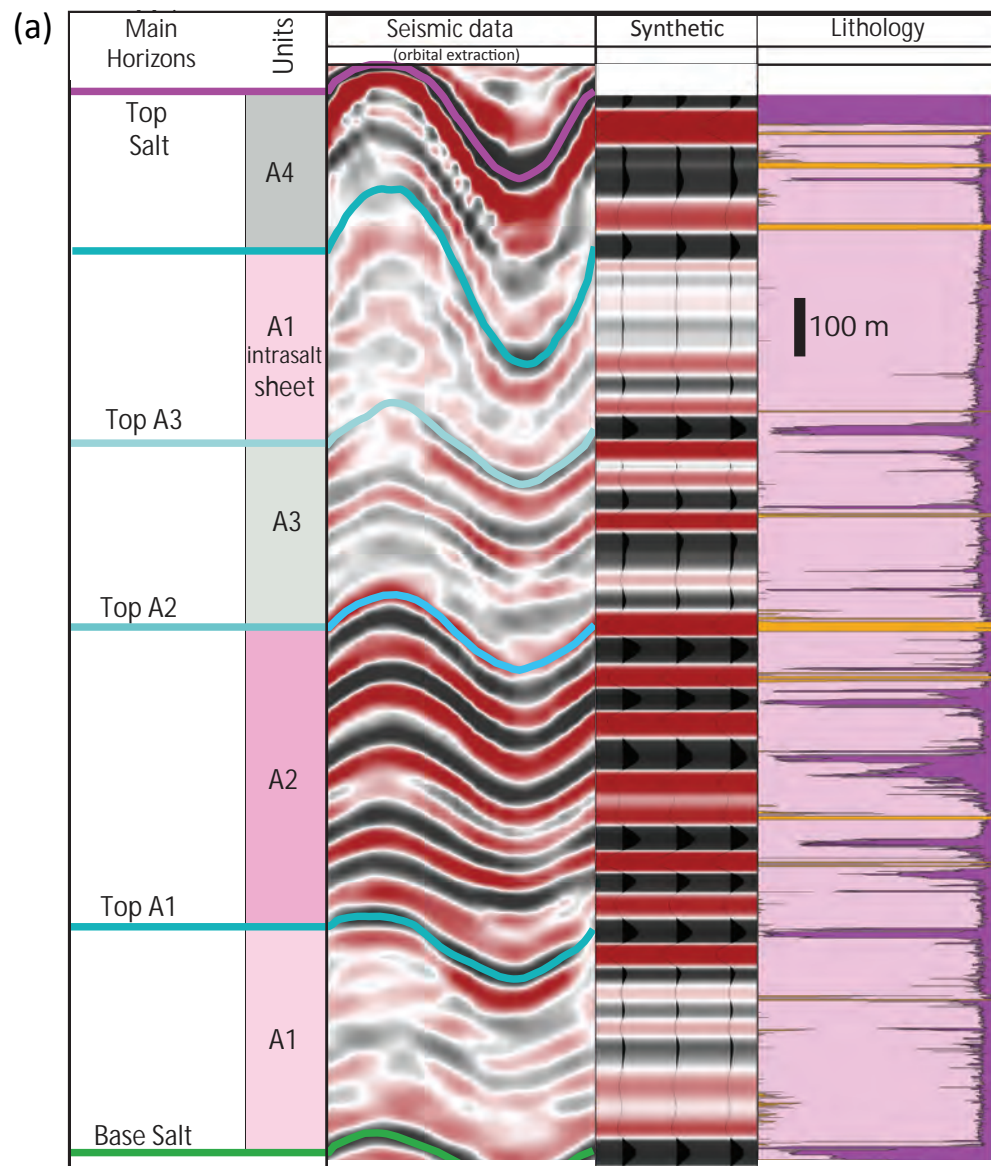
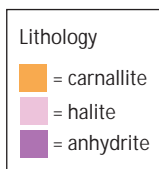


FIGURE 3: (a) Borehole (709) and seismic expression for the intrasalt stratigraphy. A1-A4 intrasalt key stratigraphic intervals are defined by vertical variations in seismic facies and the integration with borehole data. Intrasalt lithology was identified based on the typical well log response for evaporites for a combination of wireline logs; i.e., density (RHOB), sonic (DT), neutron porosity (NPHI) and gamma-ray (GR) (see also. Jackson et al., 2015; Rodriguez et al., in press); (b) Borehole (532A) and seismic expression of the Top Salt in a structurally-low and relatively undeformed area; (c) Borehole (723C) and seismic expression of the post-salt sedimentary overburden. Key post-salt seismic units are defined based on vertical variations in seismic facies and the integration with borehole data.



(c)

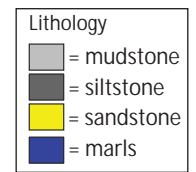
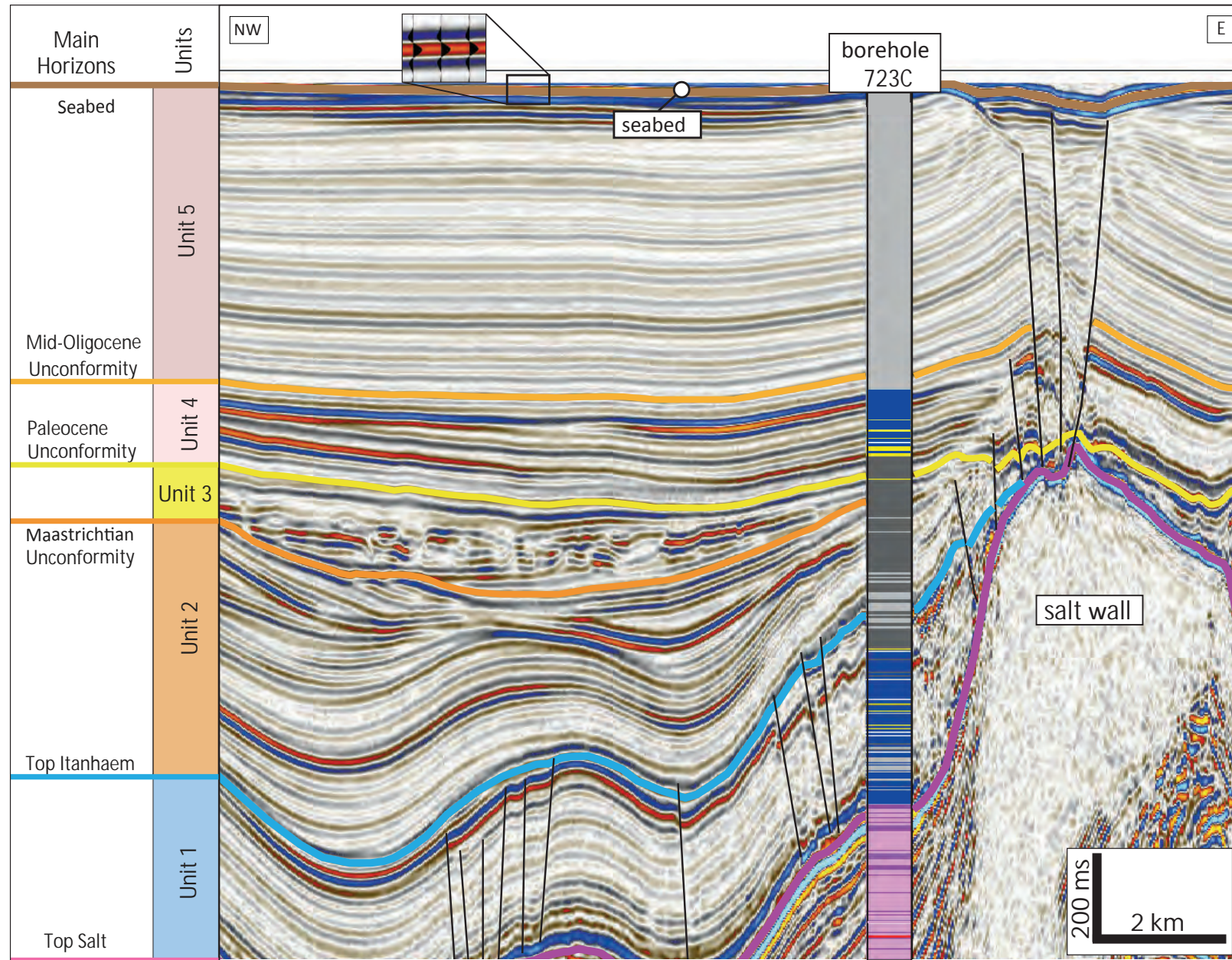


Table 2 : Overburden seismic expression and thickness variations above dissolved rugose crests.

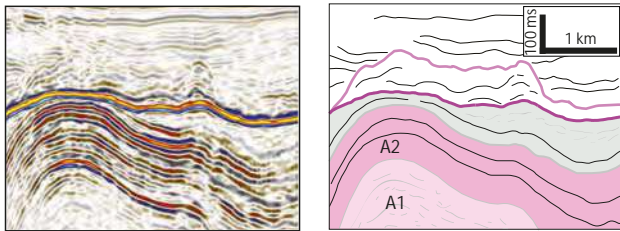
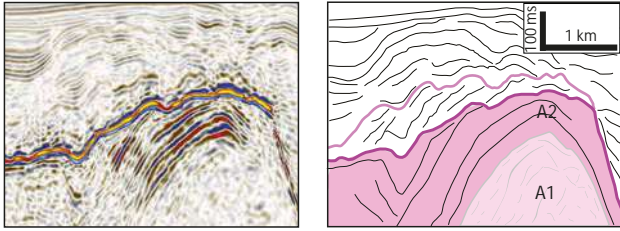
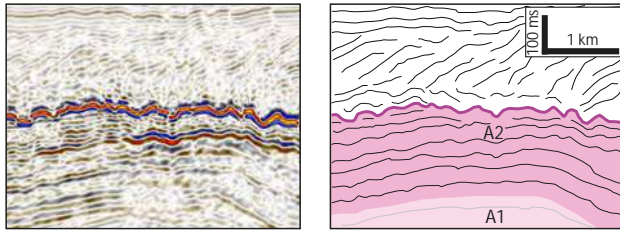
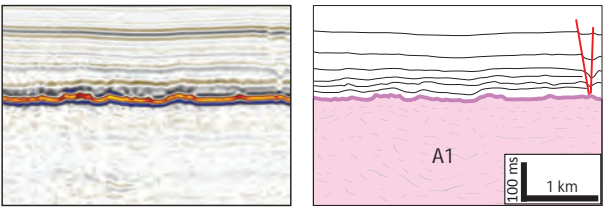
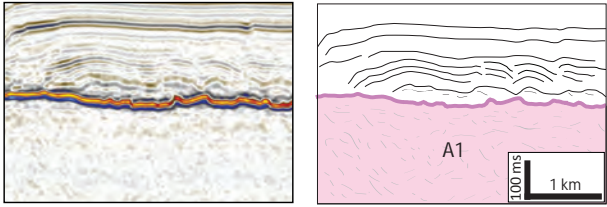
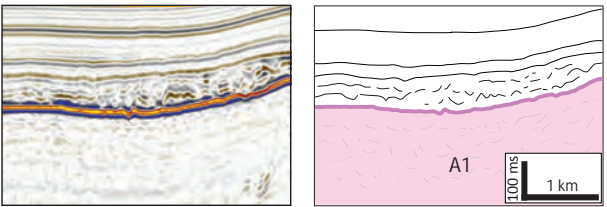
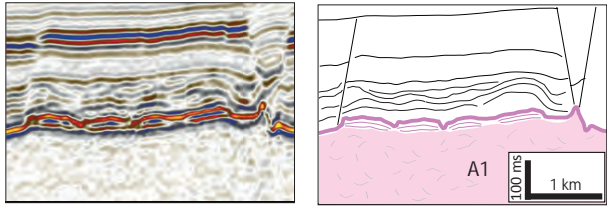
	Seismic facies	External shape relationship to salt crests	Amplitude, continuity reflection configuration	Ocurrence	Thickness variations	Interpretation
SF5		<p>mound</p> <p>sub-parallel to intrasalt stratigraphy overlapped by overburden</p>	<p>low-to-moderate amplitudes discontinuous suparallel to wavy to chaotic</p>	<p>Rugose crest-central</p> <p>Above truncated A3 reflections</p>	<p>mounds are thicker where more evaporites depletion is evident</p>	<p>Interpretation1: residual solution breccia or caprock composed by less-soluble and insoluble intrasalt and overburden lithology (e.g. anhydrite carbonates, fine-grained sediments)</p>
SF6		<p>mound</p> <p>sub-parallel and follow the dips of underlying intrasalt stratigraphy</p>	<p>low-to-moderate amplitudes discontinuous suparallel to wavy</p>	<p>Rugose crest - east</p> <p>Above truncated and tilted A2 reflections</p>	<p>mounds are thicker where more evaporites depletion is evident</p>	
SF7		<p>sheet</p> <p>downlapped by rotated overburden</p>	<p>low to moderate amplitudes chaotic subparallel to disrupted</p>	<p>Rugose crest - west</p> <p>Above truncated A2 reflections</p>	<p>overburden is thicker where more evaporites dissolution is evident</p>	<p>Dissolution at the crest led to rotation and collapse of the overbuden</p>

Table 3: Overburden seismic expression and thickness variations above dissolved flat crests.

	Seismic facies	External shape relationship to salt crests	Amplitude, continuity reflection configuration	Ocurrence	Thickness variations	Interpretation
SF1		<p>sheet drape</p> <p>conformable to top salt</p>	<p>low-to-moderate amplitudes</p> <p>continuous</p> <p>parallel to sub-parallel</p>	<p>Flat crest - east</p> <p>Above A1-allocthonous intrasalt sheet</p>	<p>minor thickness variations c.± 50ms</p> <p>local depocenters up to c.80ms above lows on top salt</p>	<p>fine-grained lithology deposited on flat crest before dissolution</p> <p>post-depositional dissolution not too obvious at seismic scale</p>
SF2		<p>sheet to mound</p> <p>apparent downlap on top salt</p>	<p>low-to-moderate amplitudes</p> <p>semicontinuous to disrupted</p> <p>parallel to sub-parallel</p>	<p>Flat crest - central</p> <p>Above flat A1-allocthonous intrasalt sheet</p>	<p>minor thickness variations c.± 75 ms</p> <p>local depocenters up to c.125 ms above lows on top salt</p>	<p>fine-grained lithology deposited on salt crest before dissolution</p> <p>post-depositional dissolution led to local collapse and deformation within the overburden</p>
SF3		<p>sheet to wedge</p> <p>conformable & apparent downlaps on top salt</p>	<p>low-to-moderate amplitudes</p> <p>discontinuous</p> <p>wavy to chaotic</p>	<p>Flat crest - central</p> <p>Above lows on A1-allocthonous intrasalt sheet</p>	<p>minor thickness variations c.± 75 ms</p> <p>local depocenters up to c.125 ms above lows on top salt</p>	<p>fine-grained lithology deposited on salt crest before dissolution</p> <p>post-depositional dissolution led to local collapse and deformation within the overburden</p>
SF4		<p>sheet to mound</p> <p>conformable & apparent downlaps on top salt</p>	<p>moderate to high amplitudes</p> <p>semicontinuous</p> <p>subparallel to wavy</p>	<p>Flat crest - west</p> <p>Above discrete mounds on top salt</p>	<p>minor thickness variations c.± 100 ms</p> <p>local depocenters up to c.150 ms above lows on top salt</p>	<p>fine-grained lithology deposited on salt crest during dissolution</p> <p>syn-depositional dissolution led to local collapse and deformation within the overburden</p>

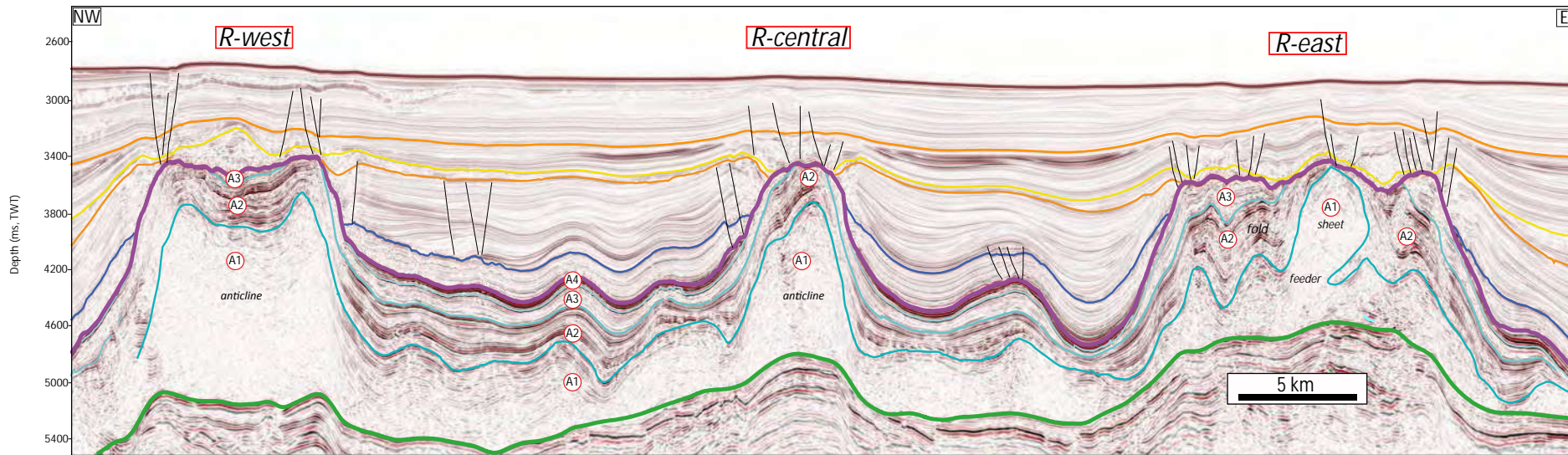


Figure 4 b: Seismic section across salt diapirs with rounded and rugose crests

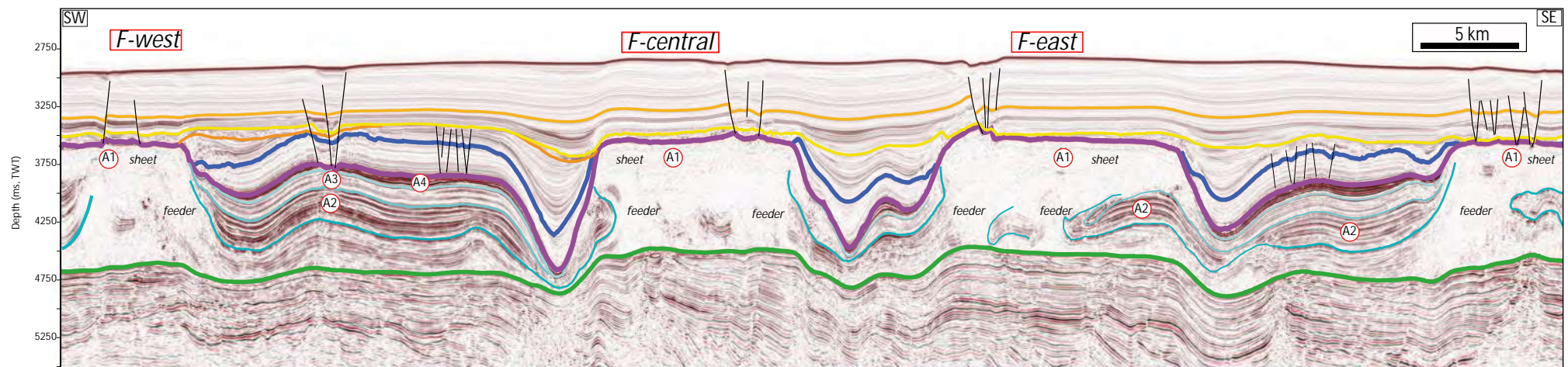


Figure 4 c: Seismic section across salt diapirs with flat crests

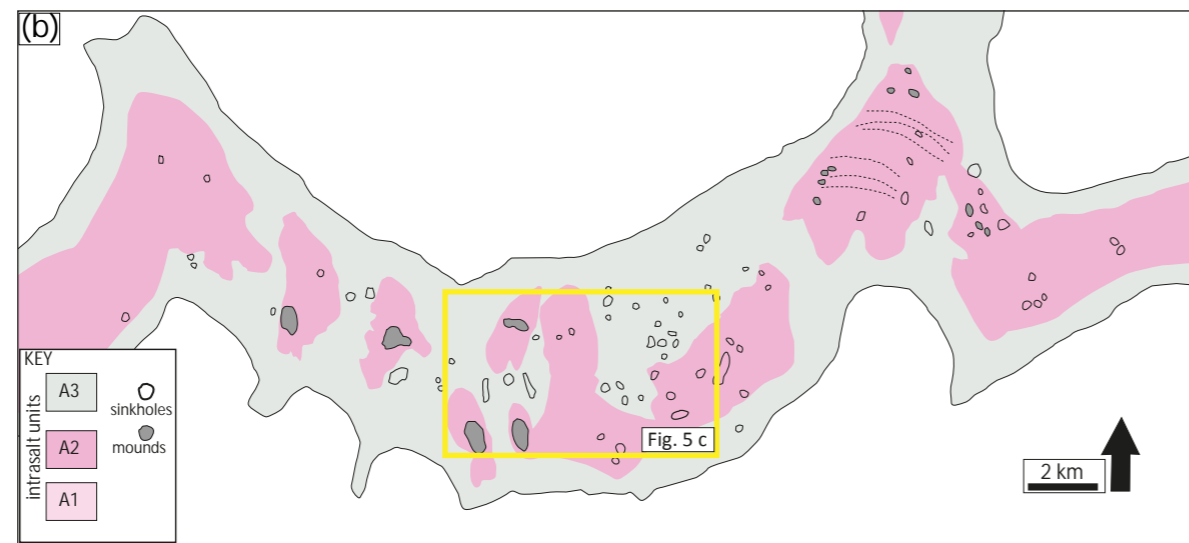
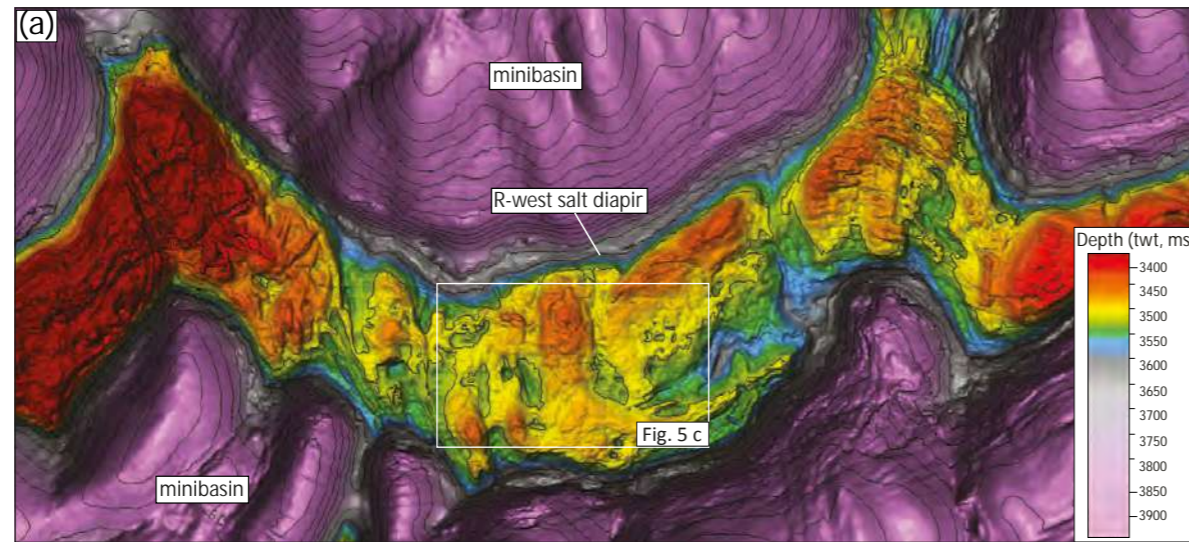


FIGURE 5: Seismic expression of salt dissolution-related sinkholes: (a) R-west top salt structural map; (b) Salt karst along Top Salt and intrasalt stratigraphy subcropping the R-west salt diapir; (c) Amplitude contrast attribute map for R-west Top Salt highlighting the sinkholes along Top Salt, see Figure 5a for location; (d) Seismic section along the crest of R-east illustrating the geometry of sinkholes (indicated by white arrows) and their relationship to halite-rich A3 intrasalt unit. Location is shown on Figure 5c; (e) Sweetness attribute of the seismic section on (d)

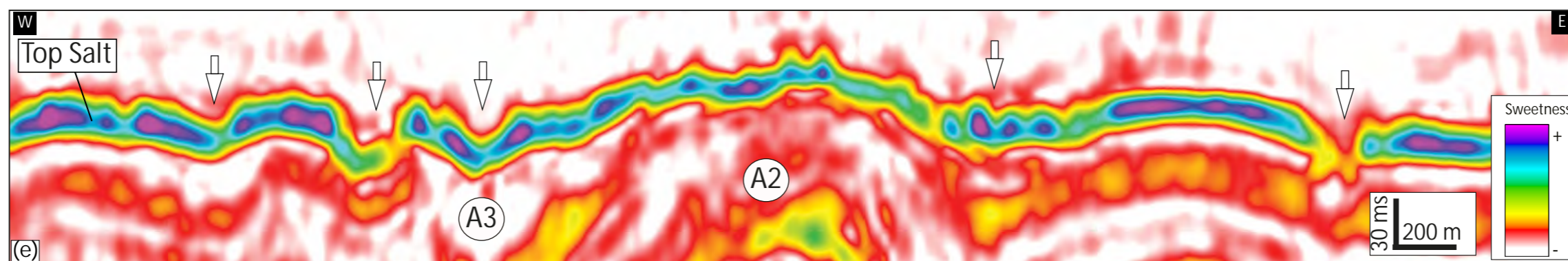
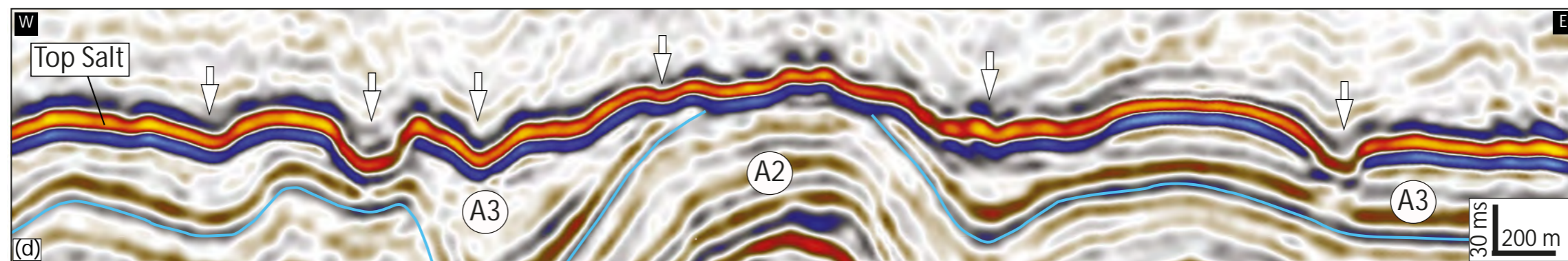
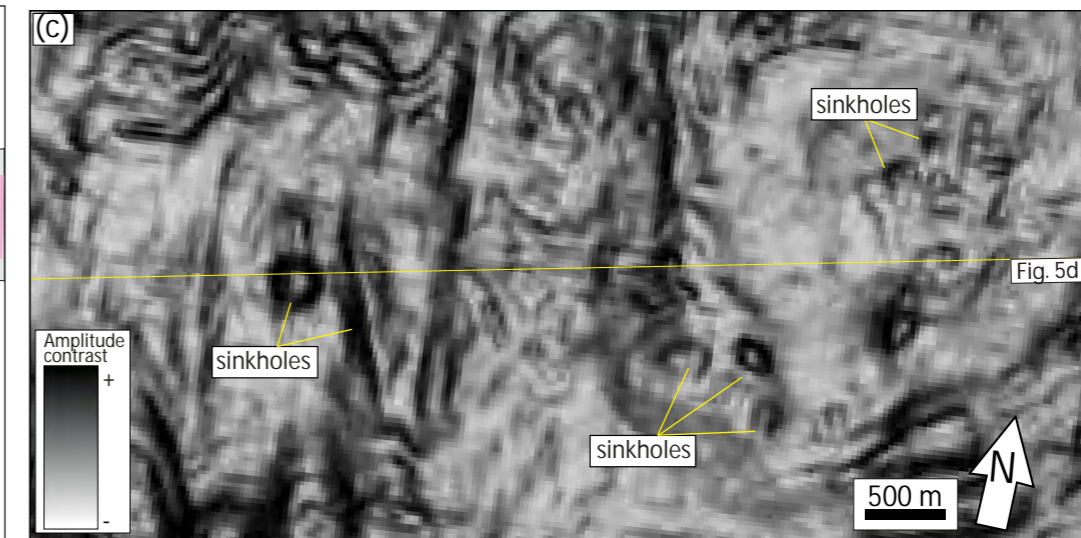
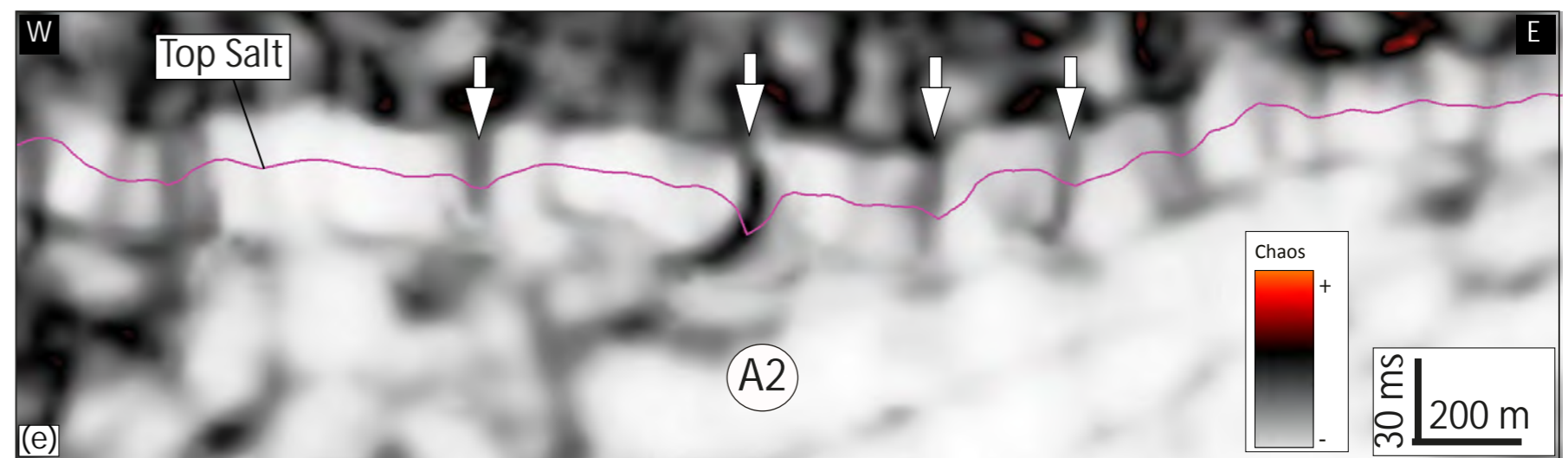
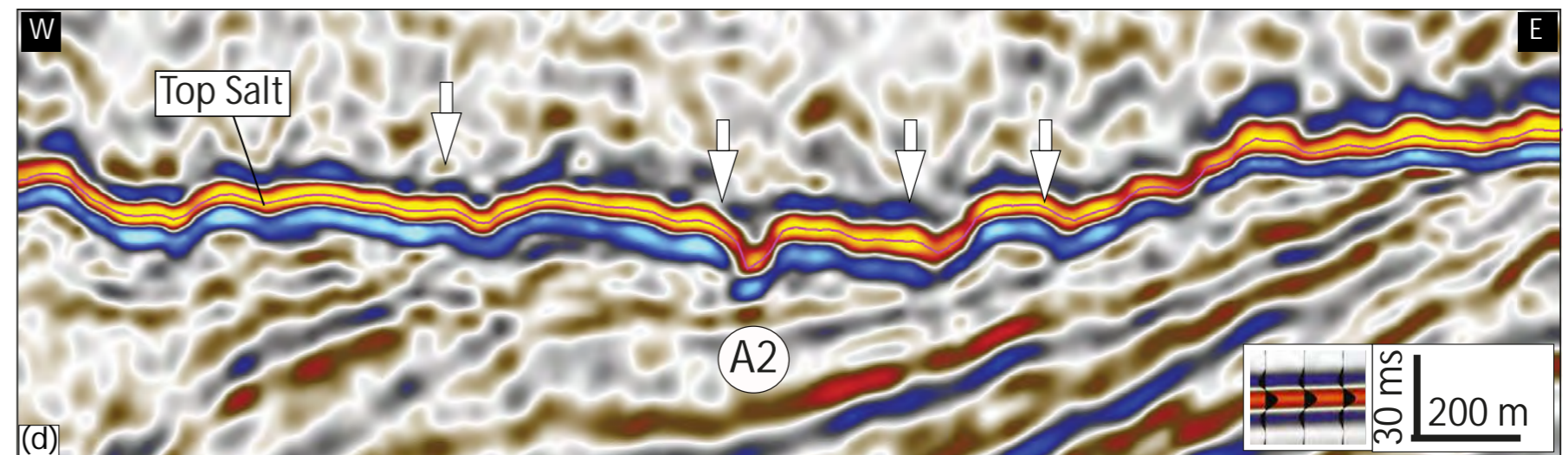
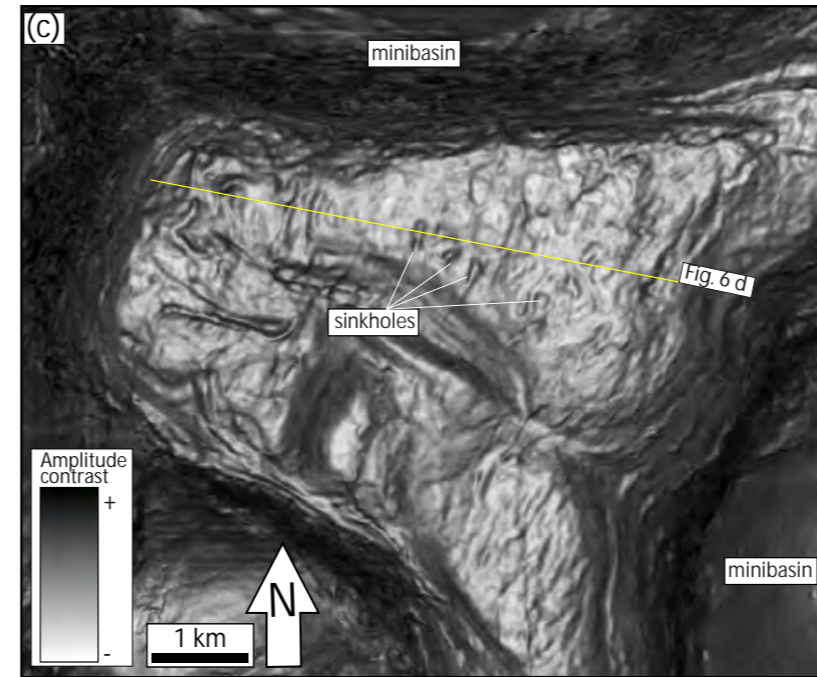
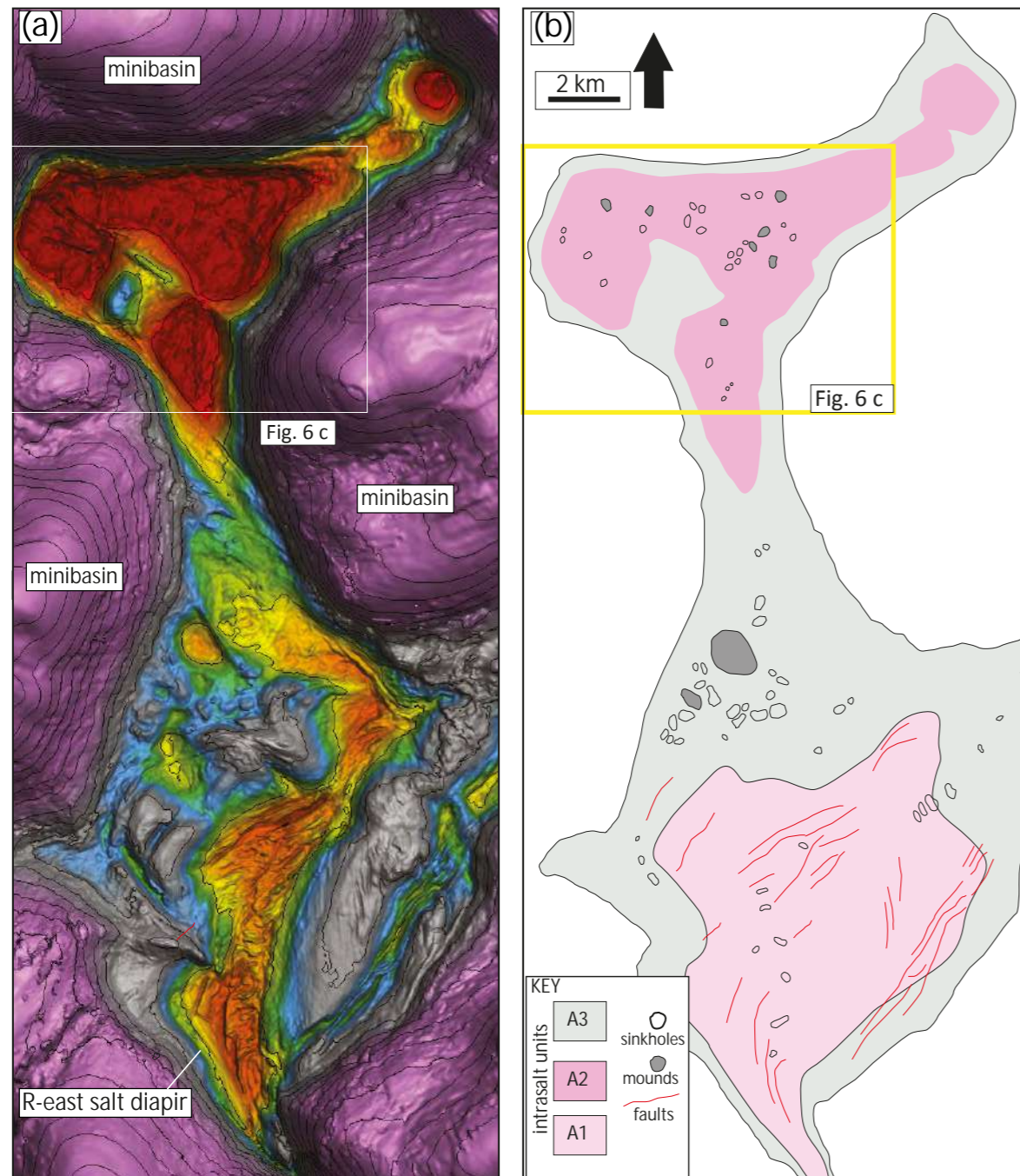


FIGURE 6: Seismic expression of salt dissolution-related sinkholes: (a) R-east top salt structural map; (b) Salt karst along Top Salt and Intrasalt stratigraphy subcropping R-east salt diapir; (c) Amplitude contrast attribute map for R-east Top Salt highlighting the sinkholes along Top Salt, see Figure 6a for location; (d) Seismic section along the crest of R-east illustrating the geometry of sinkholes (indicated by white arrows) and their relationship to dipping-A2 intrasalt stratigraphy. Location is shown on Figure 6c; (e) Chaos attribute of the seismic section on Figure 6d highlighting the sinkholes along the Top Salt.



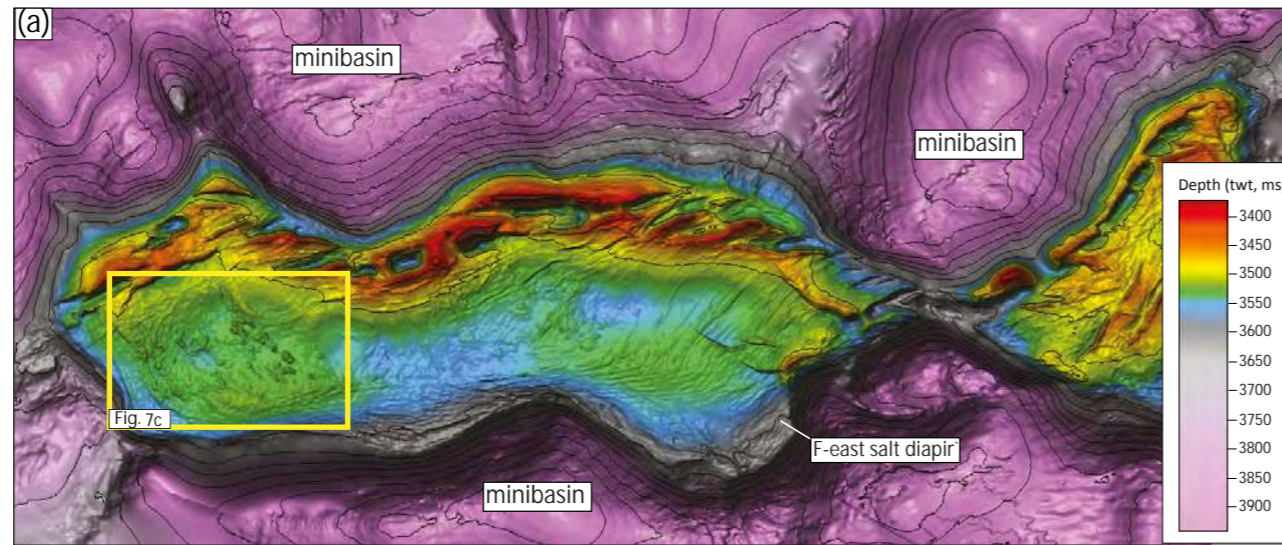
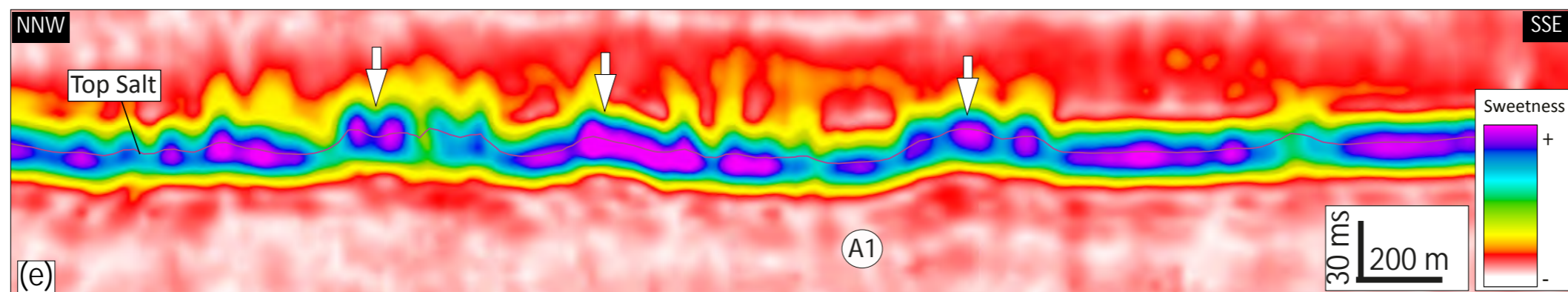
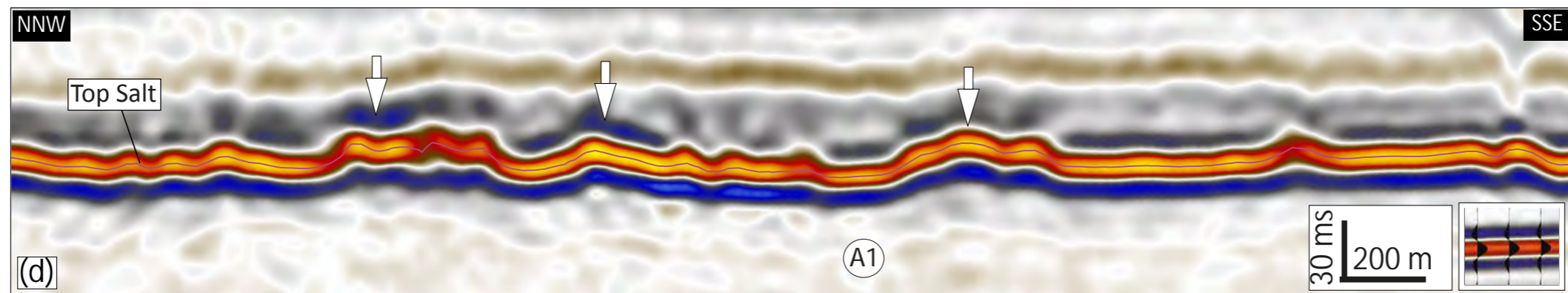
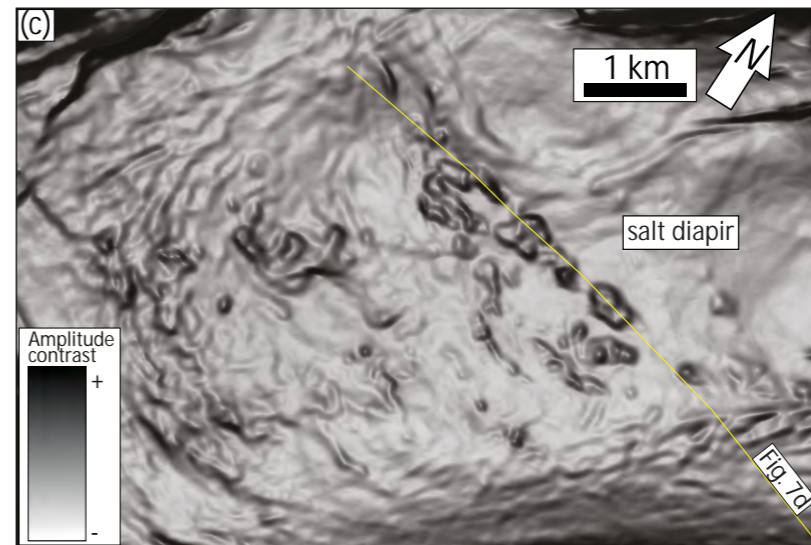
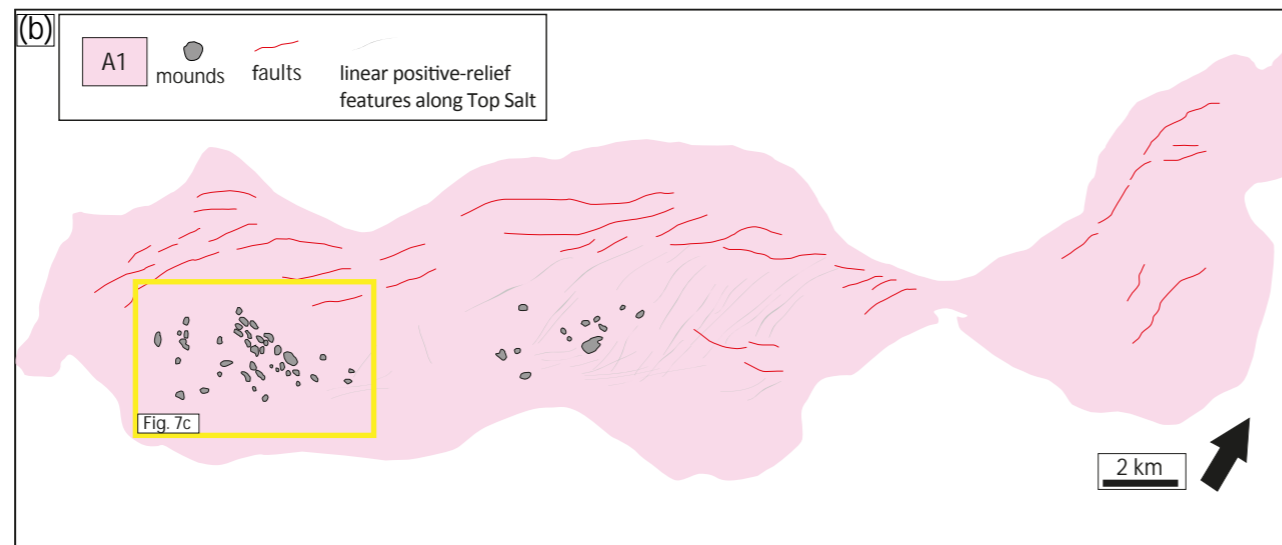


FIGURE 7. Seismic expression residual mounds: (a) F-east top salt structural map; (b) Intrasalt unit subcropping F-east salt diapir; (c) Amplitude contrast attribute map for F-east Top Salt highlighting residual mounds above the nearly-horizontal Top Salt; (d) Seismic section along the crest of F-east illustrating residual mounds above the main top salt level (mounds are indicated by white arrows). See Figure 7c for location; (e) Sweetness attribute for section on Figure 7d highlighting potential facies variations along the Top Salt.



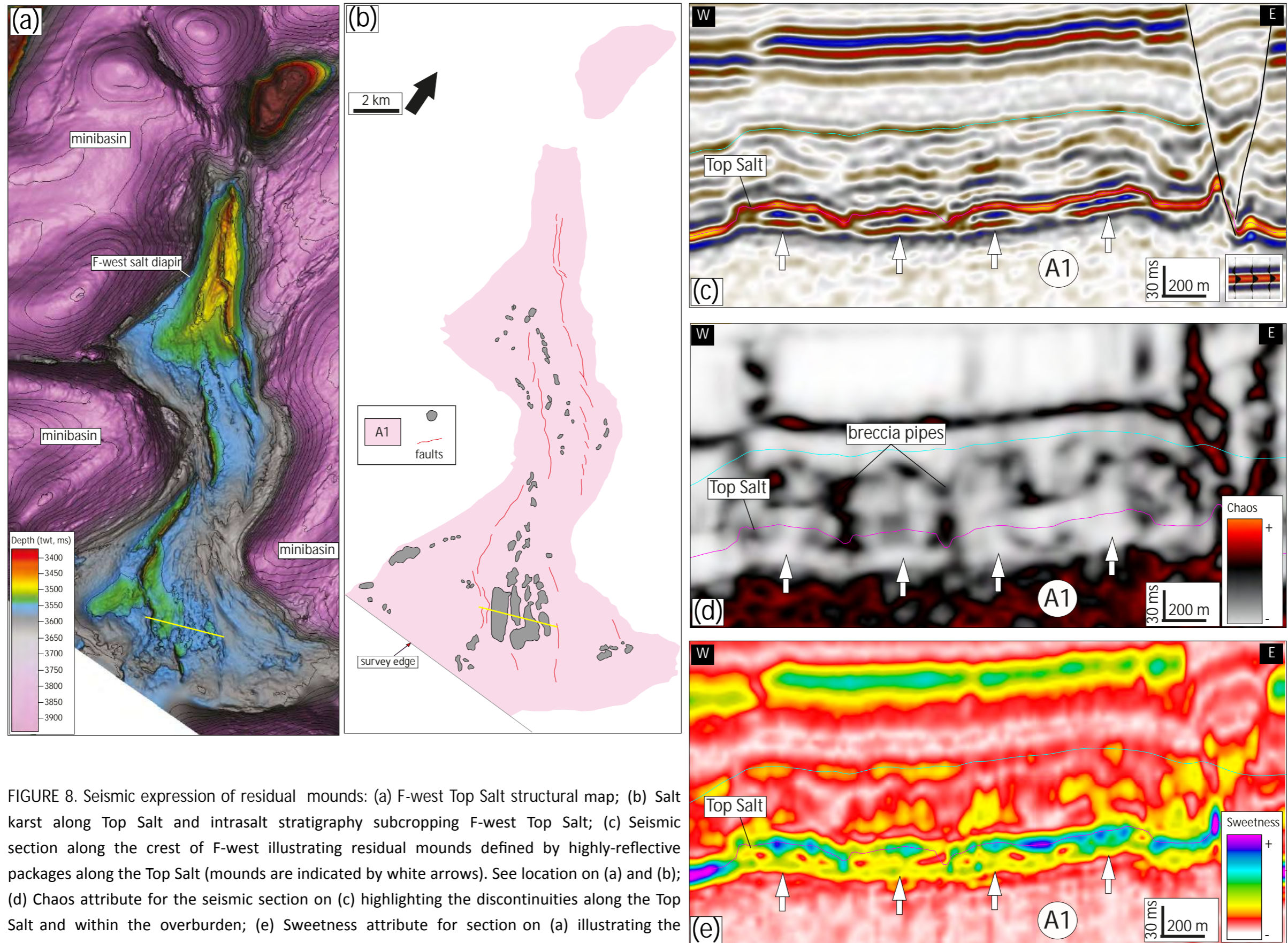


FIGURE 8. Seismic expression of residual mounds: (a) F-west Top Salt structural map; (b) Salt karst along Top Salt and intrasalt stratigraphy subcropping F-west Top Salt; (c) Seismic section along the crest of F-west illustrating residual mounds defined by highly-reflective packages along the Top Salt (mounds are indicated by white arrows). See location on (a) and (b); (d) Chaos attribute for the seismic section on (c) highlighting the discontinuities along the Top Salt and within the overburden; (e) Sweetness attribute for section on (a) illustrating the facies variations along Top Salt and within the mounds

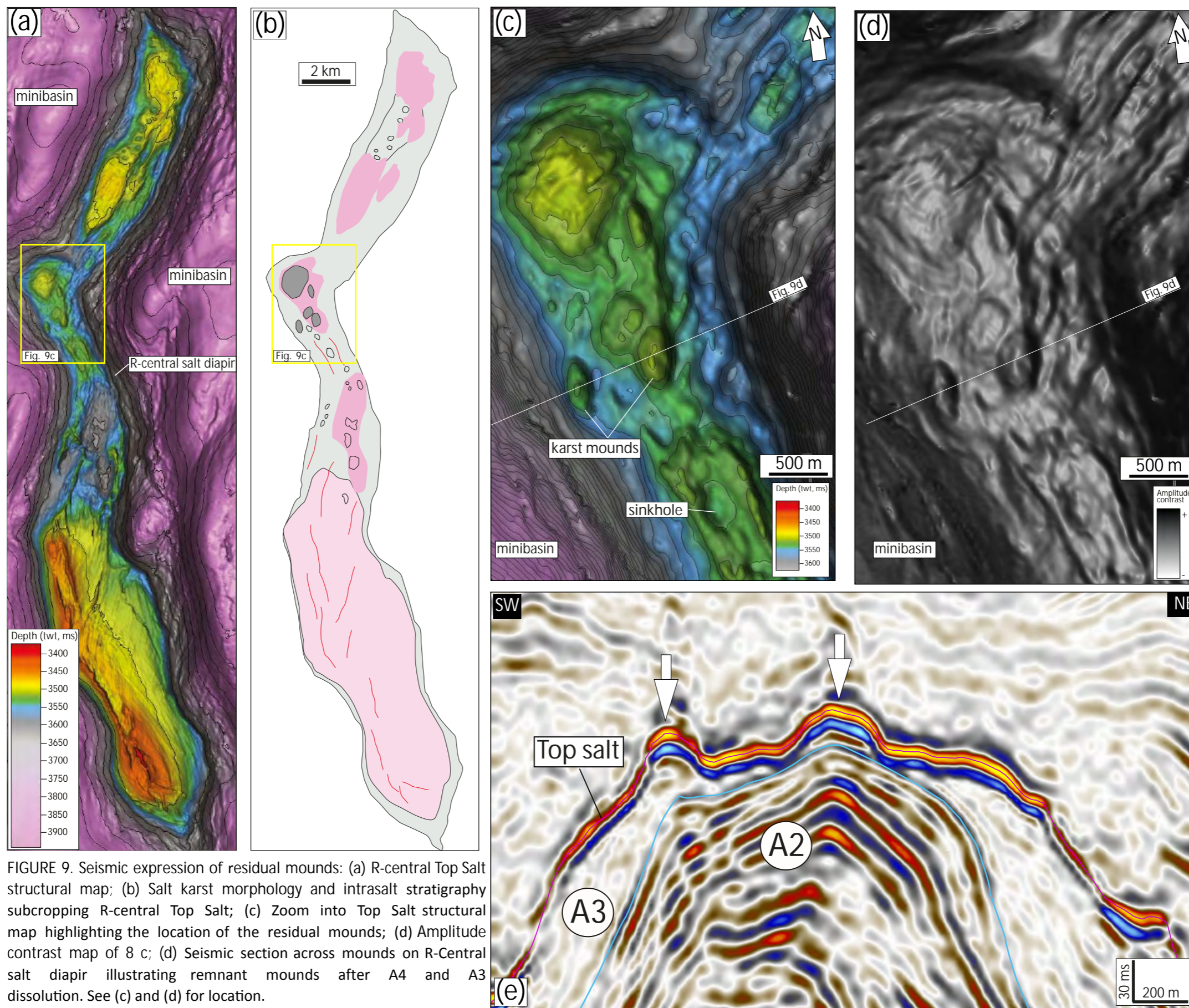


FIGURE 9. Seismic expression of residual mounds: (a) R-central Top Salt structural map; (b) Salt karst morphology and intrasalt stratigraphy subcropping R-central Top Salt; (c) Zoom into Top Salt structural map highlighting the location of the residual mounds; (d) Amplitude contrast map of 8 c; (d) Seismic section across mounds on R-Central salt diapir illustrating remnant mounds after A4 and A3 dissolution. See (c) and (d) for location.

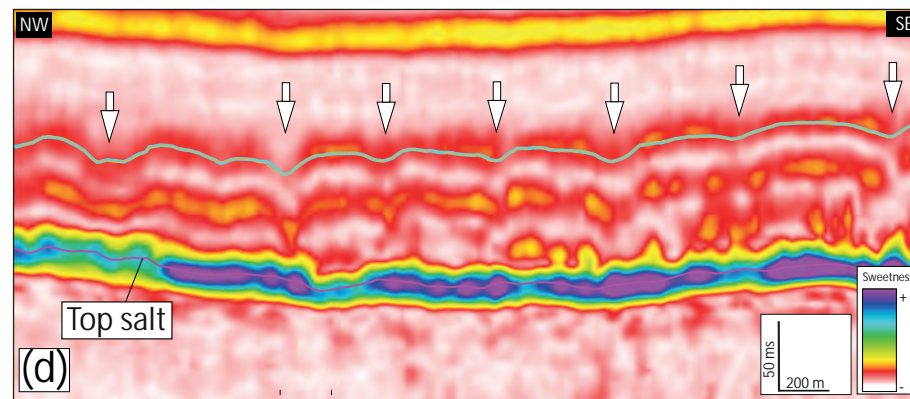
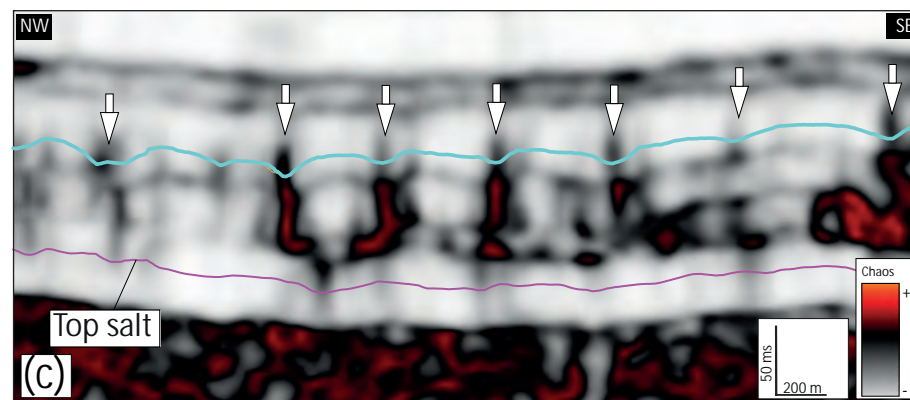
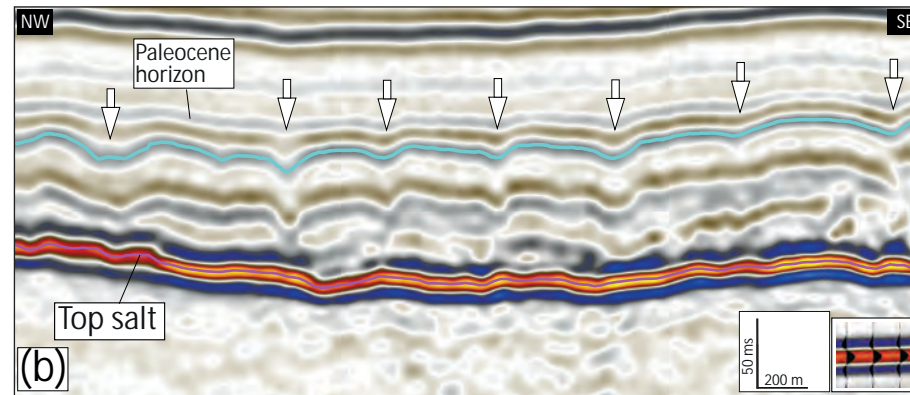
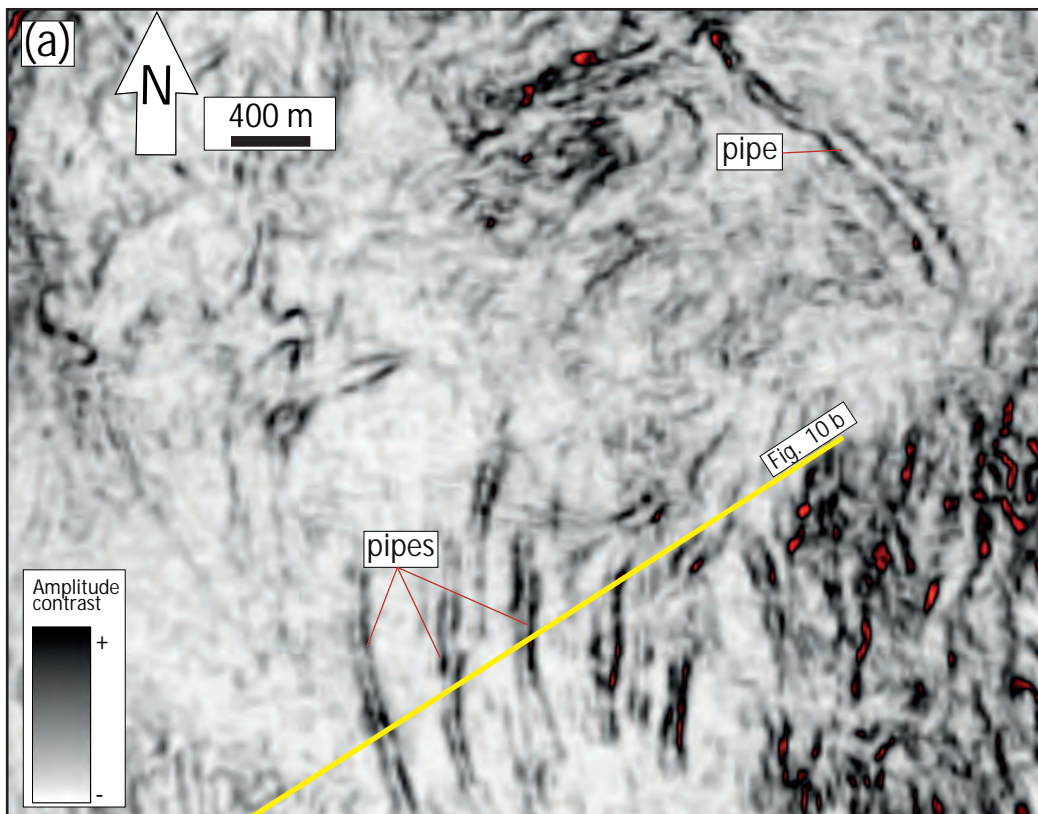


FIGURE 10: Seismic expression of breccia pipes or chimneys within the overburden: (a) Amplitude contrast seismic attribute time slice highlighting the edges of the breccia pipes. See location on Figure 11a; (b) Seismic section across the crest of F-central and overburden strata. Breccia Pipes are indicated with white arrows; (c) Chaos seismic attribute for the section on Figure 10b highlighting the breccias cross-cutting the overburden strata; (d) Sweetness seismic attribute for the section on Figure 10b. Some of the breccia pipes correlate with facies variations along the Top Salt.

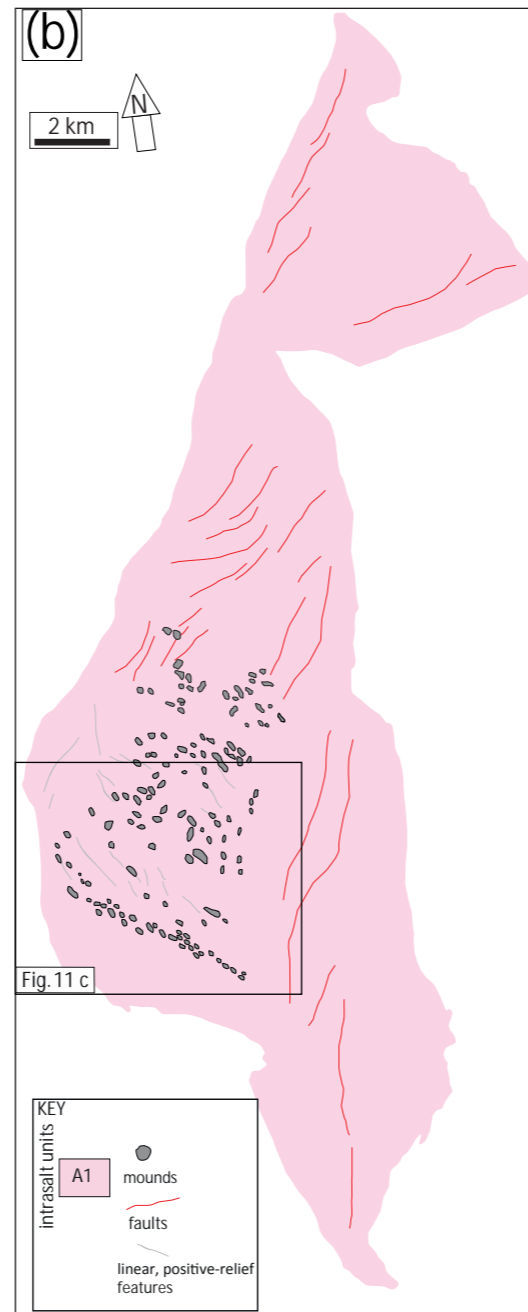
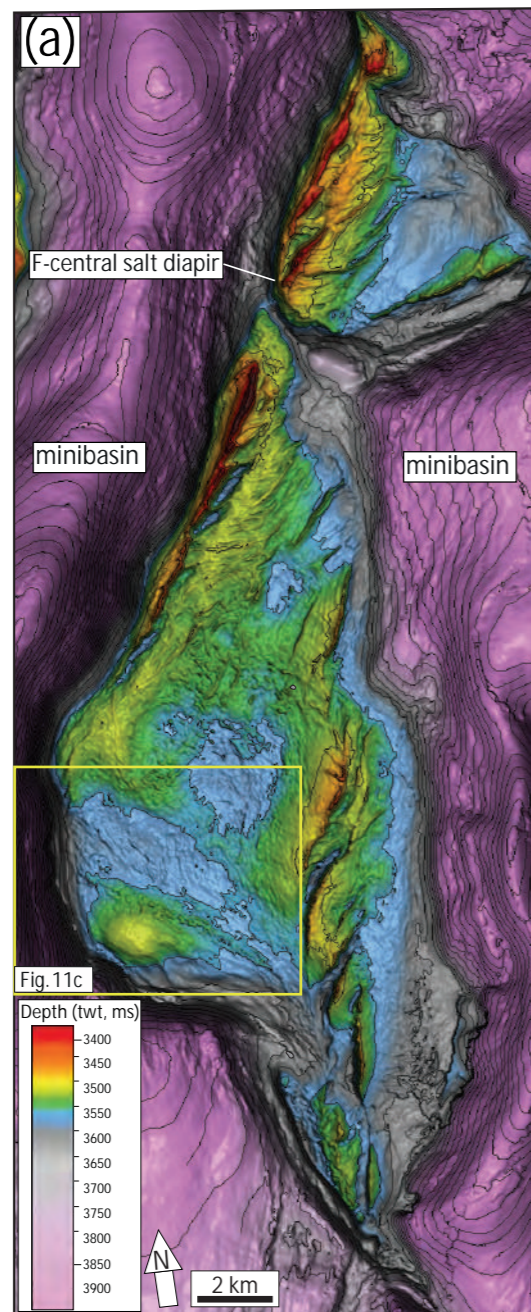
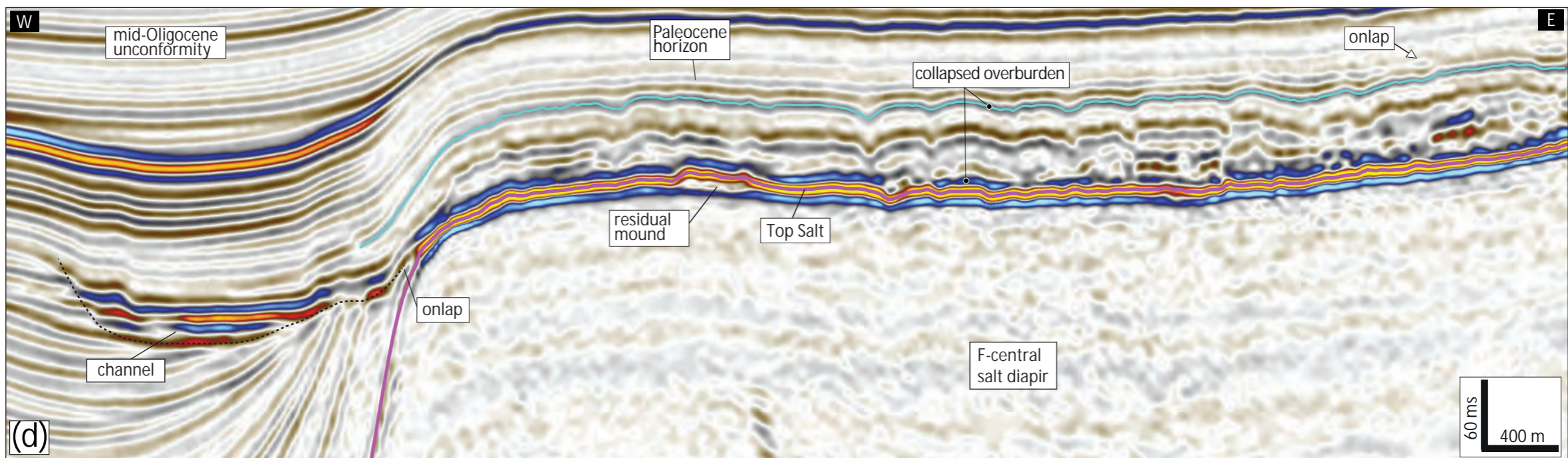
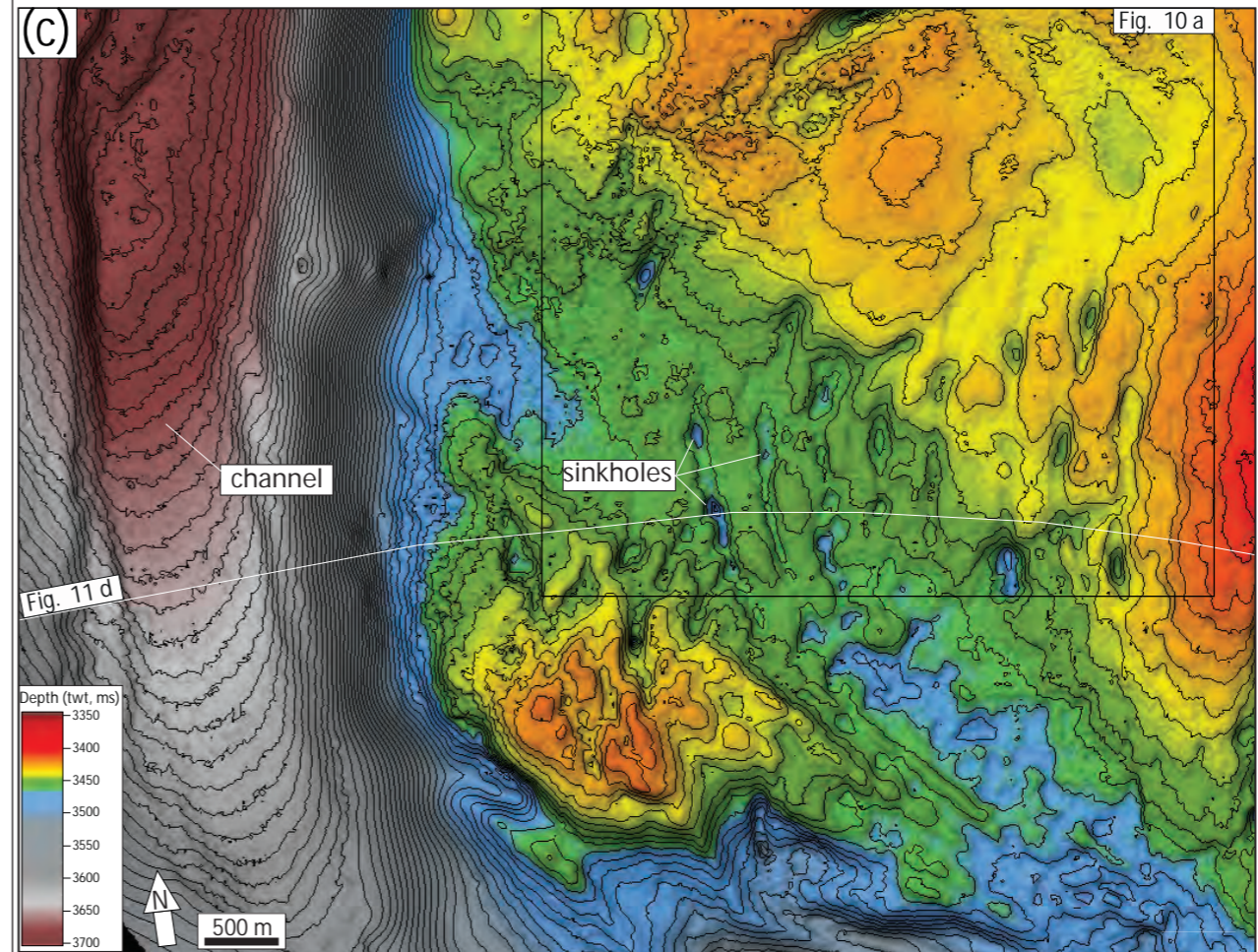


FIGURE 11: (a) F-central Top Salt structural map; (b) Salt karst morphology and intrasalt stratigraphy along the crest of F-central; (c) Structural map for the seismic horizon within the overburden (blue on (d)) highlighting the collapse associated to dissolution of the underlying halite-rich crest and the top of a channel flanking the salt wall; (d) Seismic section across F-central and the flanking minibasin illustrating the onlap of the channel and discontinuities within the overburden.



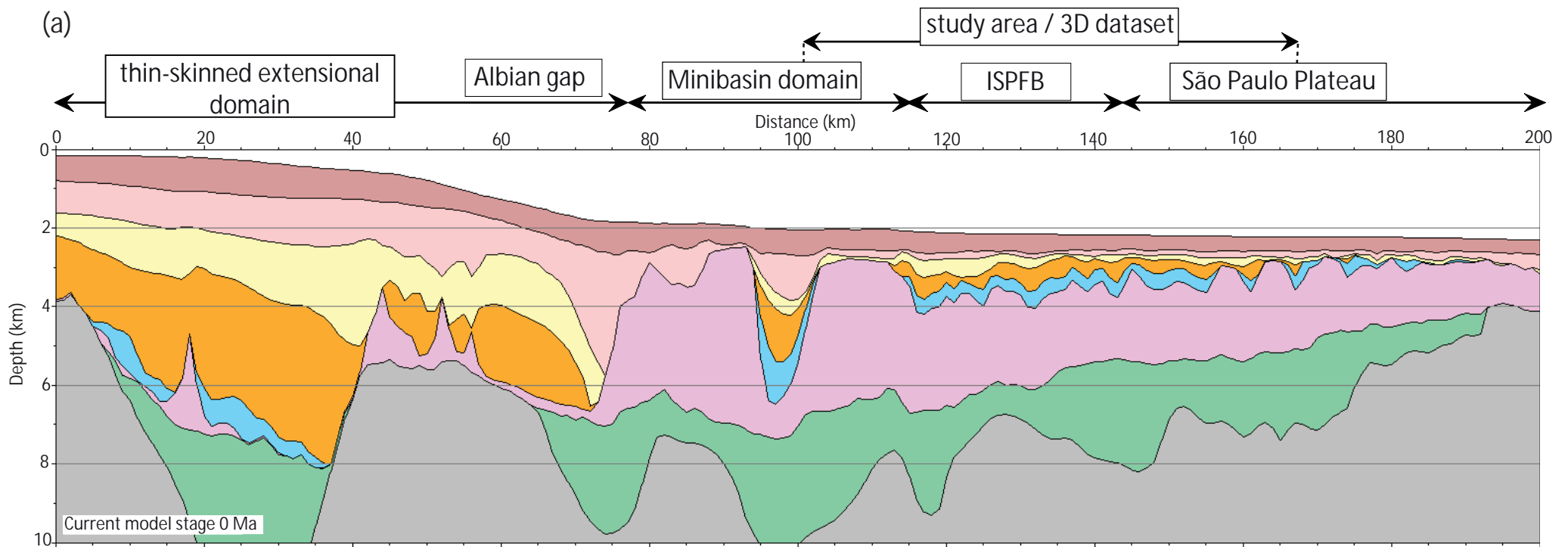
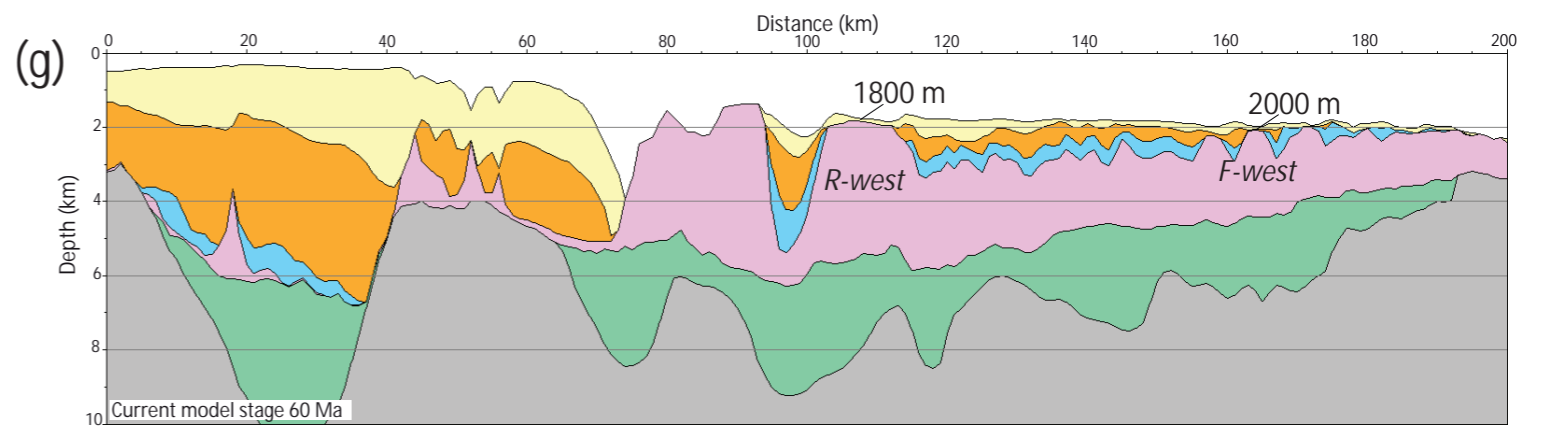
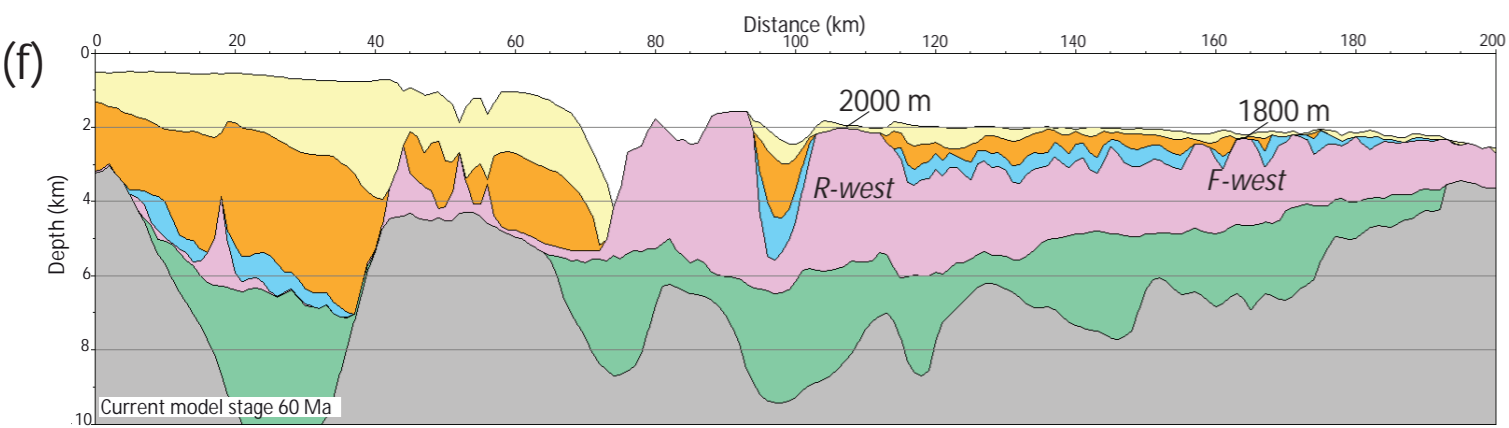
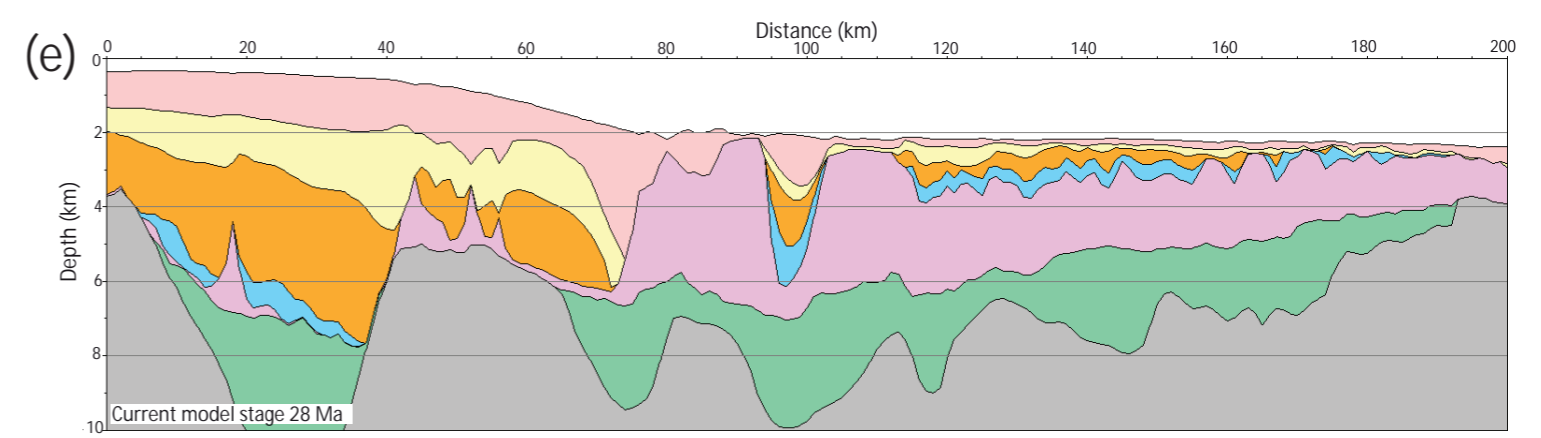
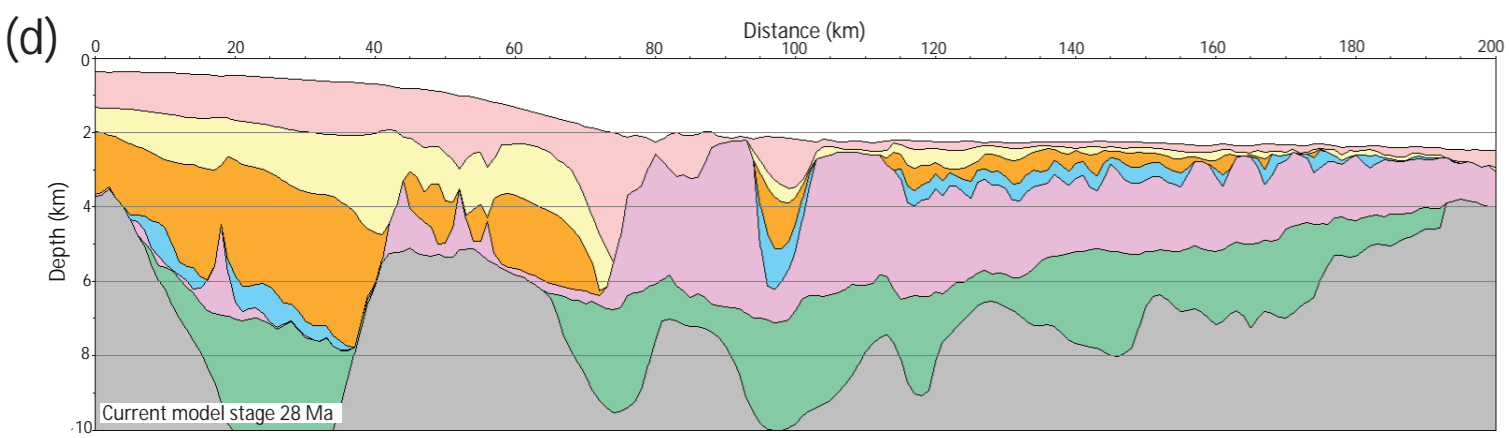
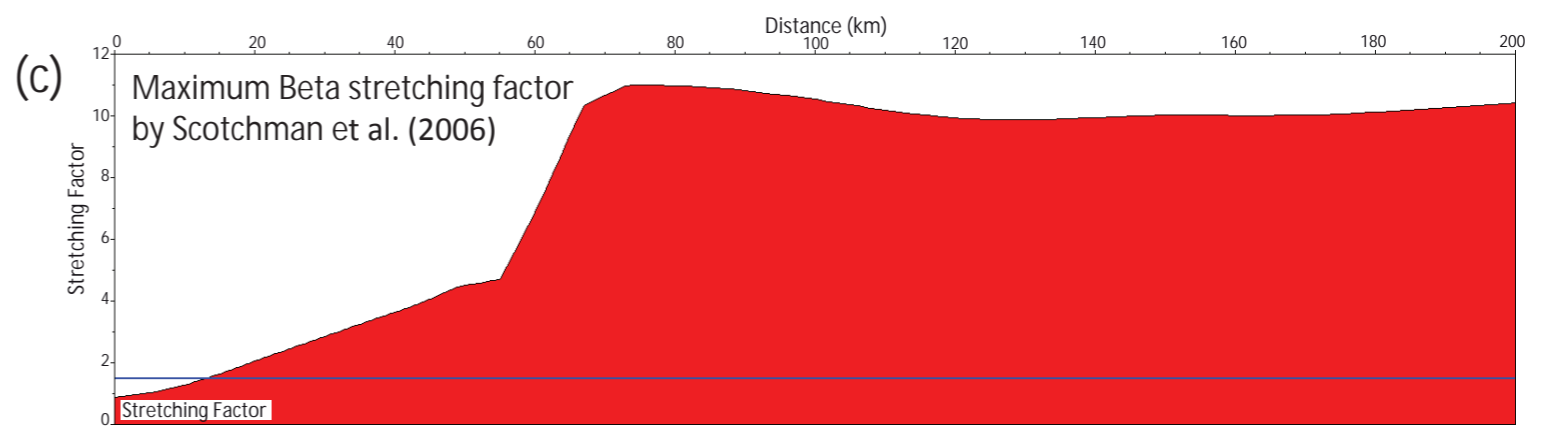
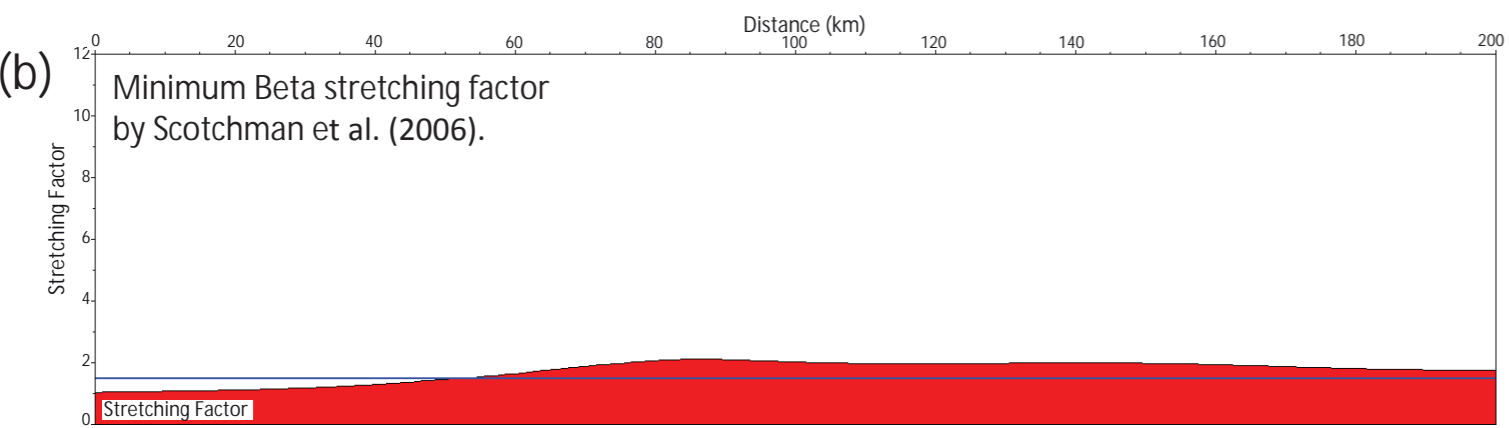


FIGURE 12: (a) Input model used for basin restoration based on the interpretation of 2D depth seismic profile (Figure 2b). See Key on Figure 2a; (b) Minimum Beta Stretching Factor along the 2D seismic profile (after Scotchman et al., 2006); (c) Maximum Beta Stretching Factor along the 2D seismic profile (after Scotchman et al., 2006); (d) Basin restoration to the mid-Oligocene (28 Ma) based on the minimum Beta Stretching Factor profile; (e) Basin restoration to the mid-Oligocene (28 Ma) based on the maximum Beta Stretching Factor profile; (f) Basin restoration to the Paleocene (60 Ma) based on the minimum Beta Stretching Factor profile; (f) Basin restoration to the Paleocene (60 Ma) based on the maximum Beta Stretching Factor profile



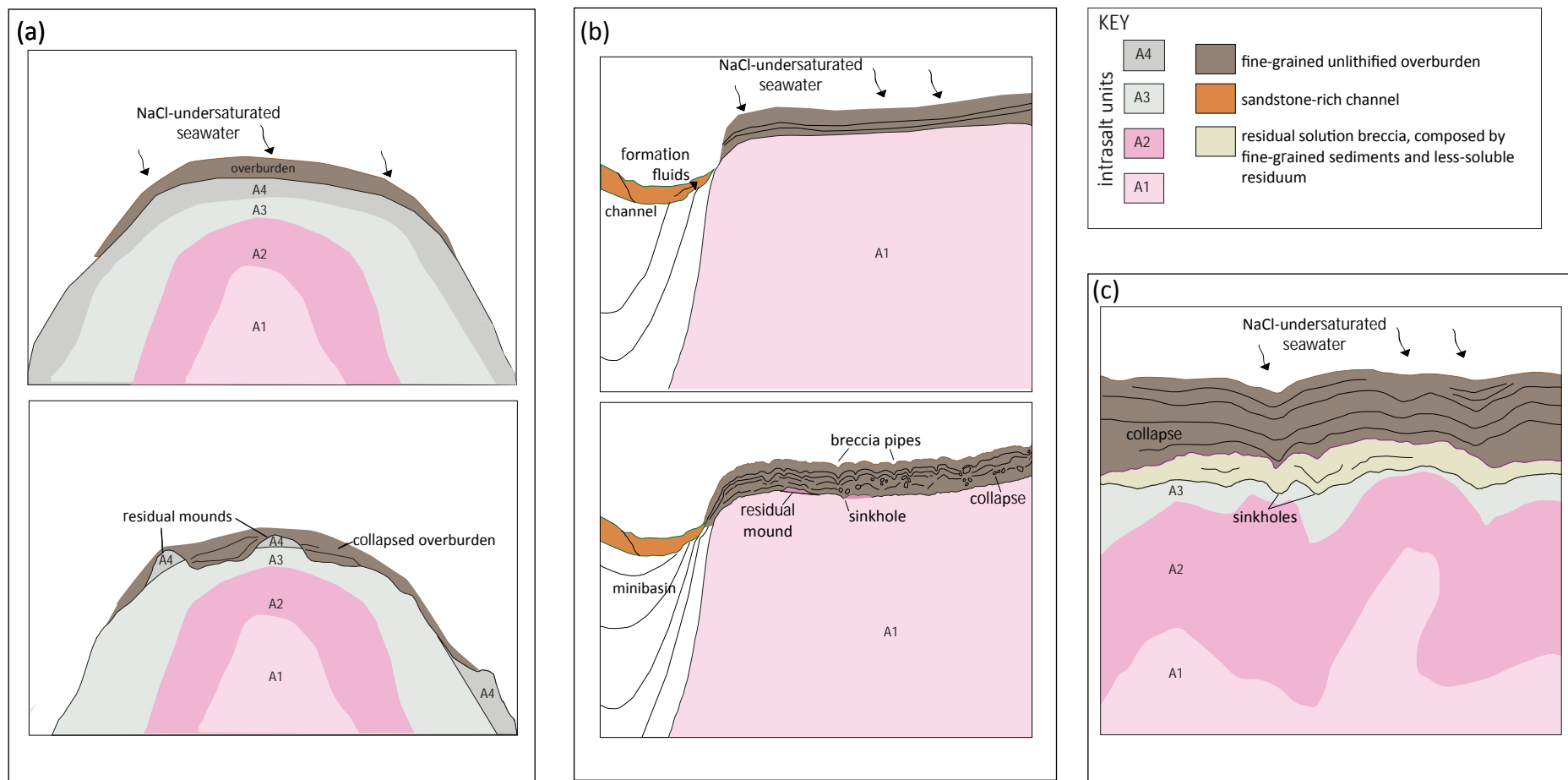


FIGURE 13: Mechanisms and styles of submarine salt dissolution: (a) Superjacent dissolution by NaCl-undersaturated seawater penetrating the very fine-grained, unlithified overburden during exposure at the seafloor; (b) Dissolution due to fluids migrating from carrier beds directly in contact with the salt; (c) Residual Solution breccia formed by the preferential depletion of the evaporite-dominated crests and collapse of the overburden.