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5 **Leaky salt: pipe trails record the history of cross-evaporite fluid escape in the**
6 **northern Levant Basin, Eastern Mediterranean**

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18 **Keywords**

19 Fluid escape; Overpressure; Fluid pipe; Cross-evaporite escape; Salt leakage; Focused fluid flow; Eastern
20 Mediterranean

21 **Abstract**

22 Despite salt being regarded as an extremely efficient, low-permeability hydraulic seal, an increasing
23 number of cross-evaporite fluid escape features have been documented in salt-bearing sedimentary
24 basins. Because of this, it is clear that our understanding of how thick salt deposits impact fluid flow in
25 sedimentary basins is incomplete. We here examine the causes and evolution of cross-evaporite fluid
26 escape in the northern Levant Basin, Eastern Mediterranean. High-quality 3D seismic data offshore
27 Lebanon image hundreds of supra-salt fluid escape pipes distributed widely along the margin. The pipes
28 consistently originate at the crest of prominent sub-salt anticlines, where overlying salt is relatively thin.
29 The fact the pipes crosscut the salt suggests this hydrofractured permitting focused fluid flow. Sequential
30 pipes from unique emission points are organized along trails that are several kilometers long, and which
31 are progressively deformed due to basinward gravity gliding of salt and its overburden. Correlation of
32 pipes in 12 trails suggests margin-wide fluid escape started in the Late Pliocene/Early Pleistocene,
33 coincident with a major phase of uplift of the Levant margin. We interpret that the consequent transfer
34 of overpressure from the central basin area, in addition to gas exsolution from hydrocarbons already
35 trapped in sub-salt anticlines, triggered seal failure and cross-evaporite fluid flow. We infer that other

36 causes of fluid escape in the Eastern Mediterranean, such as subsurface pressure changes driven by sea-
37 level variations and salt deposition associated with the Messinian Salinity Crisis, played only a minor role
38 in triggering cross-evaporite fluid flow in the northern Levant Basin. Further phases of fluid escape are
39 unique to each anticline and cannot be easily correlated across the margin. Therefore, despite a common
40 initial cause, long-term fluid escape proceeded according to structure-specific characteristics, such as local
41 dynamics of fluid migration and anticline geometry. Our work shows that the mechanisms triggering cross-
42 evaporite fluid flow in salt basins vary in time and space.

43

44 **1. Introduction**

45 The important role of salt in controlling fluid migration and accumulation has been described in various
46 basins worldwide. In particular, salt act as seals for hydrocarbon reservoirs and CO₂ storage sites (Selley
47 & Sonnenberg, 2015; Warren, 2016). Salt commonly form excellent membrane and hydraulic seals
48 because of extremely low permeability (Warren, 2016), potentially allowing volumetrically significant,
49 sub-salt fluid and gas accumulations (e.g. Esestime et al., 2016). However, recent research show that salt
50 is not a perfect seal (Warren, 2017). Tectonic evolution (e.g. basin uplift, thick-skinned faulting,
51 halokinesis), excessive overpressure, and interaction with pore fluids can reduce or completely destroy
52 the sealing capacity of salt (Davison, 2009; Schoenherr et al., 2007; Warren, 2017). This disruption can
53 permit cross-evaporite fluid escape, which remain poorly understood in the history of a salt basin not yet
54 influenced by mature halokinesis.

55 The Eastern Mediterranean is a prominent salt basin showing widespread fluid escape that started during
56 the Messinian and continues today (e.g. C. Bertoni et al., 2017; Eruteya et al., 2015). During the Messinian
57 Salinity Crisis (MSC) the isolation of the Mediterranean Sea from the Atlantic Ocean led to the relatively
58 rapid deposition of a thick, halite-dominated evaporite sequence (Roveri et al., 2016). The Messinian salt
59 reaches a thickness of c. 2 km over most of the deep water Eastern Mediterranean (Haq et al., 2020; Lofi
60 et al., 2011) Thanks to the Messinian salt, various giant hydrocarbon fields occur in the underlying, sub-
61 salt sequences (Esestime et al., 2016; Gardosh & Tannenbaum, 2014; R. Ghalayini et al., 2018). However,
62 the seal is not perfect. Despite the fact that most fluid escape features occur and appear to originate
63 within supra-salt sedimentary sequences, numerous cross-evaporitic features are observed (C. Bertoni et
64 al., 2017; C Kirkham et al., 2017). The wide range of fluid escape features, a kilometers-thick relatively
65 undeformed salt sheet, and the known basin deformation history make the Eastern Mediterranean the

66 perfect case study to investigate cross-evaporite fluid escape, from which we can develop models that
67 can be applied worldwide.

68 Thin-skinned normal faults, evaporite dissolution by undersaturated fluids, and overpressure-related
69 hydrofracturing are the main processes hypothesized to drive fluid escape in the Eastern Mediterranean
70 (C. Bertoni et al., 2017). The most effective and widespread of these processes is overpressure-related
71 hydrofracturing. The causes for overpressure formation vary (Swarbrick & Osborne, 1998), and within the
72 Eastern Mediterranean several different mechanism are proposed. For example, the rapid deposition of
73 thick, pelitic successions in the Nile deep sea fan led to compactional disequilibrium during burial and to
74 the generation of hydrocarbons (Al-Balushi et al., 2016). The resulting supra-lithostatic overpressure led
75 to the development of a large mud volcano province (C Kirkham et al., 2017). The tectonic stress
76 associated with the growth of the Syrian Arc contributed to overpressure generation and drove fluid
77 escape in the Latakia and Cyprus basins, with the formation of intrusive sedimentary bodies and
78 pockmarks (C. Bertoni et al., 2017; Hübscher et al., 2009). Three events associated with the MSC are
79 commonly identified as the main causes of overpressure generation in the Eastern Mediterranean basin:
80 1) rapid water unloading and pressure release during the initial stages of the MSC, 2) rapid deposition of
81 the thick Messinian evaporite, and 3) water loading during the sea-level rise at the end of the MSC (Claudia
82 Bertoni & Cartwright, 2015). The juxtaposition of these events during a relatively short period of time
83 during the MSC (~5.96 to ~5.33 Ma) (Roveri et al., 2016) profoundly altered the subsurface pressure
84 regime in the Eastern Mediterranean, creating multiple phases of overpressure generation and release.

85 Fluid escape systems can be regionally active on a multi-million-year time scale (Capozzi et al., 2017;
86 Maestrelli et al., 2017). However, reconstructing the timing and evolution of repeated fluid expulsion
87 events expressed in seismic reflection data can be challenging because of they may overlap in time and
88 space, and thus not be represented by discrete features. In the northern Levant Basin, distinct fluid
89 expulsion events from common leakage points formed cross-evaporite fluid escape pipes (sensu J.
90 Cartwright & Santamarina, 2015). The fluid escape pipes are clearly preserved in the stratigraphic record
91 due to the coeval and still-active Messinian salt tectonics. Salt-detached gravity gliding of the overburden
92 progressively translates the pipe away from the original emission point and towards the deeper basin.
93 This process deforms the intra-salt portion of fluid escape pipes from an initially vertical to an arcuate
94 geometry, in accordance with a dominantly Couette-type salt flow regime (J. Cartwright et al., 2018). The
95 basinward displacement of the overburden crosscut by the pipes allows the translation of an unaltered
96 sediment pile above the emission point, which is able to record new fluid escape events. This means that

97 successive fluid escape events from various unique leakage points form trails of deformed pipes and
98 overlying pockmarks. The described fluid escape process has been first observed in the deep-water Levant
99 Basin by Cartwright et al. (2018), and later by Kirkham et al (2019). The authors studied five pipe trails to
100 infer the kinematics of the Messinian salt layer in this region. The causes, significance, and implications of
101 the pipe trails have never been analyzed in detail. To date, no similar examples are documented in other
102 sedimentary basins worldwide.

103 Despite a wealth of research during the last few decades, the processes driving overpressure buildup and
104 fluid escape through thick evaporite units are still poorly understood. To fully understand the limits of salt
105 as sealing unit, it is fundamental to evaluate the mechanisms governing cross-evaporite fluid escape. In
106 addition, fluid escape features can record key geological events during the evolution of sedimentary
107 basins, such as regional tectonics and base-level changes. By understanding the fluid escape history, we
108 can obtain fundamental information to reconstruct fluid generation and migration in rapidly deforming
109 systems, such as those typified by salt basins.

110 The exceptional pipe trails in the northern Levant Basin hold important, high-resolution information on
111 the processes regulating fluid escape establishment, duration, and cyclicity in the period following the
112 deposition of a thick evaporite unit along a continental margin. We use high-quality 3D seismic reflection
113 data from offshore Lebanon (Fig. 1) to illustrate the causes and history of cross-evaporite fluid escape in
114 this region of the Eastern Mediterranean. We analyze the distribution and spacing of the fluid escape
115 pipes within twelve trails to reconstruct the history of fluid migration, charge, and expulsion. In doing so,
116 we demonstrate that basin-scale tectonic events, rather than events explicitly associated with the MSC
117 itself, are responsible for cross-evaporite fluid escape in this area of a relatively undeformed salt giant.

118

119 **2. Geological setting**

120 The Levant Basin mainly formed during multiphase rifting linked to the opening of Neotethys Ocean during
121 the Permo-Triassic and Jurassic (Nader et al., 2018). Since the Late Cretaceous, this region has been
122 shaped by the collision of the African and Eurasian plates, with the former being subducted beneath the
123 latter. Plate collision led to the formation of the Latakia Ridge as part of the Cyprus Arc System (Robertson
124 et al., 1996). The northern Levant Basin, the focus of this study, formed during the Oligocene within the
125 overall compressive regime (Steinberg et al., 2011). Compression led to folding and thrusting along the
126 basin eastern margin, leading to the generation of NE-trending anticlines that deformed the Oligo-

127 Miocene sedimentary units prior to, or at the onset of, the Messinian Salinity Crisis (MSC) (Ramadan
128 Ghalayini et al., 2014; Hawie et al., 2013). The lack of visible deformation of the post-Messinian
129 overburden, possibly because of the accommodation of anticline amplification within the salt, makes it
130 difficult to confidently demonstrate post-Messinian growth of the subsalt anticlines (Ramadan Ghalayini
131 et al., 2014). The Saida-Tyr platform represents the boundary between the northern and southern Levant
132 Basin, and forms the southern limit of the study area. The northern boundary of the Saida-Tyr platform is
133 represented by the Saida fault, an Early Mesozoic normal fault that was reactivated under dextral
134 transpression during the Late Miocene (R. Ghalayini et al., 2018; Ramadan Ghalayini et al., 2014). This
135 reactivation deformed the Tertiary sedimentary units, generating several anticlines bordering the
136 northwestern flank of the Saida-Tyr platform. Tectonic activity in the northern area of the basin during
137 the Late Miocene-Pliocene also reactivated the Latakia Ridge under sinistral transpression (Hall et al.,
138 2005), promoting the growth of thrust-related folds on its southeastern side. A fundamental tectonic
139 event started at the end of the Messinian when activity on the Levant Fracture System, onshore Lebanon
140 and Israel gradually uplifted the eastern margin of Levant Basin (Gvirtzman et al., 2013). The rate of uplift
141 was not constant, with higher rates occurring during the Late Miocene-Pliocene (R. Ghalayini et al., 2018)
142 and Late Pleistocene (Matmon et al., 1999).

143 The lack of well data in the northern Levant Basin prevents the exact calibration of the basin-fill
144 stratigraphy; age constraints are instead inferred by correlation with units preserved onshore Lebanon
145 and the southern Levant Basin (Gvirtzman et al., 2013; Hawie et al., 2013; Meilijson et al., 2019). Mesozoic
146 deposits, formed by deep-water carbonates and siliciclastic, are thought to be overlaid by a >7 km-thick
147 Cenozoic succession (R. Ghalayini et al., 2018). Undercompacted Paleogene shales pass upwards into
148 Oligo-Miocene siliciclastic sediment, sourced from the proto-Nile delta and by the erosion of the uplifting
149 Levant basin margins (R. Ghalayini et al., 2018). During the MSC, an up to c. 2 km-thick evaporite-
150 dominated succession was deposited in most of the Levant Basin. Following this, a brief phase of evaporite
151 fluvial reworking deposited the Nahr Menashe Unit in the northern Levant Basin (Kabir et al., 2019), which
152 subsequently experienced fluvial incision and deposition (Madof et al., 2019). Marine flooding of the basin
153 at the end of MSC and the renewed siliciclastic influx deposited a Plio-Pleistocene succession that, within
154 the study area, is thought to be composed of hemipelagic and pelagic sediment (Hawie et al., 2013). Uplift
155 and associated tilting of the eastern basin margin, as well as differential loading, led to gravity-driven salt
156 tectonics that resulted in salt flow towards the deep basin (Allen et al., 2016; J. A. Cartwright & Jackson,
157 2008; Gvirtzman et al., 2013). Salt movement resulted in three kinematically-linked domains that trend
158 broadly parallel to the basin margin: 1) an updip extensional domain, characterized by margin-parallel

159 growth faults; 2) a central translational domain, characterized by limited deformation of the overburden,
160 but intense intra-salt deformation; 3) a downdip contractional domain, containing widespread thrusting
161 and folding of both the salt and overburden (Allen et al., 2016; J. A. Cartwright & Jackson, 2008).

162 The petroleum system offshore Lebanon is still under-explored and thus poorly understood. However,
163 direct hydrocarbon indicators and stratigraphic correlation with nearby areas point to a potentially prolific
164 basin. Many possible source rocks spanning from the Permian/Triassic to the Miocene are identified in
165 various areas of the basin (R. Ghalayini et al., 2018). Thermogenic hydrocarbon generation has been active
166 since the Late Cretaceous in the deeper basin and Latakia Ridge (Bou Daher et al., 2016), whereas biogenic
167 methane generation started in the Miocene across the Lebanese offshore. Biogenic methane generation
168 still occurs in the upper part of the sub-salt Miocene sediments along the basin margins and in the
169 shallower units on the Latakia Ridge (R. Ghalayini et al., 2018). The reservoir units are composed of Oligo-
170 Miocene deep-water sandstones deformed in Syrian Arc-related structural traps. The most notable traps
171 are NE-trending, Oligo-Miocene anticlines and Early Miocene fault blocks (R. Ghalayini et al., 2018). The
172 main seals in the Levant Basin comprise fine-grained sediments interbedded within the Oligo-Miocene
173 reservoirs and, ultimately, the thick Messinian salt (R. Ghalayini et al., 2018).

174

175 **3. Material and Methods**

176 The seismic data used for this study are a post-stack time migrated 3D multi-channel seismic reflection
177 survey (MC3D LEB MegaSurvey Plus) acquired by PGS between 2006 and 2013. The seismic survey covers
178 ~10,000 km² offshore Lebanon in water depths between 200 and 1900 m (Fig. 1). The data are near-zero
179 phase at the seafloor reflection and are displayed here with SEG negative polarity; i.e. a downward
180 increase in acoustic impedance is represented by a trough (red color) and termed a “hard kick”, whereas
181 a peak (black color) represents a downward decrease in acoustic impedance and is termed a “soft kick”
182 (A. R. Brown, 2001).

183 Bin dimensions were 25 x 25 m during data processing. The dominant frequencies of the seismic data are
184 50 Hz in the post-salt overburden, 25 Hz in the Messinian salt, and 17 Hz in the sub-salt units. Average P-
185 wave velocities for these intervals (2,000 m/s, 4,200 m/s and 3,000 m/s, respectively) are derived using
186 information from exploration wells in the southern Levant Basin (Feng et al., 2016; Gardosh &
187 Tannenbaum, 2014) and proprietary data processing reports provided by PGS Geophysical AS. Based on

188 these data, the estimated vertical resolution of the post-evaporite, Messinian Evaporite, and pre-
189 evaporite units, calculated as a quarter of the dominant wavelength, are 10, 42 and 44 m, respectively.

190 We used the seismic data to map the top (TS), base salt (BS), and key horizons in the overburden (e.g. the
191 1.8 Ma reflection, see Section 5). Post-stack seismic attributes, including Variance (Chopra & Marfurt,
192 2007) and Root Mean Square (RMS) amplitude, were calculated (Barnes, 2016). Variance was used to
193 highlight fluid escape features and structural discontinuities (i.e. faults). RMS was calculated to image
194 anomalous amplitudes inferred to be driven by variations in pore fluid and/or gas (herein termed 'fluid'
195 to include pore water, gas, and liquid hydrocarbon), and/or variations in the degree of cementation.
196 Amplitude anomalies are qualitatively defined as zones where the amplitude of reflections is distinctly
197 higher than the average value of nearby areas, whereas Vertical Anomaly Clusters (VAC) are defined as a
198 vertical region of amplitude anomalies inferred to be genetically linked by fluid migration processes
199 (Foschi et al., 2014).

200

201 **4. Results**

202 *4.1. Seismic expression of fluid escape features*

203 In the northern Levant Basin, we classified 325 vertical seismic data anomalies as fluid escape pipes
204 according to well-established recognition criteria (J. Cartwright & Santamarina, 2015; Moss & Cartwright,
205 2010). The fluid escape pipes (herein termed 'pipes') are narrow vertical areas of locally disrupted and/or
206 attenuated seismic reflections (Fig. 2). These areas are roughly circular area in planform, varying from
207 near-seismic resolution (c. 25-50 m) to c. 255 m in diameter. Pipes taper either upwards or downwards,
208 or maintain their diameter over their visible depth range (Fig. 2). The pipe root zone is frequently difficult
209 to image because of the seismic signal degradation beneath the thick evaporite units, as well as the depth
210 at which the root zone lies. Nevertheless, we recognized that all pipes originate within the sub-salt units,
211 and no examples are present solely within the post-salt overburden. The upper terminus of the pipes is
212 either a pockmark or a small mud volcano, indicating the present or past expulsion of fluid and sediment
213 at the seafloor (Fig. 2).

214 The pipes are either linear or arcuate in section. Linear pipes connect vertically aligned root and terminus.
215 Recent pipes are typically linear and are capped by pockmarks or mud volcanoes at or near the present-
216 day seafloor (e.g. Fig. 3b, 4). Arcuate pipes are gently dipping at their roots near base-salt, increasing in
217 dip upwards to top salt. Above the salt, arcuate pipes are undeformed and vertical (Fig. 3). These two

218 geometries also have a different seismic response within the evaporite unit. The vertical pipes are in
219 agreement with the general model (i.e. disrupted and attenuated signal) whereas the deformed portion
220 of the pipes are characterized by a narrow, linear, high-amplitude reflection with a soft-kick response (Fig.
221 5) (see also Kirkham et al., 2019). Interpreting the pipes' internal geometry can pose significant challenges.
222 The presence of fluids and/or the similarity between the pipe diameter and the seismic data resolution
223 may generate seismic imaging artifacts (A. Brown, 2011). The narrower pipes seldom show recognizable
224 internal geometries and appear as vertical zones of dimmed seismic signal with occasional inverted
225 polarity (Fig. 2). In contrast, the larger pipes (diameter >100 m) have internal characteristics that
226 commonly relate to the type of upper terminus. More specifically, when either a paleo- or present-day
227 pockmark occurs, the internal reflections are either concave-downward, or disrupted and chaotic (Fig. 2).
228 When the upper terminus is a mud volcano, and the pipe is thus inferred to be associated with significant
229 sediment remobilization, the pipe internal reflections have convex-upward geometries, which may
230 become chaotic and concave upwards (Fig. 2).

231 The pipes in Fig. 6 show the variation in terminus style moving landwards. The terminus of the first pipe
232 has a mounded morphology defined by a hard kick with an amplitude anomaly on top (Figs. 6b, 7). This
233 mound is overlapped by overlying reflection and the first 68 ms TWT of the overlying succession are
234 deflected upwards (Fig. 7). The base of the mounded feature is a soft kick that lies on the onlap surface of
235 a ramp syncline basin (RSB; see Section 4.2 for details). These characteristics support the hypothesis that
236 the mounded feature is real and not a seismic artifact, and that it likely formed positive relief on the paleo-
237 seafloor. The basal reflection of the mounded feature is concave downward at the top of the underlying
238 pipe. The internal geometries of the mounded feature are difficult to determine because of the seismic
239 resolution, but they appear to be discordant with the overlying, relatively flat-lying, onlapping reflections.
240 Comparable geometries and reflection polarities have been documented in buried mud volcanoes (e.g.
241 Hansen et al., 2005). Moving further landwards still, the pipe terminus appears transitioning from mud
242 volcano to buried pockmark (Fig. 6d), a relationship clearly imaged in Fig. 6e. The last pipe forms a
243 pockmark on the present-day seafloor, recording relatively recent seepage of fluids (Fig. 6f).

244

245 *4.2. Basin-scale distribution and salt-tectonic context of fluid escape features*

246 In the northern Levant Basin, fluid escape mainly occurs along the eastern margin of the salt translational
247 domain, where most of the pipes fall into one of 12 trails (Pipe Trails, PT1-12; Fig. 8). We define a trail as

248 a series of roughly aligned pipes that lie within a 250 m belt defining the central trail trend (see inset in
249 Fig. 8). The trails are c. 2.3 to 12 km long when measured from the inferred fluid leakage point, which is
250 consistently associated with one of the NE-trending, sub-salt anticlines. The pipe trails trend
251 approximately NW, broadly parallel to regionally extensive sub-salt faults (Fig. 8). These Miocene normal
252 faults seldom extend upwards into the salt (R. Ghalayini et al., 2018). Despite similar trends, we do not
253 observe a direct connection between the pipe roots and the faults. This observation is supported by trails
254 PT2 and PT3, which have an overall different trend respect to the faults (Fig. 8). One additional small trail
255 occurs within the salt contractional domain of the basin outside the seismic data analyzed in this study
256 (Fig. 8, Oceanus structure) (J. Cartwright et al., 2018).

257 All pipe trails are associated with RSBs (e.g. Fig. 3). RSBs form in response to the down-dip translation of
258 the overburden across a detachment ramp, with the concomitant creation of accommodation at sediment
259 onlap onto the RSB hinge (Jackson & Hudec, 2005; Pichel et al., 2018). Continuous translation leads to the
260 downward rotation of the older syn-kinematic onlaps, which transform into pseudo-downlaps and define
261 pseudo-clinoforms (Jackson & Hudec, 2005; Pichel et al., 2018). Consequently, the diachronous surface
262 formed by the onlaps represents a continuum of paleo-depocenters and records the history of salt and
263 overburden movement (S. L. Evans & Jackson, 2019). After vertical forming above the sub-salt anticlines,
264 the pipes are translated into the RSB depocenter and progressively buried. The pipes therefore terminate
265 upwards at an onlap surface defining the base of the coeval RSBs (e.g. Fig. 3). This means that the age of
266 each pipe in the trail can be approximated by the age of the corresponding intra-RSB stratigraphic surface.
267 In each pipe trail, the pipe culminations (i.e. pockmarks or mud volcano) occur within progressively
268 younger sediments updip toward their source anticlines. The pipe positioned furthest basinward
269 represents the first (i.e. the oldest) cross-evaporite fluid migration event of the trail, whereas the pipe
270 closest to the anticline, occasionally forming a present-day pockmark, is the youngest (J. Cartwright et al.,
271 2018; Chris Kirkham et al., 2019).

272 Not all pipes are organized in trails. An exceptional cluster of pipes occurs SE of the Latakia Ridge. Here,
273 c. 50 pipes propagate from the culmination of a sub-salt thrust anticline where the evaporite cover is
274 absent and a primary weld (*sensu* Wagner & Jackson, 2011) occurs (Fig. 9). The pipes crosscut the Plio-
275 Quaternary overburden, occasionally reaching the seafloor and forming several pockmarks (Fig. 10). The
276 pockmarks are confined within a 2.5 x 4.7 km, up to 60 m deep depressed area directly overlying the fluid
277 escape zone. A mounded feature occurs in the depressed area and shows a central elongated depression
278 on its southern side (Fig. 10a).

279

280 *4.3. Distribution of pipes within trails*

281 For every trail we measured the distance of each pipe from its leakage point (Fig. 11b) and plotted it
282 against relative time intervals (T1 to T11), derived by our regional correlation of intra-RSB units (Fig. 11c;
283 see also Evans et al. 2020). We observed that the pipes have a first-order distribution, in which a small
284 but well-defined cluster of closely spaced (<1 km) pipes, or a single pipe, is separated from younger
285 features by a c. 1 km gap. These younger pipes are more widely dispersed along the trail length,
286 occasionally forming individual clusters separated by small gaps.

287 In addition to this distribution, which correlates the inferred trend of fluid emission among anticlines at
288 the basin scale, more unique, somewhat second-order cycles of pipe spacing and formation are observed
289 within each trail. For example, PT2 shows long quiescence intervals between periods of intense pipe
290 formation. Similar cycles of higher and lower frequency of fluid escape occur in all trails. PT6 shows a clear
291 decrease of pipe frequency towards more recent times; this trend is also observed in PTs 4, 5, and 9. An
292 end member is PT 7, which shows only an initial group of pipes and a complete lack of more recent activity.

293

294 *4.4. Amplitude anomalies and lateral fluid diffusion*

295 The fluid pipes are frequently associated with single or multiple reflections showing increased amplitude
296 with respect to the host unit (herein termed amplitude anomalies). The occurrence of amplitude
297 anomalies in areas of fluid migration and escape has been widely documented and is interpreted as an
298 accumulation of either gas-rich fluids, or hydrocarbon-mediated precipitation of authigenic minerals,
299 depending on their soft or hard kick seismic character, respectively (e.g. Gay et al., 2007; Oppo & Hovland,
300 2019). In this study, given all the amplitude anomalies associated with fluid pipes are soft kicks (e.g. Fig.
301 6), we infer they reflect higher (gas-rich) fluid saturation. Most likely, the fluids migrating through the
302 pipes are connate water and methane gas, as documented in many examples worldwide (e.g. J. Cartwright
303 & Santamarina, 2015).

304 The amplitude anomalies are commonly within, and in proximity of, the pipes (Fig. 6), or at their upper
305 terminus (Fig. 4). Amplitude anomalies only occur in the post-salt sedimentary succession. The anomalies
306 extend laterally from the pipes up to c. 1 km and either have sharp amplitude cutoffs at their edges or
307 progressively reduce in amplitude. At the edge of the amplitude anomalies, the lack of evident

308 discontinuities or likely lithology change shows that the anomalies are a fluid-related seismic response.
309 The amplitude anomalies are concordant with the host stratification, indicating fluid diffused laterally
310 along sedimentary strata defined by enhanced permeability (Fig. 6). Occasionally, amplitude anomalies
311 originate from minor normal faults overlying the interval affected by the pipes (e.g. Fig. 3). These faults,
312 which formed after the deactivation of the pipes by likely draining residual fluids from the pipes, represent
313 local high-permeability pathways in an otherwise sealing, fine-grained sedimentary succession.

314 We classify subvertical groups of amplitude anomalies as vertical anomaly clusters (VAC) following the
315 definition by Foschi et al. (2014). VACs are observed offshore Lebanon within anticlines associated with
316 RSBs (Fig. 6), within contourite-like deposits (Fig. 12), and around the pipe cluster at Latakia Ridge (Fig.
317 10). A VAC develops from the post-salt portion of a mud volcano feeder pipe and extends up-dip towards
318 the culmination of a small contourite-like deposit (Fig. 12). An RMS amplitude map shows a direct
319 connection between the mud volcano feeder pipe and the VAC, thus evidencing that cross-evaporite pipes
320 can promote extensive lateral migration, and possible accumulation, through carrier beds in the post-salt
321 overburden.

322 The Latakia Ridge pipe cluster is associated with the largest VAC in the dataset (Fig. 10). A complex VAC
323 extends laterally from the pipes along the anticline axis for a total length of c. 10 km. The anomaly cluster
324 has a maximum thickness of c. 200 ms in the northeastern half, and tapers to only two reflections on its
325 SW side. Whereas the NE portion of the VAC is well-defined, the SW sector is dissected by numerous
326 normal faults that offset the anomalies. A basal anomaly delimits the lower edge of the VAC, whereas its
327 upper limit is more fragmented (Fig. 10d). A flat soft kick anomaly delineates the upper VAC in the pipes
328 area and transitions laterally to reflections apparently dipping NE; this anomaly has a very limited lateral
329 extension in the NW-SE direction and its origin remains unclear. The flatness rapidly disappears moving
330 laterally (Fig. 9), with this feature not thought to be a bottom simulating reflection (BSR) given its
331 geometry is independent from that of seafloor. The possibility of it being a hydrocarbon-generated flat
332 spot is excluded because its soft kick character.

333

334 **5. Discussion**

335 The 325 mapped fluid escape pipes provide an exceptional record of fluid escape history in the northern
336 Levant Basin. The organization of these pipes into trails records various phases of cross-evaporite fluid
337 escape starting in the Late Pliocene/Early Pleistocene. We analyze trail lengths and pipe distributions to

338 reconstruct the processes that triggered and sustain fluid escape in the basin. The seismic reflection dated
339 1.8 Ma by Kirkham et al.(2019) in the southern study area provides the only absolute time marker, and
340 we can identify only relative time intervals using this datum as a reference point.

341 *5.1. Mechanisms of cross-evaporite fluid escape in the northern Levant Basin*

342 Fluid escape through evaporite seals is difficult because of the intrinsic salt properties, such as its ability
343 to maintain seal integrity, to flow under stress, and to quickly re-anneal fractures (Warren, 2006).
344 However, salt welding, faulting, salt dissolution, and overpressure/hydrofracturing can promote fluid
345 escape (Warren, 2006). These factors occur in the Eastern Mediterranean thanks to the unique tectono-
346 stratigraphic development of its constituent sub-basins, generating a wide range of fluid escape features
347 (C. Bertoni et al., 2017).

348 In the northern Levant Basin, the nearly simultaneous start of pipe formation and the main phase of salt
349 movement (S. Evans et al., 2020) may suggest a causal connection between the two events. Despite the
350 temporal coincidence, measured changes in rates of salt movement derived from RSBs do not directly
351 correlate with pipe distribution within the trails (S. Evans et al., 2020); i.e. increases or decreases of salt
352 gliding rate are not matched by increases or decreases of pipes spacing, respectively. This observation
353 suggests that overpressure pulses and pipe formation are independent from salt tectonics. Additionally,
354 during the initial stages of gliding the salt was quite thick and significant variations in the pressure regime
355 within the underlying reservoirs is unlikely.

356 Normal faults do not contribute to cross-evaporite fluid escape in the northern Levant Basin. Such
357 structures, which are related to thin-skinned, salt-detached extension, breach the salt seal and create
358 vertical fluid migration pathways in the Cyprus Basin (Hübscher et al., 2009). However, along the northern
359 Levant margin, thin-skinned structures detach within the top of and do not crosscut the evaporite layer.
360 Instead, the fluid pipes are occasionally associated with smaller normal faults that develop within the
361 post-salt sediments and rarely extend down into the salt (Figs. 4b, 6a). The location and characteristics of
362 these faults suggest they formed by a combination of compaction of intra-RSB sediments and overburden
363 folding during salt-detached translation. Amplitude anomalies and VACs show that the faults may favor
364 fluid migration by weakening the overburden and connecting intervals with higher permeability, thus
365 promoting both vertical and lateral fluid diffusion within the post-salt sediments. We conclude that fault-
366 induced fluid migration within the overburden is a secondary process and is not responsible for pipe
367 genesis.

368 A different scenario occurs at the Latakia pipe cluster, where E-W-striking normal faults dissect both the
369 pre- and post-salt sedimentary units (Fig 10d). One fault system crosscuts the sub-salt sediments along
370 the entire anticline, likely favoring vertical fluid migration from deeper units. Another fault system is
371 mainly confined to the post-salt overburden to the SW of the pipe cluster. Here, the faults displace the
372 present seafloor to define several grabens. Although the pipes disrupt the seismic signal and limit the
373 interpretation of the post-salt interval geometries, the faults do not appear to extend into this area as no
374 seafloor displacement occurs within the depression. Variance and RMS maps also do not show any
375 evidence for subsurface faults (Fig. 10b-d). The faults vertically offset the amplitude anomalies originating
376 from the pipe cluster. This suggests that the start of fluid escape, or at least the periods of lateral fluid
377 diffusion, predates fault formation. Additionally, the sedimentary sequence and the seafloor in the graben
378 area are barren of features related to vertical fluid migration, which are instead mostly confined within
379 the depressed area. Based on these observations, we suggest that the Latakia supra-salt faults do not
380 have a role in the fluid escape but may act as lateral barriers and/or baffles to fluid movement.

381 Salt dissolution favored cross-evaporite fluid migration in other areas of Eastern Mediterranean (e.g. C.
382 Kirkham et al., 2018). Deep-sourced fluids can propagate into evaporite units through hydrofracturing and
383 induce salt dissolution and collapse within pipes, in a mechanism comparable to the stoping of igneous
384 intrusions (C. Kirkham et al., 2018). Deep-sourced fluids can dissolve the salt, generating circular
385 depressions on the top-salt as observed in the southern Levant Basin (C. Bertoni & Cartwright, 2005), or
386 can, in combination with hydrofracturing and sediment withdrawal, cause the entire evaporite and
387 overburden sequence to sag downwards as observed in the mud volcanoes of the Nile deep-sea fan (C.
388 Kirkham et al., 2018). We do not observe these morphologies in association with fluid escape pipes in the
389 northern Levant Basin. It is possible that dissolution also occurred in this area, but the lack of visible
390 evidences points to its negligible role compared to overpressure-induced hydrofracturing.

391

392 *5.1.1. Overpressure generation and hydrofracturing*

393 Overpressure and hydrofracturing are the principal causes of cross-evaporite fluid escape in the Eastern
394 Mediterranean (C. Bertoni et al., 2017). Salt is excellent seal rock because extremely low permeability,
395 and near-lithostatic overpressure is a critical precondition to reach its fracture threshold (Warren, 2017).
396 Across the Eastern Mediterranean, the Nile and southern Levant basins have the longest record of fluid
397 escape, starting in the Late Miocene and continuing until present (C. Bertoni et al., 2017). The rapid sea-

398 level changes during the MSC had a significant role in pressure variation and promotion of fluid escape
399 (Claudia Bertoni & Cartwright, 2015). In addition, the thick Messinian salt accumulated rapidly (Roveri et
400 al., 2016), loading the underlying sediments and favoring undercompaction and overpressure (Al-Balushi
401 et al., 2016; Warren, 2006).

402 Offshore Lebanon, a few pockmarks at the base-salt reflection are the only potential fluid escape features
403 predating the Pliocene (Fig. 6 in C. Bertoni et al., 2017). Because underlying fluid pipes are not visible in
404 the seismic images, these pockmarks may represent dewatering or gas expulsion from near-seafloor
405 sediments caused by the initial MSC sea level drop. Therefore, the oldest fluid escape pipes in the
406 Lebanese offshore formed during Late Pliocene/Early Pleistocene, thus postdating the end of the MSC by
407 >2 Myr. This lag suggests that the MSC did not create sufficient overpressure within the sub-salt reservoirs
408 to reach the near-lithostatic level necessary to fracture the overlying salt. Therefore, fluid escape along
409 the Lebanese margin required other overpressure-inducing mechanisms.

410 We hypothesize that tilting of the Levant margin was the primary cause for the beginning of extensive
411 fluid escape from sub-salt anticline crests in the northern Levant Basin. The eastern Levant margin has
412 been gradually uplifting since the Late Messinian, which together with differential sediment loading and
413 tectonic subsidence near the Cyprus Arc, triggered salt-detached gravity gliding (Gvirtzman et al., 2013).
414 At the same time, this uplift would have promoted fluid migration from the deep basin towards basin
415 margin anticlines (Fig. 13). This mechanism is similar to the vertical pressure transfer described in the
416 Baram delta offshore Brunei, in which overpressurized fluids in the pro-delta migrated up-dip into the
417 inner shelf deltaic sequences after margin inversion and uplift (Tingay et al., 2007). In this model, uplift is
418 a key agent for transferring overpressure generated in deeper distal units towards shallower, more
419 proximal successions. Although we cannot conclusively show the past existence of overpressure in the
420 distal Lebanese offshore, it most likely occurred by analogy with other areas of the Eastern Mediterranean
421 (C. Bertoni et al., 2017). Our hypothesis also agrees with models for the regional petroleum system, which
422 postulate up-dip hydrocarbon migration eastwards from biogenic and thermogenic source rocks located
423 towards the deeper basin (R. Ghalayini et al., 2018; Nader et al., 2018). Besides promoting fluid migration,
424 basin margin uplift may have also reduced the water column along the margin, inducing gas exsolution
425 from the hydrocarbons already trapped in the anticlines, thus increasing overpressure by buoyancy (e.g.
426 Al-Balushi et al., 2016).

427 In addition to the basin tilt, compressive tectonic stress may have contributed to the buildup of
428 overpressure in subsalt rocks. The creation and transfer of overpressure by compressive tectonics has

429 been documented in many basins worldwide (Morley et al., 2014), where it can drive fluid escape. The
430 northern Levant Basin has a long history of compressive tectonics (e.g. Hawie et al., 2013). The most
431 recent phases started in the Messinian and formed detachment folds and transpressive strike-slip
432 structures along the eastern margin (Ramadan Ghalayini et al., 2014). Later, in the Pliocene, the Latakia
433 Ridge shifted from pure compression to transpression (Hall et al., 2005). The fluid escape started shortly
434 after these tectonic phases and originated from structures deformed during this period. We thus suggest
435 a secondary contribution of regional compression to overpressure development.

436 Therefore, we argue that the main processes responsible for fluid escape genesis in northern Levant Basin
437 differ from those in the southern Levant and Nile deep-sea fan basins. Whereas events linked to the MSC
438 likely contributed to increasing the pressure within sub-salt reservoir units, the lack of fluid escape
439 features immediately following the MSC indicates that this was (and is) a second-order control.
440 Consequent tectonic activity, at the scale of the northern Levant Basin, had an essential role in creating
441 the near-lithostatic overpressure necessary to generate cross-evaporite fluid expulsion. We argue that
442 the regional tectonics of the margin, more specifically basin tilt, were responsible for promoting both salt
443 movement and fluid leakage.

444

445 *5.2. Relationship between fluid escape and salt*

446 All the documented fluid escape features form at leakage points on the crest of prominent sub-salt
447 anticlines (this study and J. Cartwright et al., 2018) (Fig. 8). These structures act as 4-way-dip closure
448 hydrocarbon traps that allow extensive fluid accumulation, increasing the potential for overpressure
449 generation and hydrofracturing. Various NE-trending anticlines are documented in the Lebanese offshore,
450 but fluid escape occurs only when fluid accumulation combines with significant salt thinning (c. 250-500
451 m) above the anticlines (Fig. 14). The overall thickness of the Messinian salt varies from over 1 km in the
452 central basin to zero at the eastern basin margin and at the Latakia Ridge (Fig. 14). The pipes
453 predominantly occur in the latter two areas, thus suggesting a direct relationship between reduced salt
454 thickness and increased fluid escape in the Lebanese offshore, as has been demonstrated elsewhere in
455 the Eastern Mediterranean (C. Bertoni et al., 2017). Equally, the lack of fluid escape at the proximal pinch-
456 out of the salt indicates that the presence of a sub-salt trap structure is just as important as the reduced
457 salt thickness. With the exception of the Oceanus structure (J. Cartwright et al., 2018), anticlines in more
458 distal positions do not leak, despite potentially hosting fluids. We attribute this to a combination of smaller

459 anticline size and thicker salt cover (1200-1500 m). The large Oceanus structure must have accommodated
460 enough fluids to increase the overpressure above the high fracture threshold, thus overcoming the thick
461 salt cover.

462 The pipe cluster at the Latakia Ridge exemplifies the importance of thinned salt and anticline presence in
463 facilitating across-salt leakage (Figs. 9 and 10). This thrust-related fold is a 4-way structural trap where
464 fluids migrating into it may leak in absence of an efficient top seal. The anticline was already deforming
465 during the MSC, thus limiting evaporite deposition on top of the structure. Later growth of the structure
466 may have caused salt to flow off the anticline crest, causing further salt thinning at its apex. The salt
467 progressively thins towards the anticline culmination, becoming absent or sub-seismic resolution (c. 10-
468 40 m) in the area where the pipes develop. Therefore, the area where the salt is absent strictly defines
469 the fluid escape extent (Fig. 9). In the surrounding region, where salt occurs, there is no cross-evaporitic
470 fluid escape (Fig. 10d).

471

472 *5.3. Super-sheared pipes*

473 Along the Lebanese margin, the root of the pipes appears shifted downwards along the anticlines flank;
474 i.e. older pipes seem to emanate from the anticline flanks, not crest (Figs. 3, 5, 6). A similar geometry is
475 hypothesized but never demonstrated at the Saida-Tyr fold B (Chris Kirkham et al., 2019). Pipe emission
476 from the flank of the anticlines is not reasonable as the fold culmination represents the point of highest
477 buoyancy forces and likely fluid leakage, as demonstrated by the location of the most recent pipes (e.g.
478 Fig. 6a). Here, we hypothesize that the apparent displacement of the pipe roots down the anticline flank
479 may result from very high shear strains due to the large drag force acting on the base-salt. Indeed, the
480 pipes may have been sheared to such a degree (i.e. super-sheared pipes) that the lower, gently dipping
481 portion closer to the base salt is no longer imaged in the seismic data despite its root still occurring at the
482 anticline crest (Fig. 5). This observation is accurate for all the pipe trails in the northern Levant Basin,
483 except for the Oceanus Structure, which shows all the pipe roots converge at a common leakage point (J.
484 Cartwright et al., 2018). The (super) shearing of the pipe base along the anticlines flank may record the
485 fold amplification during the Plio-Pleistocene, intra-salt deformation, or a combination of both processes.

486

487 *5.4. Evolution of fluid escape recorded by pipe trails*

488 Fluid expulsion started asynchronously among the pipe trails during the Late Pliocene/Early Pleistocene
489 and is continuing at present. The 1.8 Ma reflection gives a spot age estimate for the trail formation,
490 dividing them into two groups (i.e. pre- and post-1.8 Ma). The intra-RSB stratigraphic units offer a better,
491 alternative calibration over the entire life span of each trail, allowing the relative age of the pipes to be
492 correlated across the margin (S. Evans et al., 2020). The first pipe of each trail falls within RSB units of
493 different ages (Fig. 11c), showing variability in the exact timing of initial fluid escape along the margin.

494 Prominent anticlines along the Lebanese offshore experienced an initial, geologically brief episode of
495 overpressure buildup and fluid expulsion that is separated from the more recent fluid escape by a period
496 of inactivity. We reconstructed the fluid escape activity by considering the pipes position in terms of
497 relative time during which fluid expulsion was either active or quiescent. The oldest trail in each anticline
498 started during T1 (excluding the significantly younger PTs 1 and 9, which started in T4 and T8,
499 respectively). On this basis and for the purpose of this discussion, we approximate the start of fluid escape
500 as being contemporaneous along the Lebanese margin. Fluid emission initiated with a brief episode that
501 was followed by a longer quiescent period (Fig. 11c). This first episode of fluid escape most likely led to a
502 significant reduction of fluid volume within the reservoirs. The resultant lower pressure prevented new
503 hydrofracturing across the entire margin during a relatively long interval, as testified by the long gap
504 between the oldest pipe group and the younger features (Fig. 11). A second period of fluid release begun
505 when sufficient overpressure built up again and represents the main fluid leakage phase in the northern
506 Levant Basin. This phase started during T2 and is still active, mostly in the Saida-Tyr anticlines. The
507 recorded fluid escape suggests that the Levant Basin tilt generated an exceptional initial pulse of
508 overpressure along the entire Lebanese margin, which was able to overcome the salt seal. Because of the
509 absence of further major tectonic changes, sufficient overpressure required time to be re-established by
510 more local processes, such as hydrocarbon generation within individual sub-basins and permeability of
511 local carrier beds.

512 Because pipe formation requires hydrofracturing by fluid-generated overpressure, the distribution of
513 pipes along the trails can be used as a proxy for fluid input in the anticlines. The pipes formed during the
514 second fluid escape period record cycles in hydrofracturing and quiescence, indicating overpressure
515 oscillations due to alternating fluid charge and discharge (Fig. 11). These overpressure oscillations are not
516 homogeneous between the various anticlines, as indicated by the different pipe distributions within trails.
517 While the basin tilt is likely continuing to favor fluid migration from the deep basin, the diverse
518 overpressure oscillations are most likely governed by local factors. Rate of hydrocarbon production,

519 efficiency of migration from the source rocks, trap size and geometry, reservoir porosity and permeability,
520 and salt characteristics are all possible factors. A similar variability of fluid influx into traps is widely
521 documented in hydrocarbon reservoirs (e.g. Deville & Guerlais, 2009; Oppo et al., 2013) and in fluid escape
522 systems (Judd & Hovland, 2007; Maestrelli et al., 2017; Oppo et al., 2013).

523 The variability of trap charge and discharge is particularly evident in the pipe trails originating from fold B
524 at Saida-Tyr (Fig. 8b). In this location various trails (i.e. PT2, 3, 4, 5) develop in an area where the salt and
525 overburden translate uniformly away from the structure (i.e. uniform velocity along fold strike) (S. Evans
526 et al., 2020), thus contemporaneous pipes fall within the same RSB interval (Fig. 11). The total length of
527 the pipe trails varies by up to c. 4 km among these closely spaced trails. This variation does not have a
528 defined trend; i.e. trails are neither progressively longer nor shorter moving north. The different lengths
529 also indicate distinct start times for the initiation of the trails, thus pointing to an independent fluid escape
530 history for each. This hypothesis is supported by the widely differing distributions of pipes within the four
531 trails. These differences are significant and may reflect hydraulically independent sectors within the
532 anticline. Amplitude and variance attribute analyses show that the Saida fault inversion did not disrupt
533 the lateral continuity of the NW-SE-striking normal faults within fold B (Fig. 15). Therefore, we infer that
534 the leakage points along the anticline crest are located within different tilted fault blocks. It is reasonable
535 to hypothesize that the normal faults act as barriers or baffle lateral fluid movement, thus creating
536 reservoir sectors displaying different cycles of overpressure build up and release.

537

538 **6. Conclusions**

539 We analyzed novel 3D seismic data offshore Lebanon to reconstruct overpressure generation mechanisms
540 and fluid escape duration and cyclicity following the deposition of the thick Messinian salt along the
541 continental margin of northern Levant Basin. The high number of fluid escape pipes occurring in the
542 northern Levant Basin proves the existence of a highly active regional petroleum system able to generate
543 large volumes of hydrocarbons over a relatively long time span.

544 The Lebanese offshore experienced diffuse fluid expulsion since the Late Pliocene/Early Pleistocene,
545 which peaked in the Late Pleistocene. The initial pipe formation is asynchronous across the basin despite
546 concentrating within a narrow time interval coincident with the main uplift of the eastern sector of the
547 basin. We interpret the uplift as the main event leading to cross-evaporite fluid escape in this region of
548 the Eastern Mediterranean, thanks to its role in transferring overpressured fluids into prominent

549 anticlines along the basin margin. Dissimilarities in the initiation of fluid expulsion from a single anticline
550 and, more generally, across the Levant Basin suggest that, after an initial fluid escape episode linked to
551 the margin uplift, local dynamics of fluid migration and overpressure buildup over-imposed on the
552 controls acting at a regional scale. In particular, it can be observed that: 1) the pipes location is strongly
553 controlled by the structural arrangement of the sub-salt units; 2) the cyclicity of overpressure and fluid
554 charge/discharge is regulated by fluid dynamics dependent on the individual structures.

555 In conclusion, recent efforts in the study of salt basins not yet extensively deformed by halokinesis
556 continue contributing to unravel the processes driving overpressure generation and fluid escape through
557 thick salt. While in the southern areas of the Eastern Mediterranean cross-evaporite fluid escape has been
558 mainly attributed to the MSC and compaction disequilibrium, we argue that in the northern Levant Basin
559 this is not suitable; here fluid escape was mainly driven by the tectonic evolution of the margin. In this
560 frame, our study shows that the causes of cross-evaporite fluid escape can be multiple, vary over time,
561 act in synergy, and have different impacts in the various areas of salt giant basins.

562

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570 **Data availability statement**

571 The data that support the findings of this study are available from LPA. Restrictions apply to the
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573 **Conflict of Interest**

574 No conflict of interest is declared.

575

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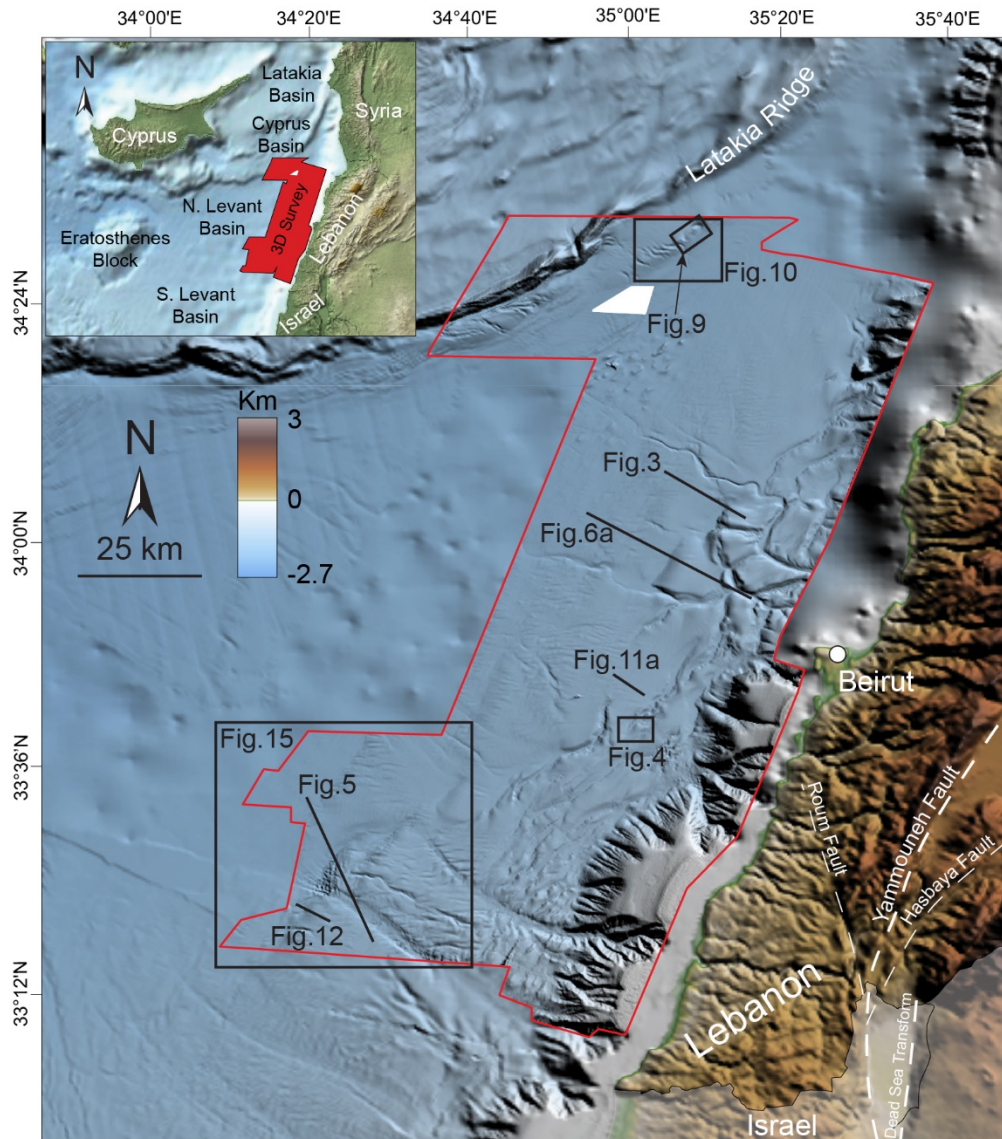
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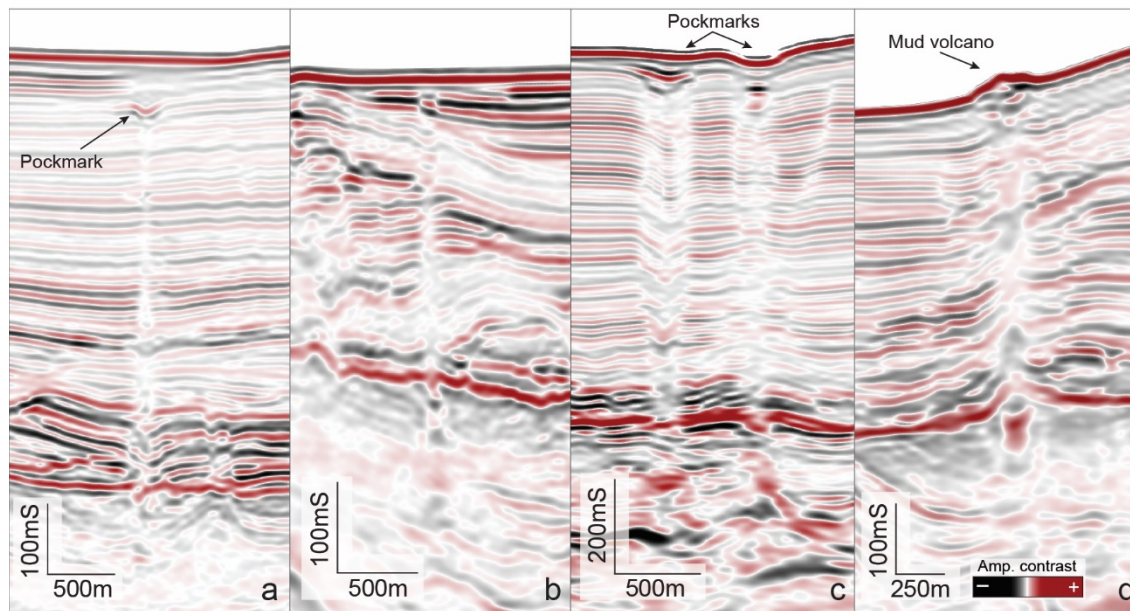
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757 Fig. 1 Map of northern Levant Basin showing the areal coverage of the interpreted 3D seismic data
 758 (red polygon) and the location of figures referenced in text. Bathymetry is derived by the 3D seismic
 759 data, GEBCO, and EDMOnet databases.

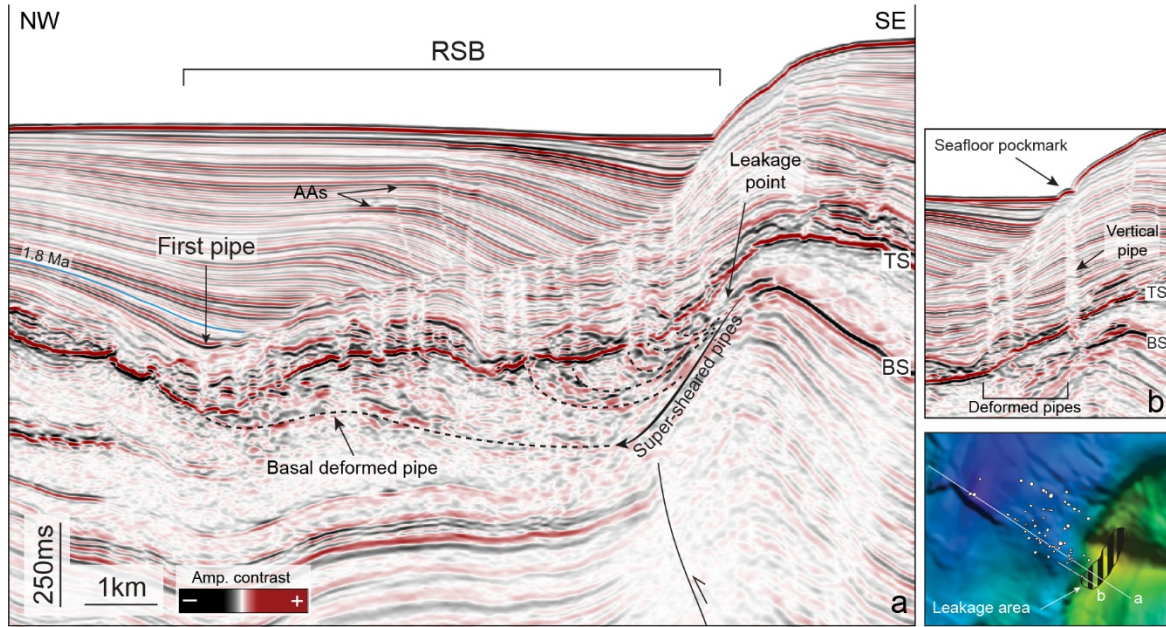


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761 Fig. 2 Seismic expression of different fluid escape pipe geometries. a) upward tapering conical pipe
 762 showing a clear pockmark terminus marked by an amplitude anomaly; b) cylindrical pipes roughly
 763 maintaining the same diameter; c) downward tapering conical pipes with large pockmark at seafloor and
 764 in the shallow subsurface; d) mud volcano feeder conduit showing lateral migration of fluid into the
 765 hosting sediments.

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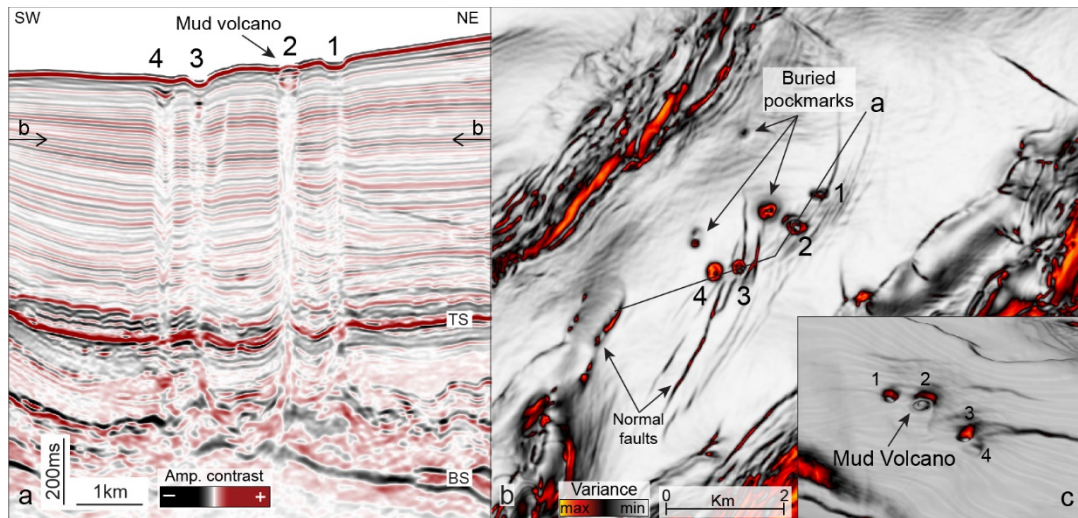
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769 Fig. 3 a) seismic cross section showing pipes originating from one thrust top anticline and
770 progressively translated basinward. The dashed basal deformed pipe marks the present-day expression
771 of the first fluid escape pipe within the salt. Arrow indicates the apparent translation of pipes root down
772 the anticline flank from the leakage point, forming a super-sheared pipe (see also Section 5.3). b)
773 Example of vertical pipe and pockmark on the present-day seafloor not yet deformed and translated by
774 the salt movement. TS: top-salt, BS: base-salt, AAs: amplitude anomalies, RSB: ramp syncline basin (see
775 text for more details).

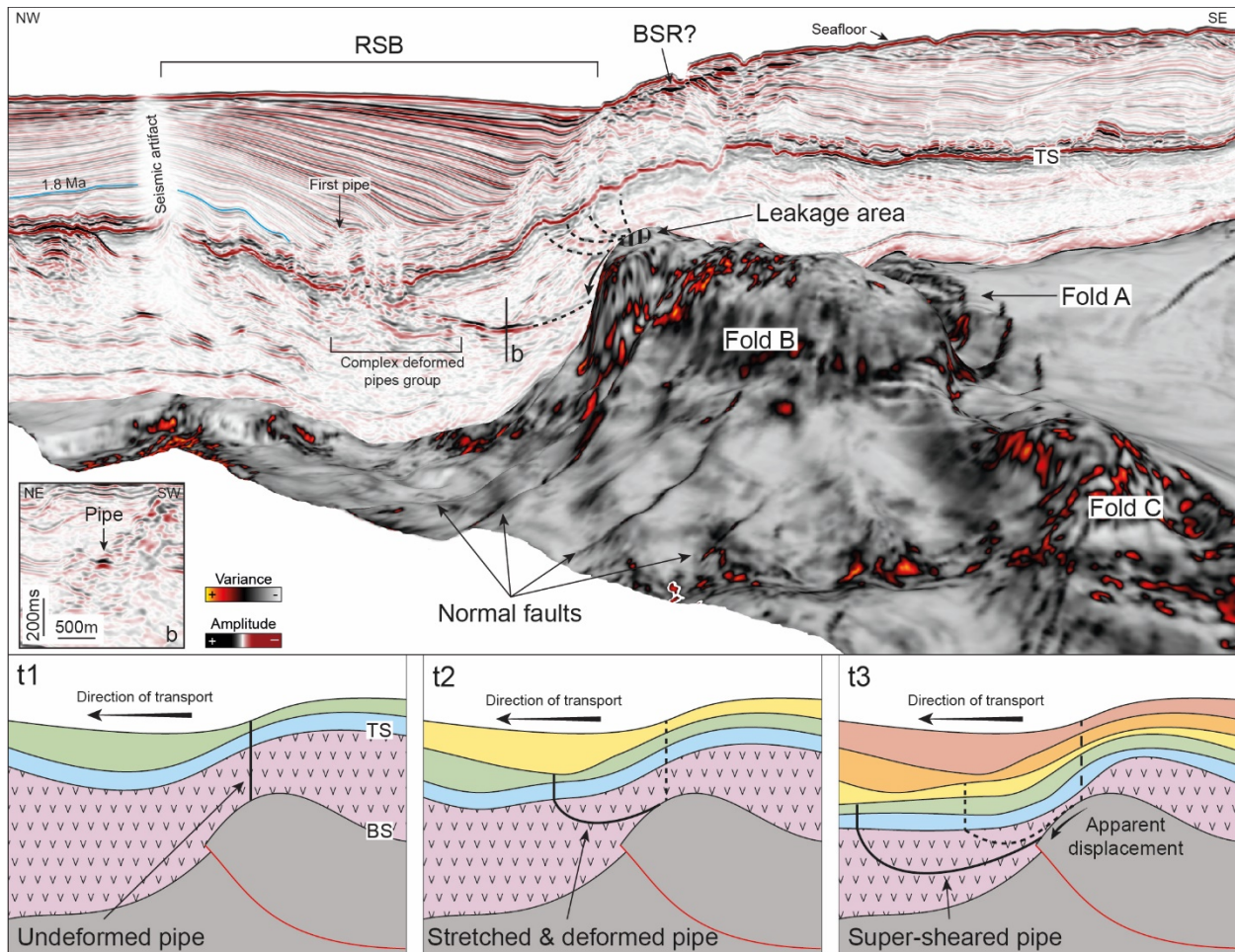
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778 Fig. 4 a) Seismic line showing example of pipes rooting on the top of a small anticline. The pipes are
 779 not organized in a trail but roughly parallel to the basin margin and have all different internal geometries
 780 and seismic response. b) variance time slice (north is up; see 'a' for location) showing a map view of the
 781 pipes. Secondary normal faults crosscut the sediment overburden but do not extend into the salt units
 782 crossed by the pipes. c) variance attribute on the present-day seafloor showing the morphological
 783 expression of pipes terminus. TS: top-salt, BS: base-salt.

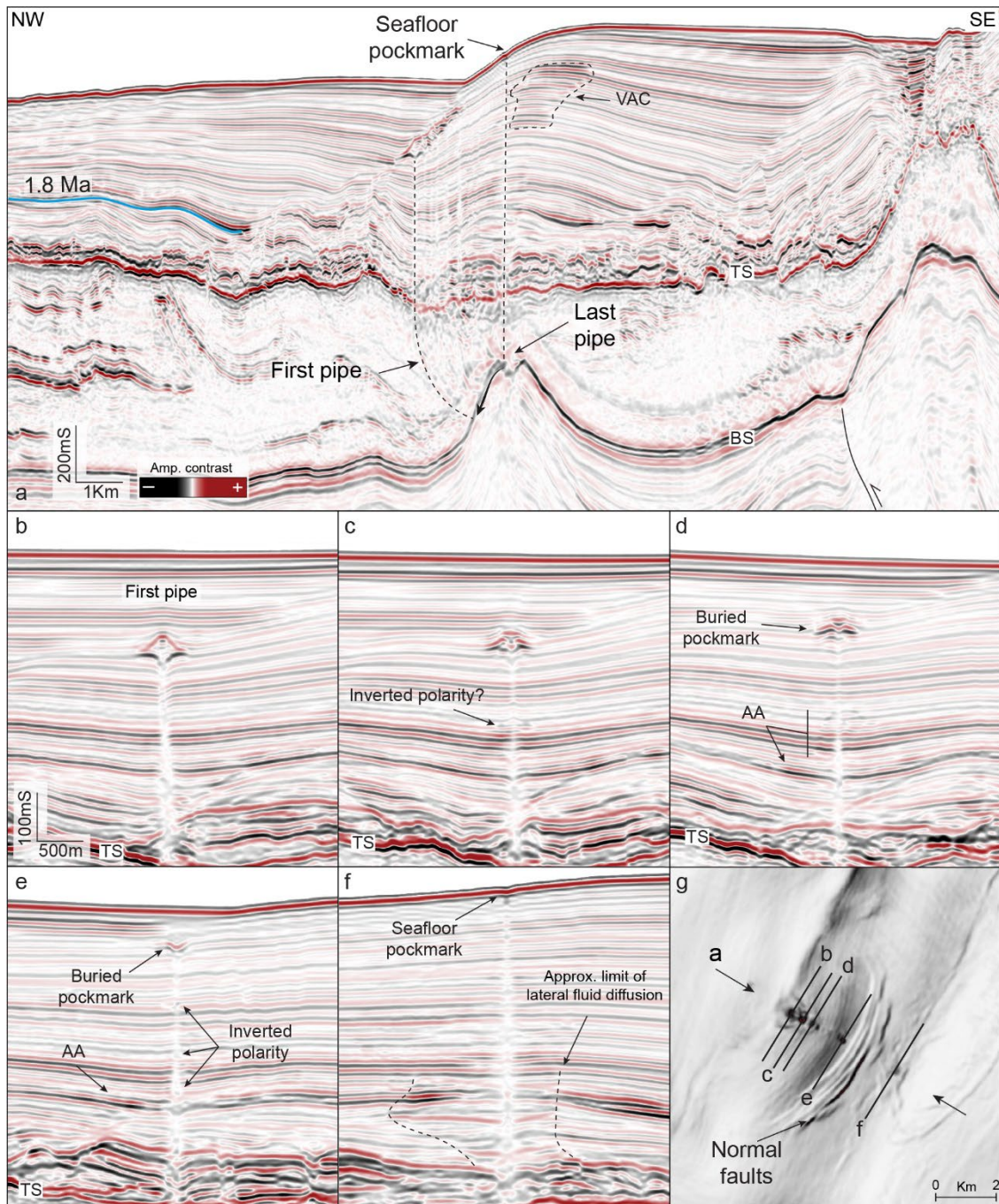
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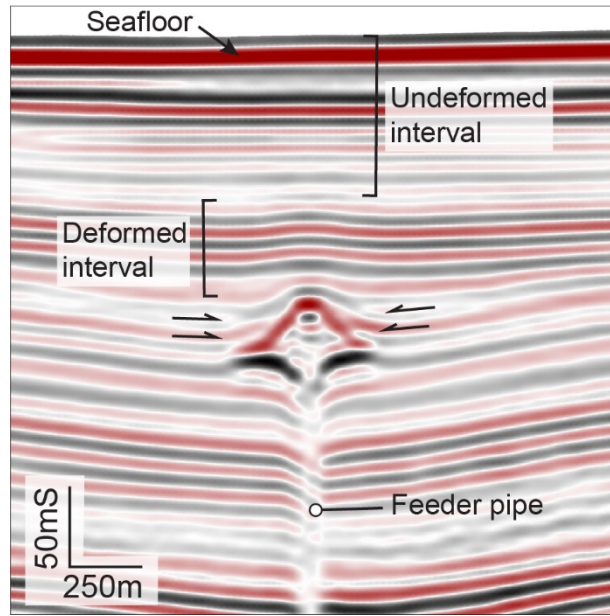
786 Fig. 5 Perspective view of pipe trail 3, originating from the culmination of fold B at Saida-Tyr. The
 787 variance attribute is calculated on the base-salt surface. Inset b shows the cross-section of a deformed
 788 pipe within the salt as a narrow soft-kick anomaly. Bottom panels: sketch of pipes formation and
 789 deformation. t1) an initial pipe is formed vertically from the anticline culmination. At the same time the
 790 RSB starts forming following the basinward salt gliding; t2) the first pipe is translated basinward while its
 791 portion within the salt is progressively stretched and deformed in an arcuate geometry. A second pipe is
 792 formed; t3) as the gliding of salt and overburden proceeds, the first pipe is stretched to such an extent
 793 that it becomes 'super-sheared'. In this phase, its lowermost portion is too fragmented to be still visible
 794 in the seismic data and the root appear shifted along the anticline flank. The second pipe started to
 795 deform while a new one forms. TS: top-salt, RSB: ramp syncline basin, BSR: bottom-simulating reflector.

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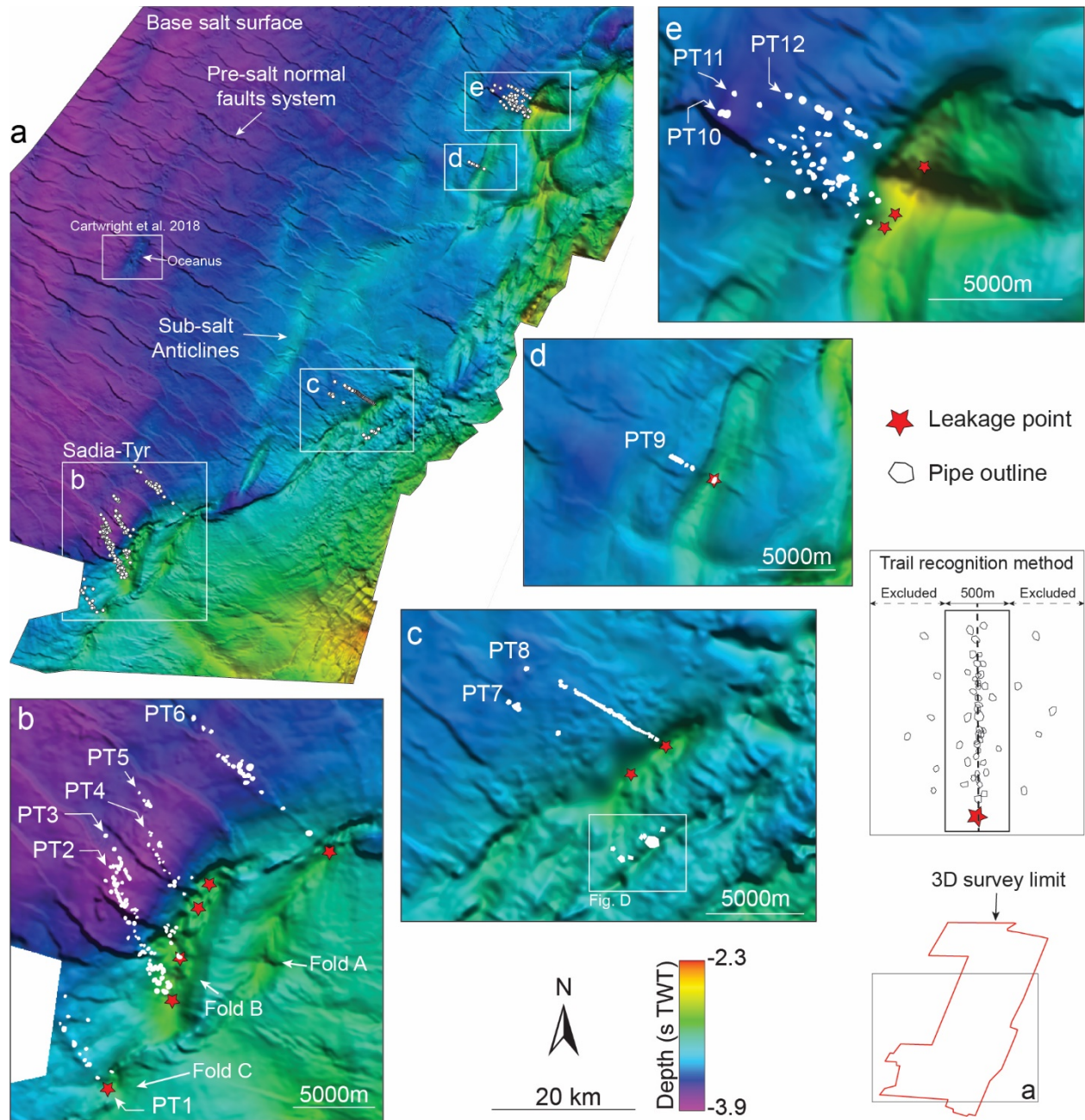
798 Fig. 6 a) Seismic cross-section showing pipe trail 9, which develops in between two superimposed
 799 RSBs. b-f) cross-sections perpendicular to the trail direction (see 'g' for location) showing the progressive
 800 transformation of the pipes terminus from mud volcano to pockmark. g) variance time slice at -2372 ms.
 801 A small set of normal accommodation faults does not crosscut the salt unit but most likely favored the
 802 lateral fluid migration within the overburden. TS: top-salt, BS: base-salt, AAs: amplitude anomalies, VAC:
 803 vertical anomaly cluster.



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805 Fig. 7 Detail of first pipe terminus in pipe trail 9 (see also Fig. 6). The geometrical and seismic
806 amplitude characteristics indicate that this likely is a mud volcano (see text for further details).

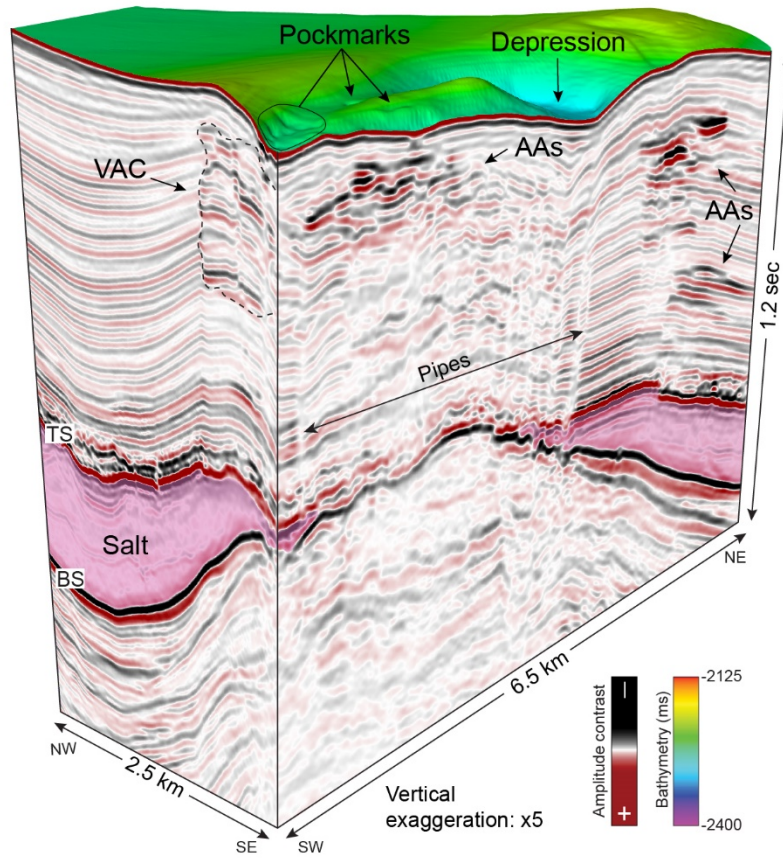
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809 Fig. 8 Base-salt surface showing the location of pipes and pipe trails along the margin. a) extended
 810 overview of the dataset showing sub-salt anticlines and normal fault system, and the location of
 811 Oceanus pipe trail. b-e) details of the twelve pipe trails occurring along the northern Levant margin.

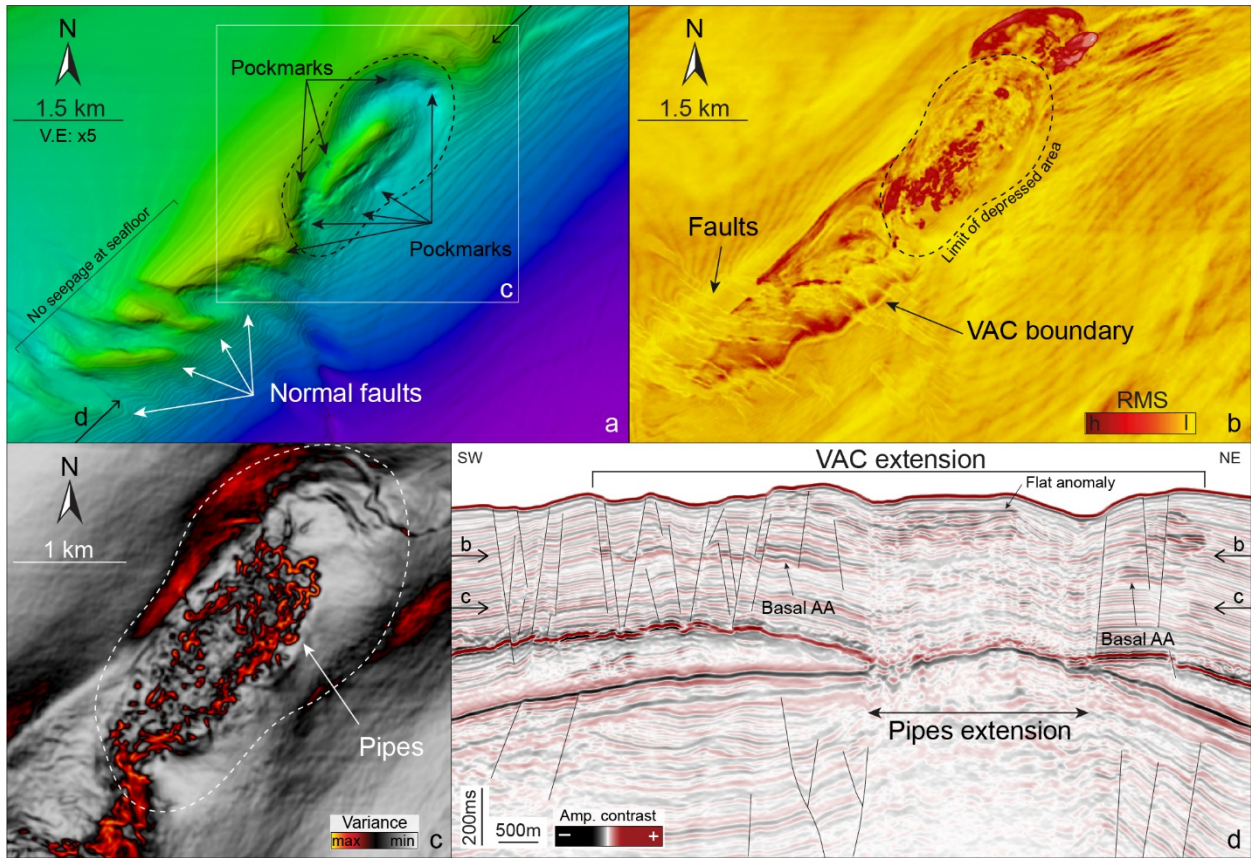
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814 Fig.9 Perspective view of pipe cluster originating from a Latakia thrust anticline. Pockmarks occur on
 815 the seafloor within a depressed area directly overlying the pipes. The pipes are located only at the
 816 anticline culmination where salt occurs. The fluids migrate laterally in the salt overburden forming VACs.
 817 TS: top-salt, BS: base-salt, AAs: amplitude anomalies, VAC: vertical anomaly cluster.

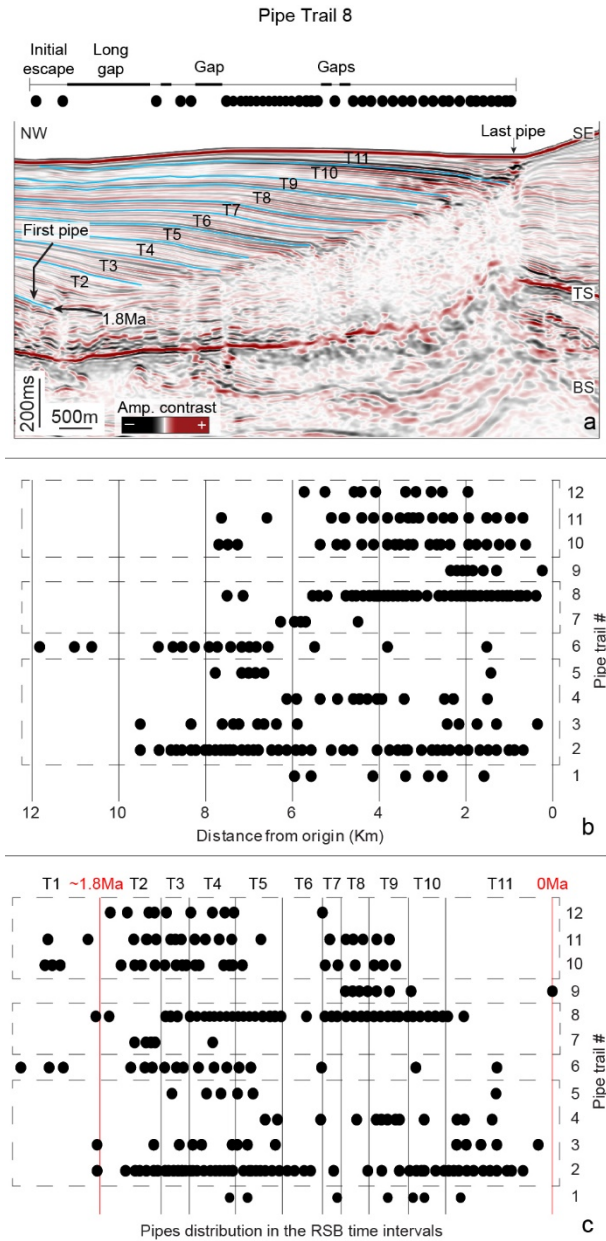
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820 Fig. 10 a) sea floor bathymetry at the Latakia pipe cluster. The pockmarks are confined in the depressed
 821 zone (dashed area), while the graben area on the SW is barren of fluid emission features. Arrows
 822 indicate the location of seismic line of panel d. b) RMS calculated on time slice (see arrows in panel d for
 823 location). The RMS clearly images the lateral extent of the VAC above the anticline. c) variance attribute
 824 calculated on a time slice (see arrows in panel d for location) and showing the pipes cluster. d) Seismic
 825 cross-section through the pipes cluster showing the two systems of normal faults and the lateral extent
 826 of the VAC characterizing this structure. AAs: amplitude anomalies, VAC: vertical anomaly cluster.

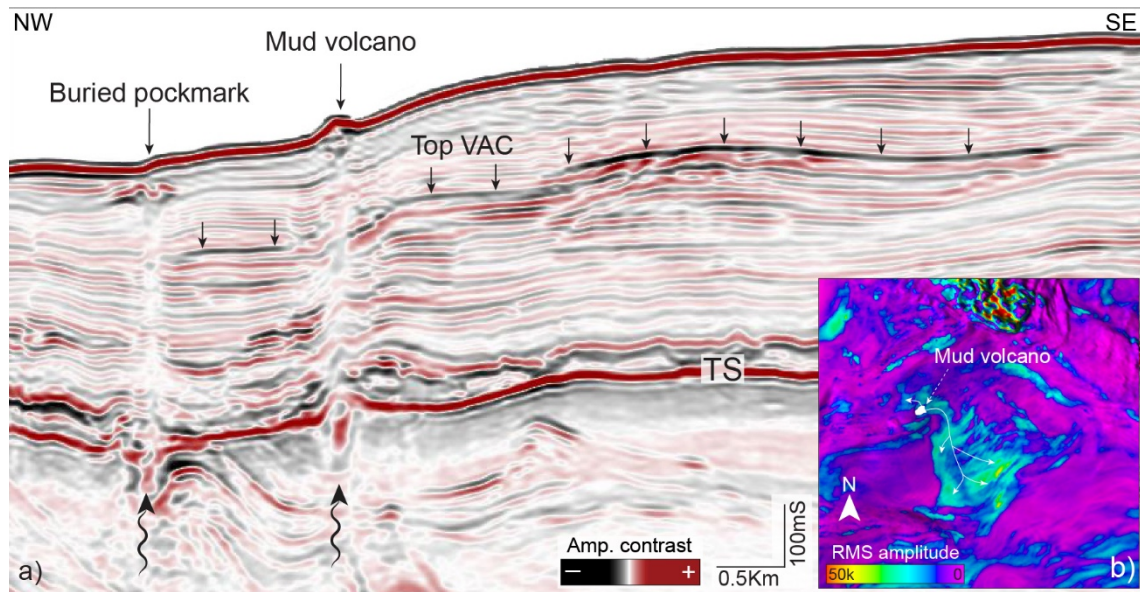
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829 Fig. 11 Quantitative characterization of the pipe trails. a) example of trail (PT8) showing the relationship
 830 between the pipes distribution and the RSB time intervals. b) horizontal distance of each pipe in a trail
 831 (black dots) from their emission point at the anticlines crest. The dashed boxes group the trails
 832 originating from the same sub-salt anticline. c) distribution of the pipes within trails according to their
 833 occurrence into the time intervals (T1-T11) calculated through RSB analysis. In figure, the length of the
 834 time intervals is displayed according to that of the anticline where PT2-5 occur.

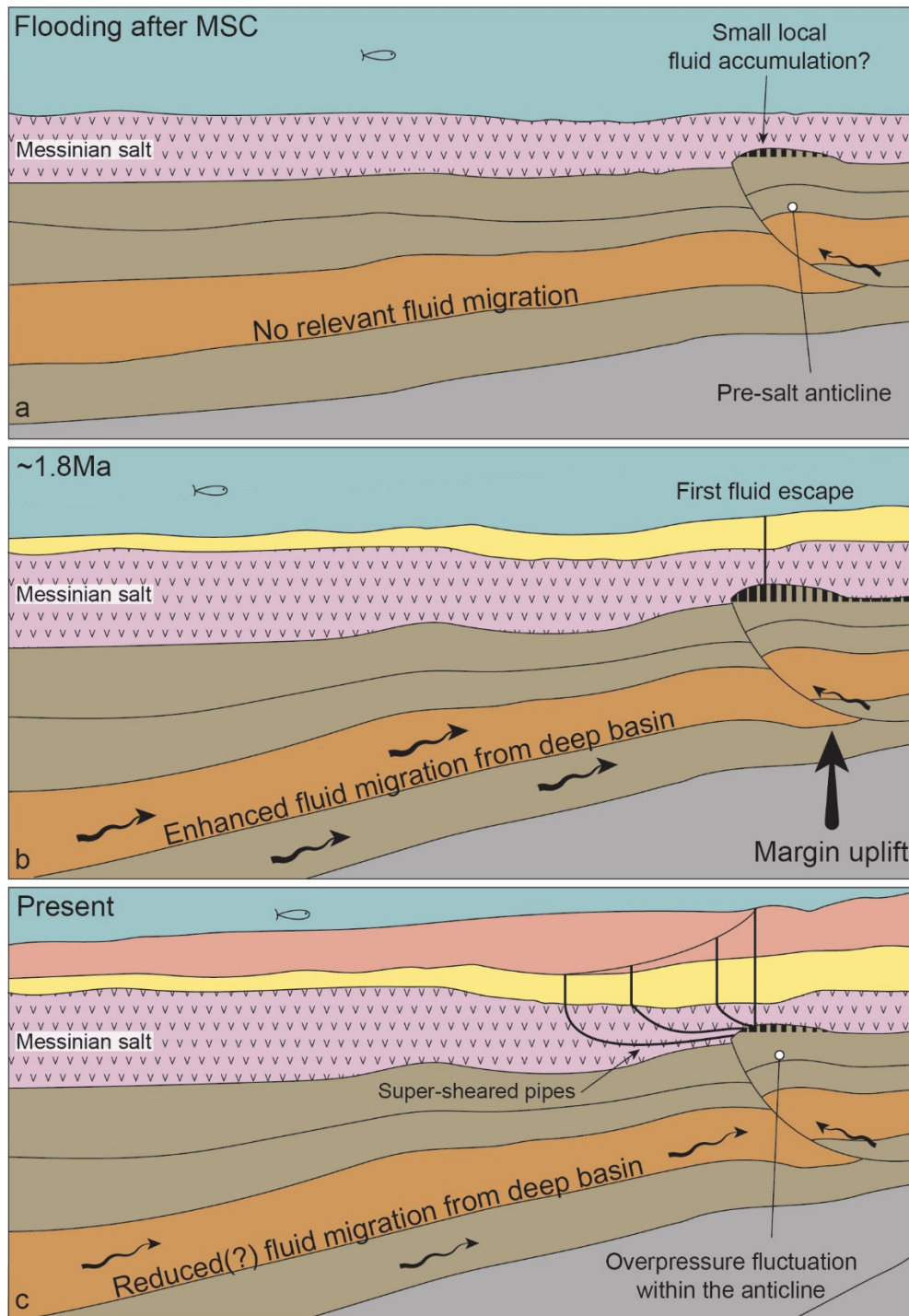
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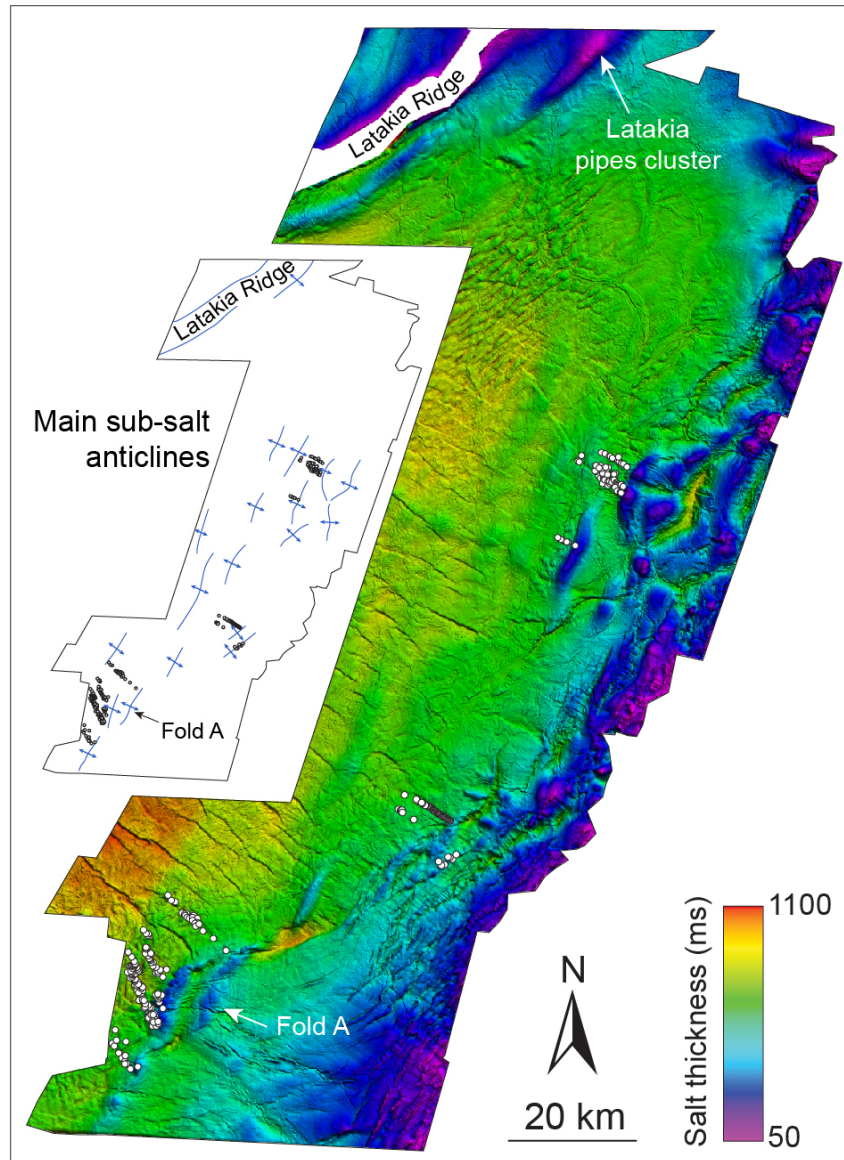
837 Fig. 12 a) vertical anomaly cluster originating from a mud volcano feeder pipe, which promotes the
 838 lateral up-dip fluid diffusion in the hosting sediment. b) RMS calculated on the VAC top to show the
 839 lateral extent of the amplitude anomaly and its origin from the mud volcano.

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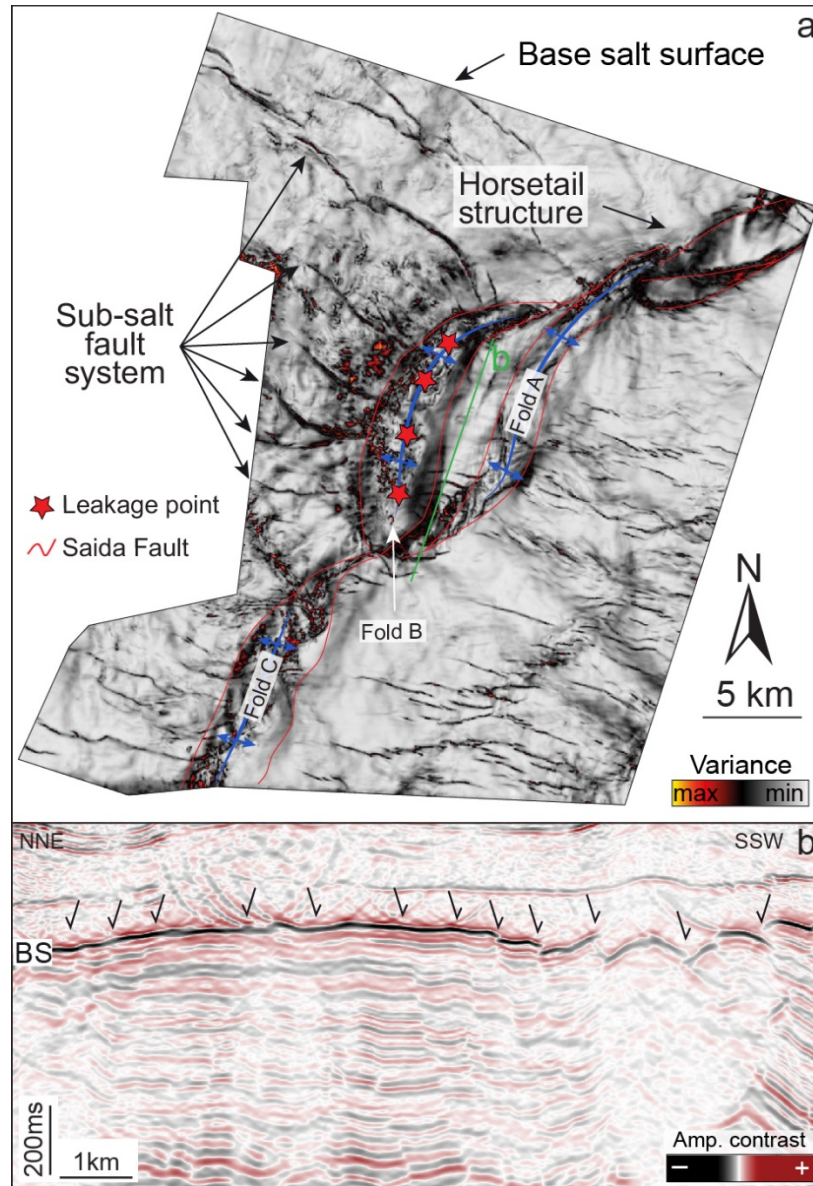
842 Fig. 13 Sketch of pipe trails evolution. An increased uplift of the Levant margin at c. 1.8Ma triggered
 843 enhanced fluid migration towards the sub-salt anticlines from the deeper areas of the basin (b). As
 844 consequence, supra-lithostatic overpressure formed inside the anticlines leading to hydrofracture and
 845 the formation of the first pipes. During the subsequent period and until present, local processes govern
 846 overpressure buildup and the formation of cross-evaporite fluid escape.



847

848 Fig. 14 Isopach map of the Messinian salt. The pipe trails constantly originate from the top of anticlines
 849 where the salt thickness is reduced.

850



851

852 Fig. 15 a) variance attribute calculate on bas-salt surface to evidence the Saida-Tyr structure and
 853 showing the interaction of the sub-salt fault system with the fold B (see also panel b). The location of
 854 fluid leakage points supports the hypothesis that the faults are barrier to fluid movement and form a
 855 compartmentalized reservoir, which parts experienced fairly independent fluid charge and discharge
 856 histories.