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21 fluid or gas flow, or form traps for hydrocarbon accumulations, is critical to de-risk hydrocarbon
22 exploration and production. Here we focus on evaluating how buried volcanoes affect the bulk
23 permeability of hydrocarbon seals, and channel and focus hydrocarbons. We use high-resolution 3D
24 seismic reflection and borehole data from the northern South China Sea (SCS) to show how ~10
25 km wide, ~590 m high Miocene volcanoes, buried several kilometers (~1.9 km) below the seabed
26 and fed by a sub-volcanic plumbing system that exploited rift-related faults: (i) acted as long-lived
27 migration pathways, and perhaps reservoirs, for hydrocarbons generated from even more deeply
28 buried (~8-10 km) source rocks; and (ii) instigated differential compaction and doming of the
29 overburden during subsequent burial, producing extensional faults that breached regional seal rocks.
30 Considering that volcanism and related deformation are both common on many magma-rich passive
31 margins, the interplay between the magmatic products and hydrocarbon migration documented here
32 may be more common than currently thought. Our results demonstrate that now-buried and inactive
33 volcanoes can locally degrade hydrocarbon reservoir seals and control the migration of
34 hydrocarbon-rich fluids and gas. These fluids and gases can migrate into and be stored in shallower
35 reservoirs, where they may then represent geohazards to drilling and impact slope stability.

36

37 **Keywords**

38 Hydrocarbon, volcano, fault, seal, migration, South China Sea

39

40 **Introduction**

41 Extrusive and intrusive igneous rocks are widespread in sedimentary basins (e.g. [Berndt et al.,](#)
42 [2000; White et al., 2003; Jackson et al., 2013; Magee et al., 2016; Schofield et al., 2017; Weinstein](#)

43 [et al., 2017](#)). Fluids and gases released in response to magmatism, such as hydrocarbons generated
44 by intrusion-induced heating of source rocks or hydrothermal fluids derived from the magma itself,
45 can migrate to shallower levels within basins and may even be expelled into the ocean or atmosphere
46 (e.g. [Lee et al., 2016](#); [Hasenclever et al., 2017](#); [Moussallam et al., 2017](#)). For example, the
47 synchronous and widespread extrusion of substantial volumes of methane-rich hydrothermal fluids,
48 emanating from the tips of intruding igneous sills, may have triggered or contributed to ancient
49 climate change events (e.g. [Jamtveit et al., 2004](#); [Svensen et al., 2004, 2012](#); [Iyer et al., 2017](#);
50 [Reynolds et al., 2017](#)). Aside from inducing formation of syn-emplacement fluid-escape structures
51 (e.g. hydrothermal vents and volcanoes), fractured igneous intrusions can also provide fluid
52 migration pathways long after their solidification ([Rateau et al., 2013](#); [Schofield et al., 2017](#)).
53 Networks of igneous intrusions may thus potentially divert fluids (e.g. hydrocarbons) into and
54 reactivate ancient, now-buried extrusive vents and volcanoes, allowing fluids to migrate upwards
55 and bypass significant thicknesses of strata ([Holford et al. 2017](#)). Several studies document how
56 extrusive and intrusive components of igneous systems can inhibit fluid flow and create traps (e.g.
57 [Schutter, 2003](#); [Monreal et al., 2009](#); [Gudmundsson and Løtveit, 2014](#); [Infante-Paez and Marfurt,](#)
58 [2017](#)). Understanding how igneous systems impact later fluid flow events is critical to de-risking
59 the exploration and production of hydrocarbon, water, and geothermal resources (e.g. [Wohletz and](#)
60 [Heiken, 1986](#); [Babiker and Gudmundsson, 2004](#); [Holford et al., 2017](#); [Schofield et al., 2017](#)).

61 Deciphering how igneous systems influence fluid flow events is problematic, because the
62 physical properties (e.g. porosity and permeability) of intrusive and extrusive rocks can be highly
63 heterogeneous over a range of scales ([Millett et al., 2016](#)), and related bodies can either act as
64 reservoirs (e.g. [Yang et al., 2016](#)) or seals (e.g. [Holford et al., 2012](#)). Moreover, differential

65 compaction of sedimentary rocks across (nearly) incompressible igneous rocks can cause folding
66 and faulting (e.g. [Zhao et al., 2014](#); [Holford et al., 2017](#)), which may facilitate or inhibit, post-
67 magmatic fluid flow ([Holford et al., 2017](#)). Despite its clear importance, there are very few studies
68 describing the precise control volcanoes and related overburden deformation have on post-magmatic
69 fluid flow (e.g. [Holford et al., 2017](#)).

70 Here we use high-resolution 3D seismic data and borehole data to analyze spatial and temporal
71 relationships between buried, Early Miocene volcanoes, pre- and post-eruption normal faults, and
72 post-eruption free gas accumulations in the northern SCS. We show the presence of volcanoes
73 instigated post-eruption, syn-burial overburden deformation, specifically differential compaction
74 and normal faulting. These faults locally disrupted regional seals and allowed gas to ascend through
75 the volcanic system into shallower reservoirs. Our results support recent findings that volcanoes and
76 their underlying plumbing system can focus fluid (and gas) flow within sedimentary basins long
77 after igneous activity has ceased ([Holford et al., 2017](#)).

78

79 **Geological setting**

80 The SCS is the largest (>3,500,000 km²) and deepest (>5,000 m of water depth) marginal sea in
81 the western Pacific Ocean. Seafloor spreading initiated in the northeast SCS in the Early Oligocene
82 (~ 32.0 Ma) in response to the extensional Nanhai Event (e.g. [Franke, 2013](#)), before propagating to
83 the southwest and ceasing at 15.0-15.5 Ma ([Briais et al., 1993](#); [Li et al., 2014](#)). Post-spreading
84 magmatism in the SCS has obscured seafloor spreading fabrics, making it difficult to precisely
85 identify the timing of cessation of seafloor spreading ([Sibuet et al., 2016](#)).

86 The Pearl River Mouth Basin is one of several Cenozoic rift basins located on the northern
87 continental margin of the SCS, covering an area of $\sim 17.5 \times 10^4$ km², and comprising several NE-
88 trending grabens, half grabens, and flanking massifs (Fig. 1a). During continental rifting (Late
89 Cretaceous - Early Oligocene), non-marine mudstones and coals, which now represent the main
90 hydrocarbon source rocks within the region, were deposited in the fault-bound depocentre sags
91 (Zhang & Huang, 1991; Huang et al., 2003). During the syn-to-post rift transition (Late Oligocene
92 - Early Miocene), marginal marine sandstones were deposited; these form the most important
93 hydrocarbon reservoir units and carrier beds in the Pearl River Mouth Basin (Zhu et al., 2009).
94 During the syn-to-post rift transition, the Nanhai Event caused three active periods of normal
95 faulting (32-29 Ma, 23.8-21.0 Ma, and 18.5-16.5 Ma), which can be tied to initial opening, ridge
96 jump, and maximum extension events in the SCS ocean basin (Deng et al., 2018). Deposition during
97 the subsequent period of post-rift thermal subsidence (Early Miocene - Present), was dominated by
98 very fine-grained, pelagic and hemipelagic strata, which provide an excellent regional seal (Zhu et
99 al., 2009). Hydrocarbons were generated in the source rocks during the Early-Middle Miocene (Zhu
100 et al., 2009). The latest Dongsha Event occurred from 10.5 Ma onwards, generating extensional
101 faults that deform relatively young strata (Lüdmann & Wong, 1999; Zhao et al., 2012). These faults,
102 together with highly permeable unconformities and mud diapirs, provided the main pathways for
103 hydrocarbon migration in the northern SCS (Zhu et al., 2012).

104 The SCS lacks seaward-dipping reflectors (SDRs) and can thus be classified as magma-poor
105 rifted margin (Yan et al., 2006; Franke, 2013). However, post-rift (Paleocene - Pliocene) magmatism,
106 in the form of sills and relatively small, mafic-intermediate volcano complexes, are documented
107 across the SCS (e.g. Zou et al., 1995; Yan et al., 2006; Franke, 2013; Li et al., 2014; Lester et al.,

108 2014; Sun et al., 2014b; Zhao et al., 2014, 2016, 2018; Ma et al., 2018; Deng et al., 2018). The
109 emplacement of subaerial and submarine volcanoes in the Pearl River Mouth Basin occurred during
110 two main phases, during the Paleocene (57.1 ± 2.5 Ma) and Early Miocene (17.1 ± 2.5 Ma) (e.g. Li
111 and Liang, 1994; Yan et al., 2006; Sun et al., 2014; Zhao et al., 2016; Deng et al., 2018). Early
112 Miocene volcanoes were emplaced at broadly the same time as hydrocarbons *generation* in the
113 deeply buried source rocks, but before the main stage of hydrocarbon *migration* (since ~ 10.5 Ma)
114 (Zhu et al., 2012). Given their spatial and temporal relationship, and normal faults caused by the
115 Nanhai Event may provide pathways for the Early Miocene volcanoes have been genetically related
116 (Deng et al., 2018).

117

118 **Data and Methods**

119 We use a high-resolution 3D seismic dataset covering an area of ~ 530 km², in water depths of
120 ~ 500 -1200 m, and acquired in 2010 by a 3000 m long streamer with 240 channels. The dataset has
121 a bin spacing of 12.5 m for both N-S oriented inlines and E-W oriented crosslines. The data is zero-
122 phase processed and displayed with SEG (Society of Exploration Geophysicists) normal polarity,
123 whereby a downward increase in acoustic impedance corresponds to a positive reflection (red on
124 displayed seismic profiles). We use borehole data (well loggings, core cuttings, micropaleontology)
125 from BY7-1 to constrain the lithology and age of the volcano-bearing succession and, thus, the age
126 of volcano emplacement (Qin, 2000; Zhao et al., 2016; Ma et al., 2018) (Fig. 2). These borehole
127 data also allow us to derive interval velocities for the volcanic complexes (~ 4500 m/s) and
128 surrounding strata (~ 2800 m/s). Coupled with the dominant frequency of the seismic data, which
129 gradually decreases downwards from the seabed (~ 45 Hz) to ~ 35 Hz where the volcano complexes

130 are located, we estimate approximate limits of separability ($\lambda/4$) of ~ 32 m and ~ 20 m for the volcanic
131 complexes and surrounding sedimentary strata, respectively (Zhao et al., 2016). Accordingly, we
132 estimate the limit of visibility ($\lambda/30$) of the seismic data to be ~ 5 m for the volcanoes and ~ 3 m for
133 sedimentary strata. For shallow strata at depths < 500 m where no borehole data is available, an
134 estimated velocity of 1700 m/s and a dominant frequency of ~ 45 Hz suggests limits of separability
135 and visibility are ~ 10 m and ~ 5 m, respectively.

136 We mapped six regional stratigraphic boundaries, which we correlated to borehole BY7-1 (T0
137 (2.58 Ma), T1 (5.0 Ma), T2 (10.5 Ma), T4 (16.5 Ma), T5 (17.5 Ma) and T6 (23.8 Ma); e.g. Pang et
138 al., 2007; Zhao et al., 2016; Deng et al., 2018; Ma et al., 2018) (Figs. 1b-c). We identify 14 mounded
139 structures in the 3D seismic survey and map their top (TV) and base (BV); the former coincides
140 with T5 (i.e. Early Miocene; Figs. 2-4). To identify and map free gas and normal faults, we extracted
141 RMS attribute and variance slices from the 3D seismic volume (Fig. 5); the former measures the
142 reflectivity of a given thickness (window) of seismic data and is calculated by dividing the square
143 root of the sum of squared amplitudes with the number of samples within a specified window
144 (Brown, 2004; Chopra and Marfurt, 2005) (Figs. 5f, 6). The variance, which is operated within a
145 time window/interval, converts a volume of continuity (the normal reflections) into a volume of
146 discontinuity and is free of interpretive bias (Brown, 2004; Chopra and Marfurt, 2005) (Figs. 5c-e).

147

148 **Results**

149 **Buried volcanoes complexes**

150 Composition and age

151 One of the 14 mounds we study here was drilled in 1988 by exploration borehole BY7-1 (Qin,
152 2000) (Figs. 2, 5a). The well shows that the mounded structure comprises mainly basalt and tuff,
153 interbedded with a thin limestone layer and a thin claystone layer (Qin, 2000; Zhao et al., 2016; Ma
154 et al., 2018) (Fig. 2). Based on its geometry and composition we therefore interpret the mounded
155 structure as a volcano. The volcano intersected by BY7-1 is $\sim 17.1 \pm 2.5$ Ma (Early Miocene) based
156 on K-Ar dating of a sample taken close to its top (Qin, 2000) (Fig. 2). Dead oil, i.e. residual oil
157 without volatile components, occurs within samples from the volcano, as well as within the
158 interbedded limestone (Fig. 2). Sub-volcanic strata are mainly composed of sandstone interbedded
159 with volcanic material (basalt and tuff) and claystone. The oldest volcanic material intersected by
160 BY7-1 yields a K-Ar date of 35.5 ± 2.78 Ma (Middle Eocene) (Qin, 2000) (Fig. 2). Strata above the
161 volcano comprise a ~ 260 m thick, Early Miocene sandstone package, which is overlain by Middle
162 Miocene (and younger) claystone interbedded with several thin layers of sandstone and siltstone
163 (Fig. 2). Well BY7-1 intersected free gas in the Early Miocene sandstone package and four younger,
164 thinner, sandstone and siltstone layers (Fig. 2).

165

166 Seismic expression

167 The tops of the volcanoes are characterized by undulating, positive, high-amplitude seismic
168 reflections (T5) (Fig. 4). Some volcanoes have relatively flat tops ($< 1^\circ$) whilst others are conical
169 (Fig. 4). Volcano bases are relatively flat (Figs. 4a-b, 4d) and are characterized by a continuous,
170 high-amplitude seismic event broadly conformable with underlying reflections (Fig. 4). Individual
171 volcanoes are circular or elliptical, with their long axis trending WNW ($\sim 301^\circ$) (Figs. 3, 5a-b).
172 Several volcanoes are connected to form linear complexes that trend WNW ($\sim 301^\circ$) (Figs. 3, 5a-b).

173 From their mapped external morphology, we calculate that volcano diameter and height ranges from
174 1–6 km and 50–590 m, respectively. Volcano flank dip ranges from $\sim 1^\circ$ to $\sim 14^\circ$, and is typically $>10^\circ$.
175 The volcanoes cover a total area of at least $\sim 245 \text{ km}^2$ and individually have a volume of at least
176 $\sim 62.5 \text{ km}^3$ (Fig. 5b).

177 The cores of individual volcanoes are usually characterized by chaotic seismic reflections, and
178 layered seismic reflections; the latter may downlap the basal surface (T5; Fig. 4).

179 The volcanoes are onlapped and draped by post-eruption sedimentary strata of the Early Miocene
180 Zhujiang Formation (Figs. 1b, 4). Strata directly overlying the volcanoes are typically folded and
181 faulting, with dome-shaped folds being $\sim 1\text{--}3 \text{ km}$ wide and having amplitudes of $\sim 350\text{--}1100 \text{ m}$ (Figs.
182 4a, 7). The dome-shaped folds have similar sizes with the underlying volcanoes (Fig. 7). In some
183 cases, seismic imaging is relatively poor directly above the volcanoes (including the dome-shaped
184 folds) due to velocity wipe-out zones that are associated with anomalously low seismic frequencies
185 (Figs. 4a, 7). The strata directly beneath the volcanoes are characterized by weak and chaotic seismic
186 reflections (Figs. 4a-b) that are typically cut by normal faults (Figs. 1c, 8).

187

188 **Seismic and geometrical characteristics of normal faults**

189 Normal faults are widely developed across the study area. We distinguish two fault populations
190 based on their distribution relative to the volcanoes: i.e. those largely restricted to sub-volcanic strata
191 and those largely restricted to supra-volcanic strata.

192

193 Sub-volcanic faults

194 Normal faults within sub-volcanic strata (i.e. below surface T5) typically strike WNW-ESE
195 ($300\pm 15^\circ$) (Figs. 7b, 8c-d, 5e, 9a), similar to the elongation trend of overlying volcanoes (Figs. 3,
196 5b, 9b-c). These faults are, on average, ~1.4 km long, but may reach lengths up to ~7.2 km (Figs.
197 9d, 9g). The faults are ~0.35–3.5 km tall (~85% are <1.1 km) and have throws of <160 m (Fig. 8c-
198 d). Some of the largest normal faults (i.e. >3.0 km tall) in the pre-volcanic strata terminate directly
199 beneath volcanoes (Figs. 7b, 8c-d), extending downwards into crystalline basement.

200 A few WNW-striking normal faults penetrate supra-volcanic strata shallower than T0 (~2.58 Ma),
201 crossing-cutting the level at which the volcanic complexes are developed (Fig. 4c). These faults
202 are >4.0 km tall (Fig. 4c), yet they are still relatively short in terms of their strike length (<6.1 km
203 long) (Figs. 9e-f). These tall faults usually offset volcanoes that are associated with growth strata
204 (i.e. volcano strata are thicker in the fault hangingwall than the footwall; Figs. 4c, 8a-b).

205

206 Supra-volcanic faults

207 Most supra-volcanic normal faults, especially those developed between T4 (16.5 Ma) and T1 (5.0
208 Ma), have limited vertical extents, ranging from ~0.3–2.0 km tall (Figs. 4a, 4c-d). Most (~68%)
209 faults are <1.2 km tall. Supra-volcanic faults are usually rather short (typically < 3.0 km) in terms
210 of their strike length (e.g. Fig. 9e and Fig. 9f), and the longest one reaches up to ~6.1 km long (Figs.
211 9e-f, h-i). The maximum displacement observed on the supra-volcano faults is ~90 m (Fig. 7).
212 However, in some cases fault displacement cannot be quantified, especially where faults are poorly
213 imaged below areas of free gas (see section below). The most important observations for the supra-
214 volcanic faults is that they best-developed and most closely spaced (~0.4-2.0 km) directly above the
215 volcanic complexes (Figs. 4, 5c-d), some terminating immediately above the underlying volcanoes

216 (Fig. 4a). The gross strike of these faults (WNW-ESE; $\sim 300 \pm 15^\circ$) (Figs. 9b-c) is similar to the trends
217 of the underlying volcanic complexes (Fig. 3).

218

219 **Seismic expression and geochemical characteristics of free gas**

220 Reflection anomalies characterized by anomalously low frequencies and negative polarity are
221 frequently observed in the seismic profiles (Fig. 4). These anomalies are always located directly
222 above the volcanoes (Figs. 6c-f), within the Middle Miocene and younger (i.e. supra-surface T5
223 strata; Figs. 4, 7). These anomalies occur as either isolated seismic features distributed along a
224 discrete stratigraphic level, or are vertically stacked across multiple stratigraphic levels (Figs. 4, 7).
225 Nearly all these seismic anomalies are related to the supra-volcanic faults (i.e. they are bound on
226 one side by these faults; Figs. 4, 5f, 6).

227 Based on their seismic characteristics (e.g. enhanced, low-frequency and negative-polarity
228 seismic reflections), we interpret these seismic anomalies as representing areas of free gas (e.g. Judd
229 & Hovland, 2007; Cartwright et al., 2007). Strata beneath areas of stacked free gas layers are
230 characterized by weak, low-frequency seismic reflections; this occurs due to absorption of the
231 seismic signal by gas-charged layers (Fig. 4). So-called velocity ‘push-downs’ are indicative of low-
232 acoustic velocities probably caused by free gas in the pore spaces (e.g. Judd & Hovland, 2007; Sun
233 et al., 2012) (Fig. 4c).

234 Within borehole BY7-1, free gas is mainly found in siltstone and sandstone layers (Fig. 2). These
235 gas-charged layers are usually characterized by anomalously low p-wave velocity (~ 0.3 - 0.8 km/s
236 lower than the velocities of surrounding strata; Fig. 2), consistent with seismic evidence (i.e. push-
237 downs) for slower velocities (Figs. 4a-c). Total gas is usually in excess of 30,000 ppm in gas-charged

238 layers, which is higher than in those strata lacking gas (i.e. <10,000 ppm). $\delta^{13}\text{C}$ values gradually
239 decrease upward from the top of the drilled volcano (-34‰ PDB) (Fig. 2). However, it is >-55‰
240 (PDB) even in the shallowest strata, indicating that the gas is mainly thermogenic (e.g. Tissot &
241 Welte, 1984; Zhu et al., 2009).

242

243 **Discussions**

244 **Interaction between volcano complexes and normal faults**

245 The volcano intersected by the borehole BY7-1 formed in response to at least three eruptive
246 episodes, separated by periods of deposition of limestone and claystone (Fig. 2). The occurrence of
247 shallow-water limestone (Qin, 1996) between the eruptive products, as well as the petrologic
248 characteristics of eruptive products (e.g. massive accumulation of volcanic-clastic deposits, glassy
249 and welded textures; Ma et al., 2018), suggests volcanism occurred in a shallow, fully submarine
250 setting (Zhao et al., 2016; Ma et al., 2018). Volcanism probably ceased around 17.5 Ma, given that
251 the related volcanoes are draped by surface T5 (~17.5 Ma; Fig. 4). This interpretation is supported
252 by the recovery of Early Miocene (17.1±2.5 Ma) igneous material from the crest of the volcano
253 (Qin, 2000) (Fig. 2). Igneous rocks dominating the cores of the volcanoes have lower primary
254 porosities and are thus less compactable than the surrounding clastic sediments (e.g. Chopra and
255 Marfurt, 2012). We therefore interpret that the dome-shaped folds directly overlying the volcanoes
256 formed due to differential compaction. Relatively slow and continuous growth of these folds is
257 supported by the observations that related growth strata progressively thin towards to the fold and
258 do not onlap a discrete surface (Figs. 4a, 7).

259 The faults located within sub-volcanic strata (i.e. below surface T5) correspond to those
260 documented by [Deng et al. \(2018\)](#) in the adjacent Baiyun Sag ([Fig. 1a](#)), implying many may have
261 been active before and during volcanism (i.e. during the Oligocene to Middle Miocene; ~32-16.5
262 Ma). The observation that volcanoes overlie faults, which occasionally terminate at volcano bases,
263 and are typically elongated parallel to fault-strike ([Figs. 3, 5a-b, 5d, 7, 9a](#)), suggest the faults may
264 have facilitated magma ascent. Such fault-controlled magma ascent is consistent with the spatial
265 and genetically relationships between volcanoes and faults in active and ancient sedimentary basins
266 (e.g. [Gaffney et al., 2007](#); [Mazzarini, 2007](#); [Magee et al., 2013b, 2016](#); [Isola et al., 2014](#); [Weinstein
267 et al., 2017](#)), and in numerical models (e.g. [Le Corvec et al., 2013](#); [Maccaferri et al., 2014](#)). Volcano
268 growth by fault-controlled magma ascent is further supported by the across-fault thickening of
269 volcanic strata; this indicates faulting and extrusion were synchronous (red dashed ellipses in [Figs.
270 8a-b](#)). We highlight that sub-vertical dykes, not hosted by faults, may have also fed the volcanoes.
271 Dykes commonly intrude the crust during the continent rifting (e.g. [Kendall et al., 2005](#); [Maccaferri
272 et al., 2014](#)), but such structures are not typically imaged in seismic reflection data because their
273 (sub-) vertical attitude does not reflect acoustic energy back to the surface (e.g. [Phillips et al., 2017](#)).
274 Furthermore, even if present, dykes would likely be located in the very poorly imaged zone directly
275 beneath the volcanoes, compromising their imaging and recognition ([Figs. 4a-b, 7](#)).

276 Supra-volcanic faults developed between surfaces T4 (16.5 Ma) and T1 (5.0 Ma), which bound
277 Middle-Late Miocene strata, are younger than the early Middle Miocene (~>17.5 Ma) volcanoes.
278 Some faults offsetting T0 (~2.58 Ma) indicate that they were also active in the Quaternary ([Fig. 4](#)).
279 Because the supra-volcanic faults are: (i) clustered above the volcanoes ([Figs. 4, 5b-d](#)); (ii) terminate
280 down-dip at the tops of volcanoes (e.g. [Fig. 4a](#)); and (iii) have similar strikes (~WNW) to the

281 volcano long-axes (Figs. 5b-d, 9b-c), we suggest the volcanoes influenced their distribution and
282 formation. We also note that dense zones of supra-volcano faults occur within and offset folded
283 strata directly above the volcanoes. We consider two potential mechanisms that may have driven
284 supra-volcanic faulting. First, volcanoes and their underlying intrusions can locally perturb a
285 regional stress field associated with stretching of the crust. These perturbations influence the style
286 and patterns of strain (e.g. Maccaferri et al., 2014; Magee et al., 2014; Lee et al., 2016; Weinstein et
287 al., 2017). It is plausible the WNW-trending supra-volcanic faults formed to accommodate westward
288 movement of the Philippine Plate, which commenced in the Middle Miocene (surface T3; ~13.8 Ma)
289 (Lüdmann & Wong, 1999; Sun et al., 2014a), with strain being localized above the rigid volcanoes.
290 An alternative interpretation is that the faults formed to accommodate stratal (outer-arc extension)
291 bending associated with differential compaction above the volcanoes. These two models for fault
292 generation are not mutually exclusive.

293

294 **Focused fluid flow promoted by buried volcanoes and neotectonics**

295 Our observations from seismic reflection data (Figs. 4, 5f, 6), combined with borehole and
296 geochemical data (Fig. 2), show that free gas is locally preserved in clastic layers located directly
297 above the volcanoes (Fig. 10). Areas of free gas are delineated by (Figs. 4, 5f, 6-7) or occur
298 immediately above the tips of normal faults (Figs. 4c-d). These observations suggest the free gas
299 likely migrated upward along these faults and charged the more porous sandstone and siltstone
300 layers (Figs. 2, 10d). Whilst deep-seated faults could have provide long-lived pathways for fluid
301 and gas (e.g. CO₂) ascent from mantle to the shallow free gas accumulations (e.g. Lee et al., 2016),
302 chemical data show the free gas has a thermogenic origin (Fig. 2). This indicates the gas was sourced

303 from thermally activated decomposition of relatively deeply buried (>900 m) organic material (e.g.
304 remains of plant and animals). The thin, coarse-grained sediments (Eocene – Early Miocene) that
305 directly underlie the volcanoes (Fig. 2) mean that the source rocks are lack and the thermogenic free
306 gas cannot be generated in the study area (Yunkai Low Massif, Fig. 1a). Considering that the Baiyun
307 Sag, which is located close to the study area (Fig. 1), is a hydrocarbon-rich ‘kitchen’ area with a
308 sedimentary thickness of >10 km (e.g. Pang et al., 2008), it is likely that thermogenic hydrocarbons
309 were sourced from there (Fig. 10d). Hydrocarbons may have migrated from the deep-seated source
310 rock in the Baiyun Sag to structural highs in the Yunkai Low Massif (study area) through permeable
311 strata and/or unconformities located along the western flank of the Baiyun Sag (Figs. 1a, 10d).
312 Because they are mounded and represent natural four-way dip-closures, volcanoes in the Yunkai
313 Low Massif may have temporarily housed gas. This interpretation is supported by the presence of
314 dead oil within at least one of the volcanoes (Fig. 2). Gas may have also accumulated within the
315 porous, folded layers/structural traps above the volcanoes (Fig. 2). The latter interpretation is
316 confirmed by the presence of residual gas in supra-volcanic layers, with this gas expressed by
317 relatively low p-wave velocities (~0.3-0.8 km/s lower than the velocities of surrounding strata) and
318 high total gas readings (>30,000 ppm) (Fig. 2). The widespread, thick, very fine-grained sediments
319 overlying the volcanoes likely serve as regional seals across the northern SCS (e.g. Zhao et al.,
320 2009). Post-eruption faulting reduced the bulk permeability of the seal, permitting hydrocarbon
321 migration along faults to shallower structural levels (Fig. 4). It is, however, difficult to precisely
322 constrain when hydrocarbon leakage from the volcanoes occurred. Considering the Dongsha Event
323 started at around ~10.5 Ma (peaking at ~5.3 Ma; Lüdmann & Wong, 1999; Zhao et al., 2012), and
324 that this event triggered the hydrocarbon migration in the neighboring Baiyun Sag (e.g. Zhu et al.,

325 2009, 2012), gas leakage in this study was also likely punctuated. The latest period of gas migration
326 along the faults probably occurred in the Quaternary, based on the observations that the shallowest
327 free gas occurs within uppermost Pliocene strata (Fig. 4b) and that many faults penetrate upward
328 into Quaternary strata (Fig. 4).

329

330 **Model for volcano-tectono interactions and related fluid flow**

331 Here we propose a four-stage model to account for the link between magmatism, faulting and
332 fluid flow in the northern SCS. In the first stage, crystalline basement of Yunkai Low Massif, which
333 lay west of the Baiyun Sag, was deformed by deep-seated faulting (Fig. 10a). Magma was extruded
334 onto the paleo-seabed in relatively shallow water (Qin, 1996; Yan et al., 2006). Magma likely
335 ascended along the deep-seated faults (Figs. 8c-d, 10a). Though one sample from the erupted
336 materials was dated to 35.5 ± 2.78 Ma (Paleocene; Qin, 2000), how long magmatism lasted cannot
337 be determined in this stage, because the base of the volcanic pile is not penetrated or dated.

338 During the second stage, coarse-grained clastic material was deposited, with intermittent periods
339 of relatively weak volcanism; we infer punctuated volcanism based on the interbedding of sandstone
340 and thin layers of volcanic eruptive material such as basalt and tuff (Figs. 2, 10b). Normal faulting,
341 which occurred prior to the main Miocene eruptive phase, offset the clastic strata (Deng et al., 2018).
342 Some of these faults linked with deep-seated, basement-involved faults (Figs. 7, 10b). After this
343 relatively quiescent second stage, a second main period of intense volcanic activity, which was
344 focused in this study, occurred. Several volcanic complexes were emplaced on the shallow paleo-
345 seabed (Fig. 10c); volcanoes emplaced in this third stage were probably also fed by magma
346 ascending along the deep-seated faults (Fig. 7). Volcanism ceased in the study area before ~ 17.5 Ma.

347 During the fourth and final stage (~17.5 Ma onwards), thick sequences of predominantly very
348 fine-grained clastic material were deposited above the volcanoes (Fig. 10d). Another important
349 period of normal faulting occurred during this stage, forming the supra-volcanic normal faults (Fig.
350 10d). Hydrocarbons sourced from the Baiyun Sag were transported along the flanks of Baiyun Sag
351 through porous layers or along unconformities (Fig. 10d) (e.g. Pang et al., 2008; Zhu et al., 2009).
352 These hydrocarbons probably temporarily accumulated within the topographic highs defined by the
353 volcanoes, before migrating further upwards via the supra-volcanic normal faults (Figs. 4, 7-8, 10d).

354

355 **Implication for hydrocarbon exploration and production**

356 Drilling data indicates the volcanoes studied here lack live oil (Fig. 2). However, the presence of
357 dead oil and minor staining suggests hydrocarbons migrated into and through the volcanoes.
358 Regardless of whether the volcanoes served as reservoirs or simply as pathways for hydrocarbons,
359 they clearly focused post-eruption fluid and gas flow (Fig. 4). Dome-shaped differential compaction
360 folds above the volcanoes may have acted as structural traps for fluids and gases migrating upwards
361 from the volcanoes or from the porous sediments lining unconformities developed on their flanks
362 (Fig. 10d). However, faults within the folded strata allowed gas to leak upwards to shallower levels
363 (Figs. 4, 10d). Our results suggest buried volcano-related, focused fluid and gas flow conduits could
364 be a common occurrence in volcanogenic basins, particularly since differential compaction-related
365 domes and related structures (e.g. normal faults) are often observed above many ancient, seismically
366 imaged volcanoes (e.g. Li et al., 2015; Yang et al., 2016; Schofield et al., 2017). The presence,
367 evolution and importance of these coupled systems will likely become clearer as more 2D and 3D
368 seismic reflection data are available within volcanically influenced basins. The risk of seal

369 degradation, and secondary migration and accumulation of hydrocarbons related to buried
370 volcanoes should be taken into consideration during hydrocarbon exploration in such basins.

371 The accumulation of gas in shallowly buried and thus weakly lithified strata may have caused an
372 increase pore pressure within those units. Overpressure of the gas-charged strata could represent a
373 drilling hazard, with higher-than-expected pore pressures being encountered during drilling. Failure
374 to accurately prognose such high pore pressures in such strata could lead to collapse of the wellbore
375 and may even trigger a blow-out (e.g. [Eruteya et al., 2015](#)). Overpressure could also cause decrease
376 the shear strength of particular units or interfaces, priming them (and the overlying material) to
377 catastrophically fail and generate a submarine landslide in response to an appropriate trigger (e.g.
378 seismicity, gas hydrate dissociation; e.g. [Kvalstad et al., 2005](#)). Such a scenario is envisaged in the
379 nearby Baiyun Sag (Baiyun Slide; [Sun et al., 2018](#)). Because landslides can trigger tsunamis and may
380 damage seabed infrastructure, attention should be paid to the way in which deeply buried, non-
381 inactive volcanoes influence subsurface flow of fluids and gases.

382

383 **Conclusions**

384 We used high-resolution 3D seismic data and borehole data from the northern South China Sea
385 to document the impact of faults on magma ascent and the spatial location of volcanic centers, and
386 the role the latter has on fluid flow. Volcanism was multi-staged, ceasing before ~17.5 Ma (T5),
387 with migration of hydrocarbons lasting until the Early Pleistocene (~2.58 Ma). Hydrocarbons
388 migrated upwards along post-eruption faults, which are related to regional stress and the bending of
389 strata caused by differential compaction. The transported hydrocarbon (mainly methane) finally
390 charged porous layers (sandstone and siltstone) offset by the post-eruption faults. This study shows

391 that the volcano-related deformations can influence the surrounding, regional stress fields and
392 subsurface fluid flow. These processes likely increase the bulk permeability of otherwise sealing
393 sequences, facilitating the cross-stratal migration of hydrocarbons from deep sources to shallower
394 reservoirs. This study highlights the underappreciated role buried volcanoes may have on focused,
395 subsurface fluid flow. Shallow fluid and gas can drive the development of overpressure; not only
396 this can cause problems when drilling wellbores, but it can prime material to catastrophically fail,
397 which itself can drive the generation of tsunamis and damage costly seabed infrastructure.
398 Considering that buried volcanoes are widespread in both the passive and active continental margin
399 basins, more attention should be paid to their role in controlling subsurface fluid flow.

400

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409

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- 619

620 **Figure Captions**

621

622 Figure 1: (a) Geological setting and subdivision of the Pearl River Mouth Basin (enlargement of
623 pink square in the top left corner). The study area (blue square: 3D seismic survey) is located in the
624 Yunkai Low Massif between the Kaiping Sag and the Baiyun Sag. Well location (BY7-1) is marked
625 with green star. The boundary faults are modified from [Pang et al. \(2007\)](#) and [Sun et al. \(2014a\)](#).
626 Top left: Geological background of the South China Sea; (b) Schematic stratigraphic column of the
627 Pear River Mouth Basin (modified from [Pang et al. \(2008\)](#) and [Sun et al. \(2014b\)](#)). SR = seismic
628 reflectors, TE= tectonic evolution, BE = basin evolution, DE= sedimentary environment; (c)
629 Geoseismic interpretation of the study area; see (a) for location.

630

631 Figure 2: Correlation of seismic profile and borehole (BY7-1). Five layers of free gases (mainly
632 shown as enhanced negative seismic anomalies or blanking reflection with low frequency) are
633 drilled by BY7-1, which can also be identified in the well loggings and geochemical analysis. The
634 items marked with ® and © (Lithology, K-Ar dating, Ages and depositional environments (DEs),
635 $\delta^{13}\text{C}$ (planktonic foraminifera) and $\delta^{18}\text{O}$ (planktonic foraminifera)) are modified from [Qin. \(1996\)](#)
636 and [Qin. \(2000\)](#). Parts of the well loggings are also used in [Qin. \(1996\)](#), [Qin. \(2000\)](#) and [Zhao et al.](#)
637 [\(2016\)](#). The item ($\delta^{13}\text{C}$) marked with§ is from the analysis of headspace gas.

638

639 Figure 3: Three-dimensional visualization of the top of volcano complexes (Surface T5). The
640 volcano complexes show as positive reliefs. Normal faults which present as linear structures with
641 sharp boundaries are also observed.

642

643 Figure 4: (a)-(d): Seismic characteristics of free gas, normal faults and volcano complexes. See
644 locations of (a)-(c) in Fig. 6c and location of (d) in Fig. 5a. Free gas shows as stacked or isolated
645 enhanced seismic anomalies with low frequencies. It distributes in several layers and its extent is
646 outlined by normal faults. Sometimes, wipe-out zone (blanking seismic reflections) and pull-down
647 seismic reflections are observed underneath the enhanced seismic anomalies. Faults are denser
648 within the strata above volcano complexes (light green polygon). Some large normal faults can
649 penetrate into the basement and they extend upward to surface T0. The semi-transparent green and
650 blue squares are the windows of RMS amplitudes of Fig. 6a and Fig. 6b, respectively. Variance slice
651 locations of Fig. 5c (straight dashed blue line) and Fig. 5d (straight dashed red line) are also labeled.
652 TV = Top of volcano; BV = Base of volcano; PDs = Pull-down seismic reflections.

653

654 Figure 5: The configurations of volcano complexes, free gas and normal faults. (a) Top of volcano
655 complexes (Surface T5). The volcano complexes show as positive reliefs; (b) Thickness of the
656 volcano complexes, which shows that the volcano complexes linearly trend NW-SE; (c) and (d)
657 variance slices of 1150 ms and 1800 ms (in the post-eruption strata). Faults can be clearly observed;
658 (e) variance slice of 30 ms below the base of volcano complexes (in the pre-eruption strata) and
659 faults are also clearly identified; (f) RMS amplitude (1150 ms with windows of ± 25 ms) of the entire
660 3D survey. The free gas has very high RMS amplitude and it only distributes in the southeastern
661 part of the 3D seismic survey.

662

663 Figure 6: Enlargements showing the relationships of volcano complexes, free gas and normal faults.

664 (a) and (b): RMS amplitude of 1150 ms with windows of ± 50 ms and 1800 ms with windows of
665 ± 100 ms. Free gas shows as high values of RMS amplitude (warm colors). See locations in Fig. 5;
666 (c) and (d): outlines of volcano complexes and interpreted faults are superimposed on the RMS
667 amplitude maps. Free gas is usually limited by faults and locates within the extents of volcano
668 complexes; (e) and (f): line drawings of (c) and (d). The superimposed relationships of volcano
669 complexes, normal faults and free gas are clearly shown.

670

671 Figure 7: (a) and (b) uninterpreted and interpreted profiles show seismic characteristics of the strata
672 above the volcano complex. See location in Fig. 5a. These strata are bended and normal faults
673 densely occurred within these strata. Free gas is closely linked to the normal faults and the seismic
674 reflections below free gas are blanking or wipe-out. The semi-transparent green and blue squares
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677

678 Figure 8: (a) Normal faults crosscut the volcano complex and (b) its line drawing. The eruptive
679 materials in the hanging wall are thicker than its footwall counterpart. See location in Fig. 6c; (c)
680 Normal faults immediately terminated at the base of volcano complexes and (d) its line drawing.
681 See location in Fig. 5a.

682

683 Figure 9: (a)-(c): Fault strikes of Figure 5e ($n = 202$), 5c ($n = 90$) and 5d ($n = 196$). Both the faults
684 within the pre-eruption and post-eruption strata have similar strikes (NWW-SEE); (d)-(f): Fault
685 lengths of Figure 5e, 5c and 5d. The faults have small scales and usually below 3 km long; (h)-(j):

686 Fault strike vs fault length of Figure 5e, 5c and 5d.

687

688 Figure 10: Model for the magmation, faulting and focused fluid flow in the study area. (a) Fault fed
689 pioneer magma extruded in the shallow water at a very early stage; (b) In the quiescent stage, detrital
690 sediments deposited on the pioneer eruptive materials; (c) Large-scale magma extruded onto the
691 paleo-seabed and formed the mounded volcano complexes; (d) Thermogenic hydrocarbon
692 accumulated to the volcano complexes or the traps above it. Faulting directly occurred within the
693 strata above volcano complex and hydrocarbon leakage through these faults.

Figure 1

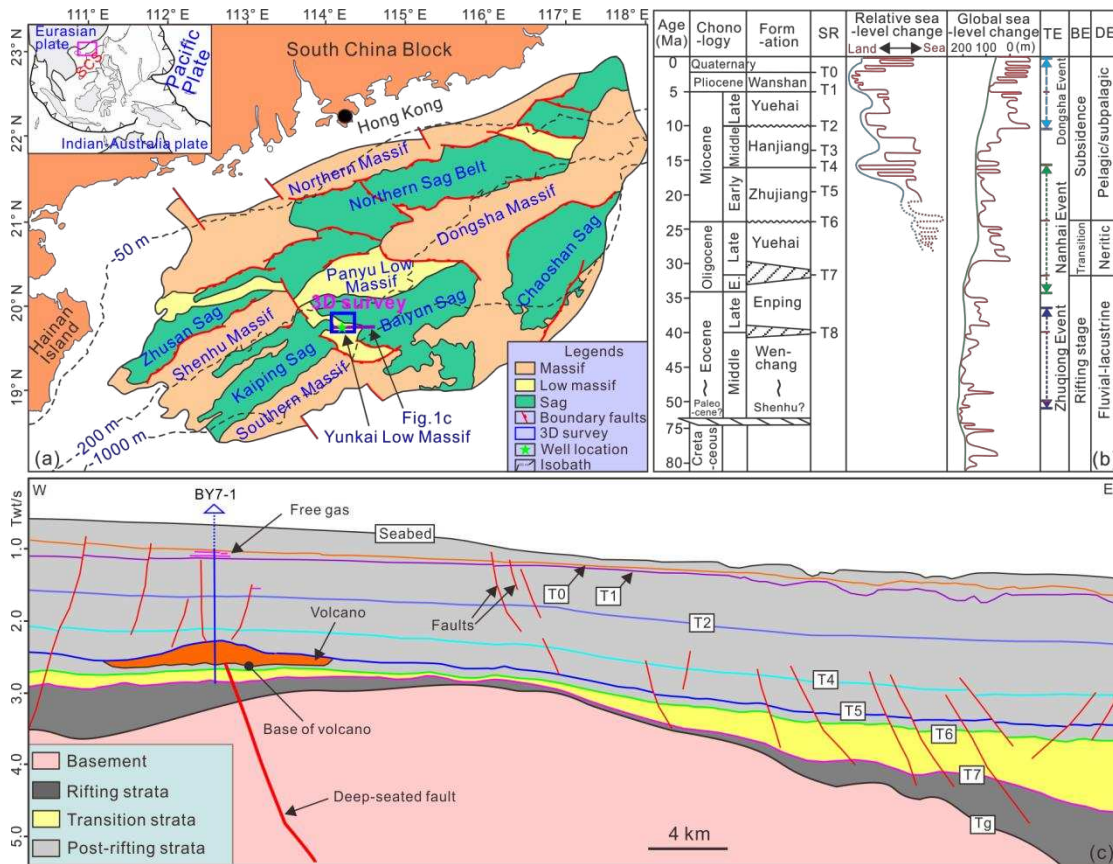


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Figure 2

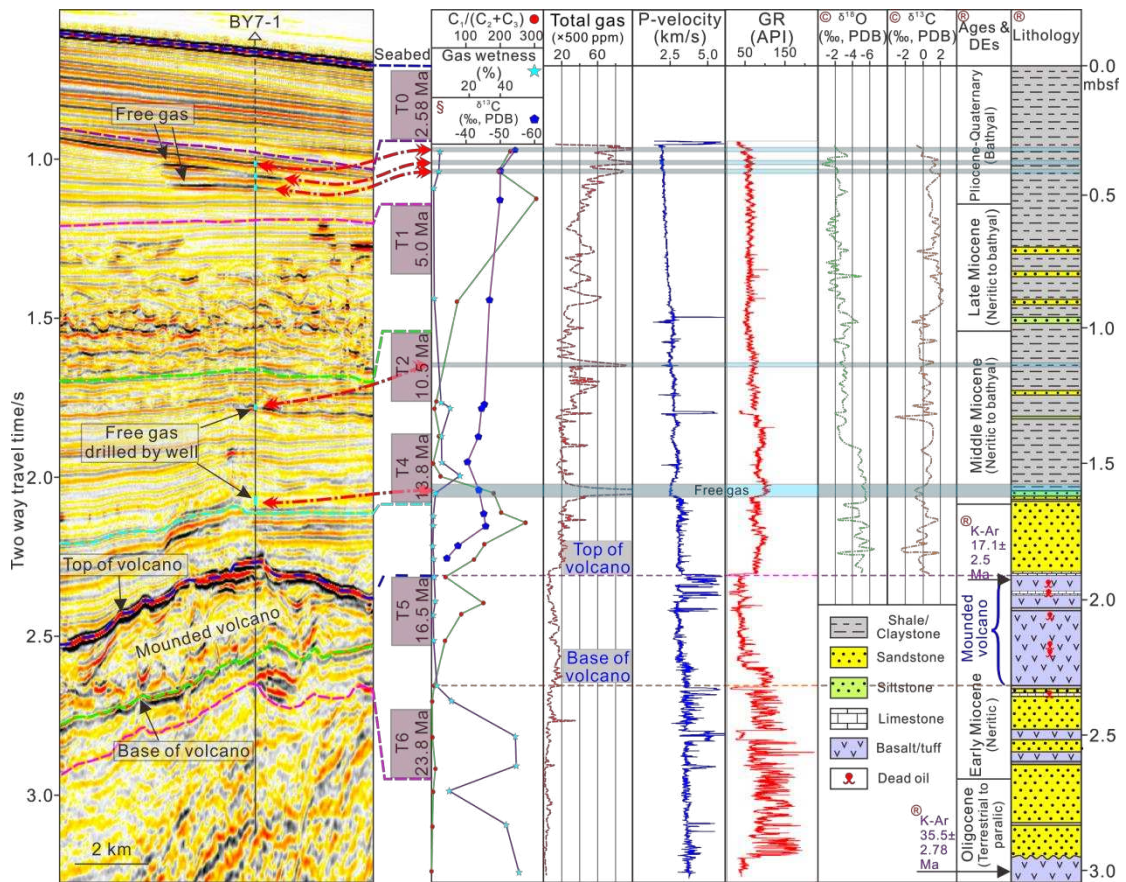


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Figure 3

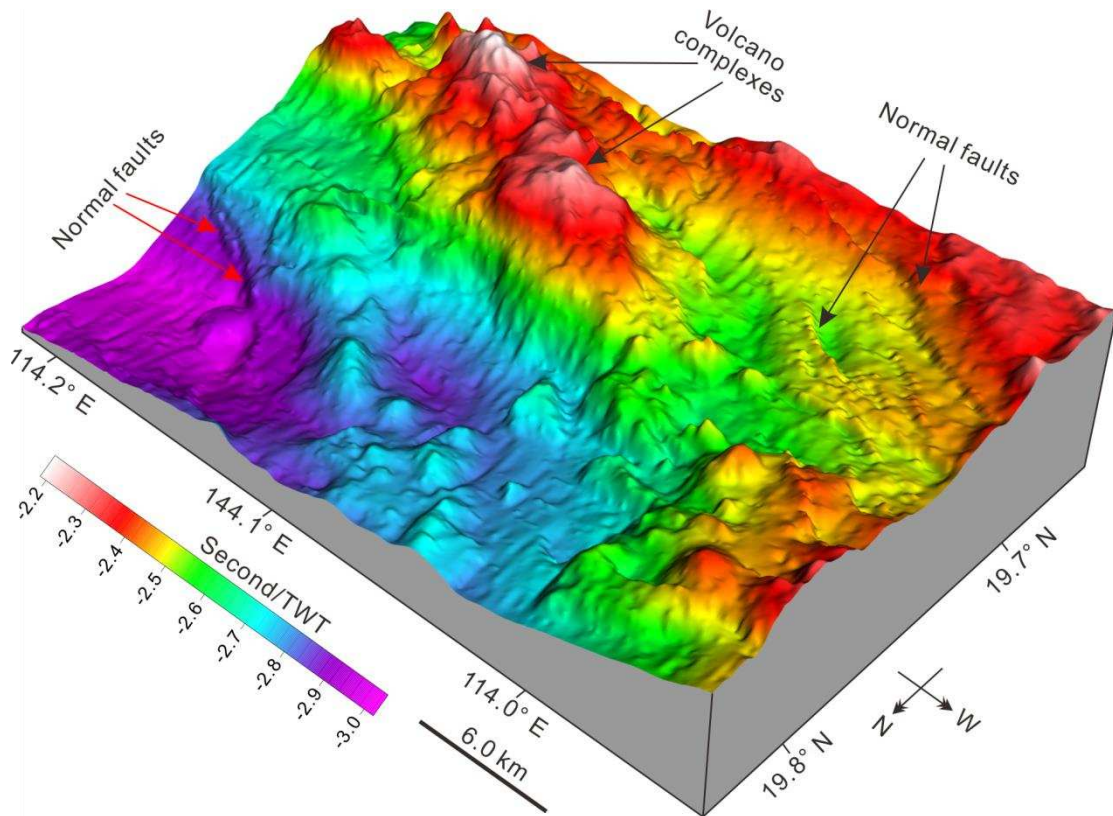


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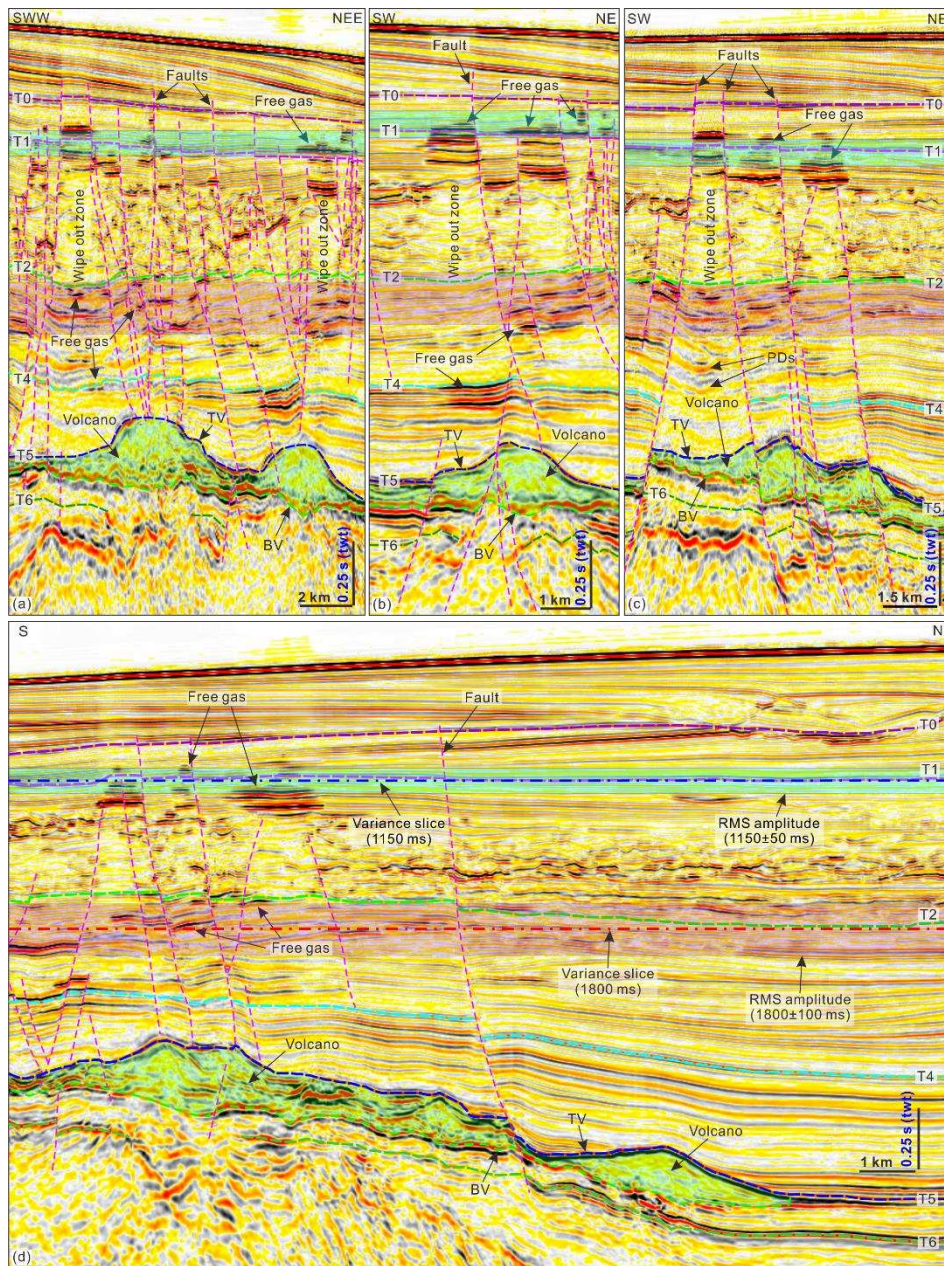


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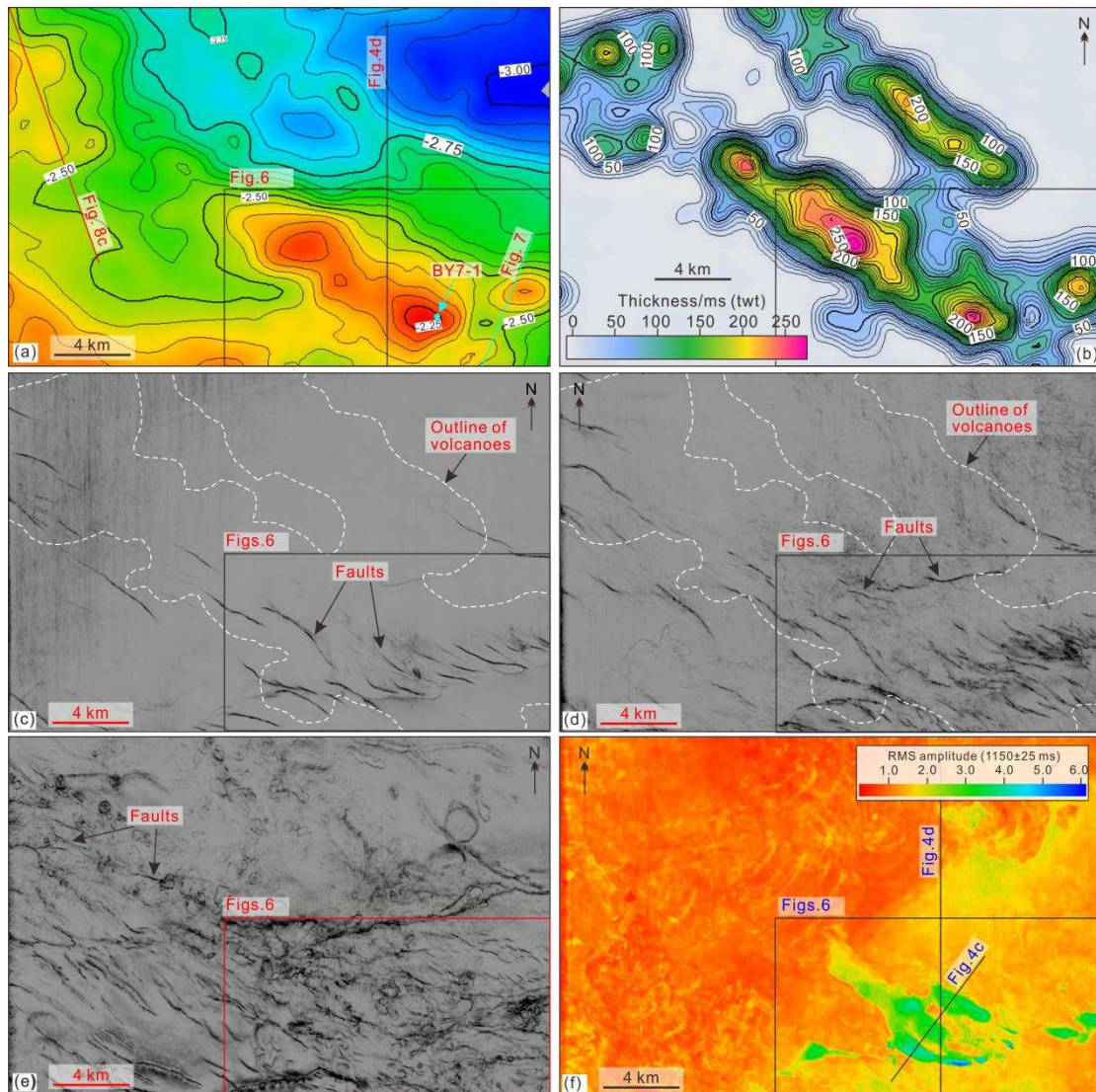


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Figure 6

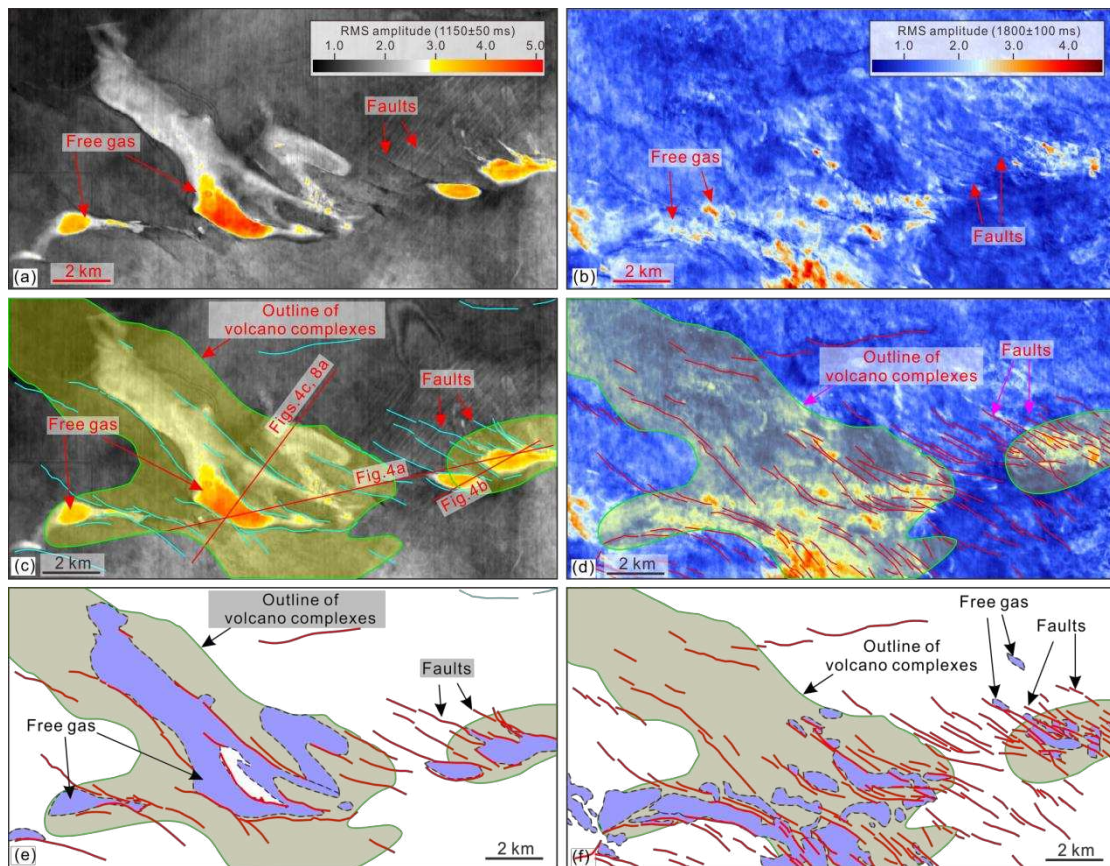


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Figure 7

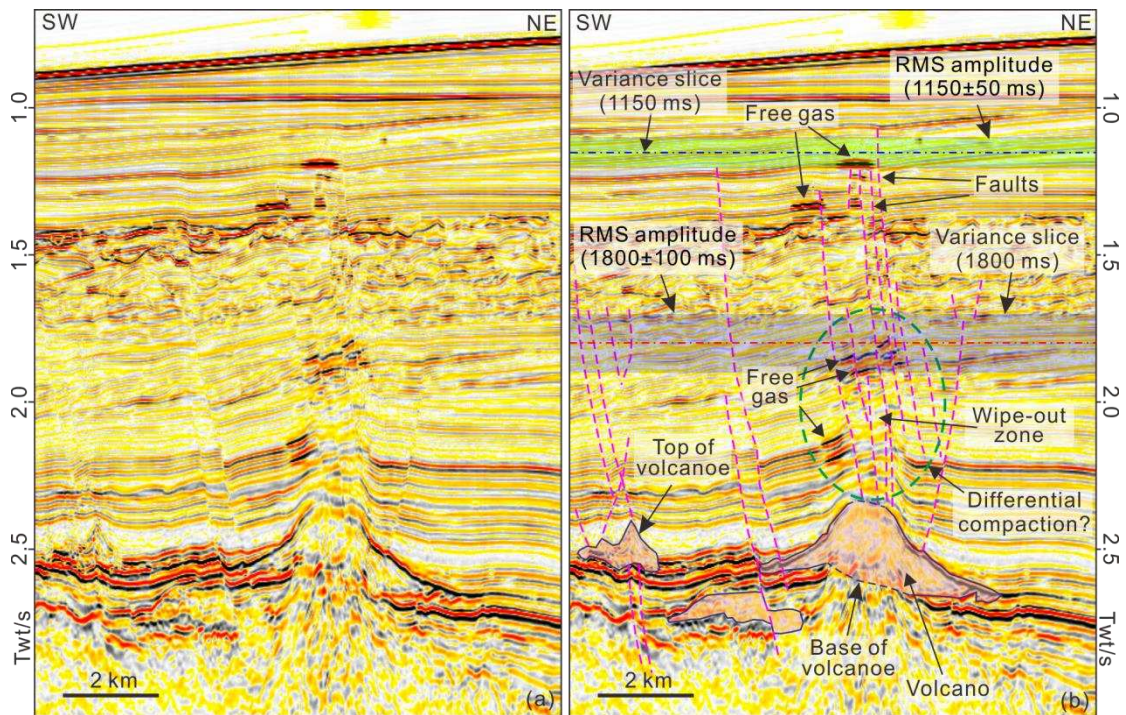


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Figure 8

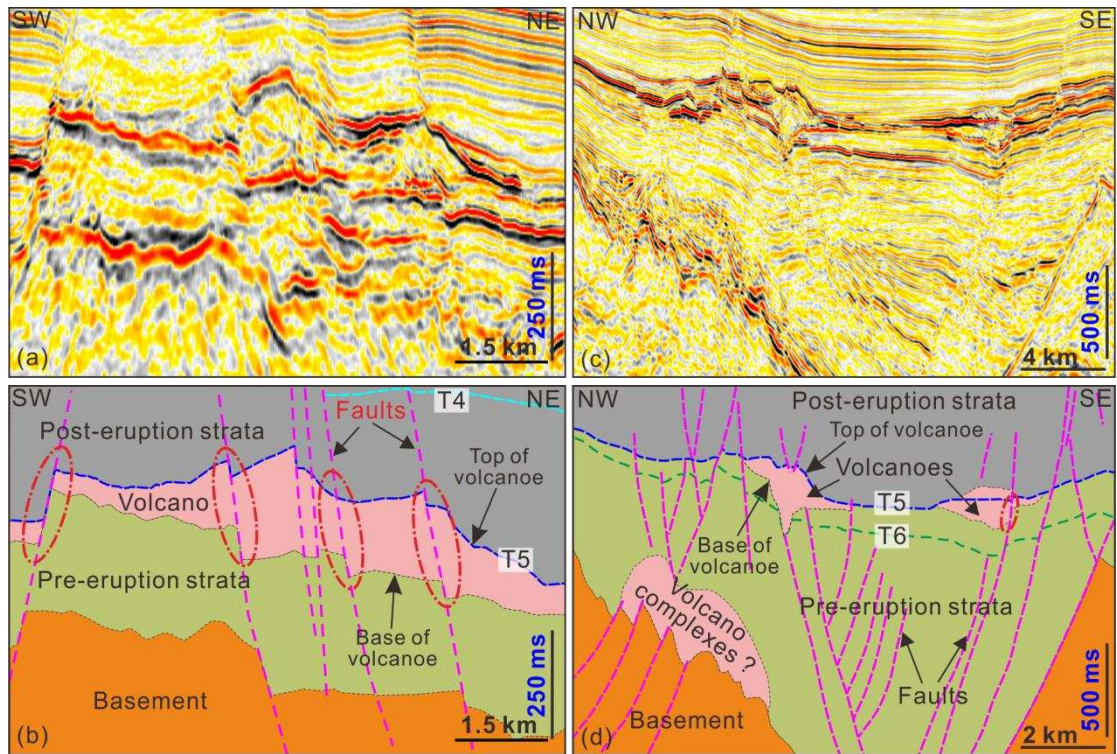


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Figure 9

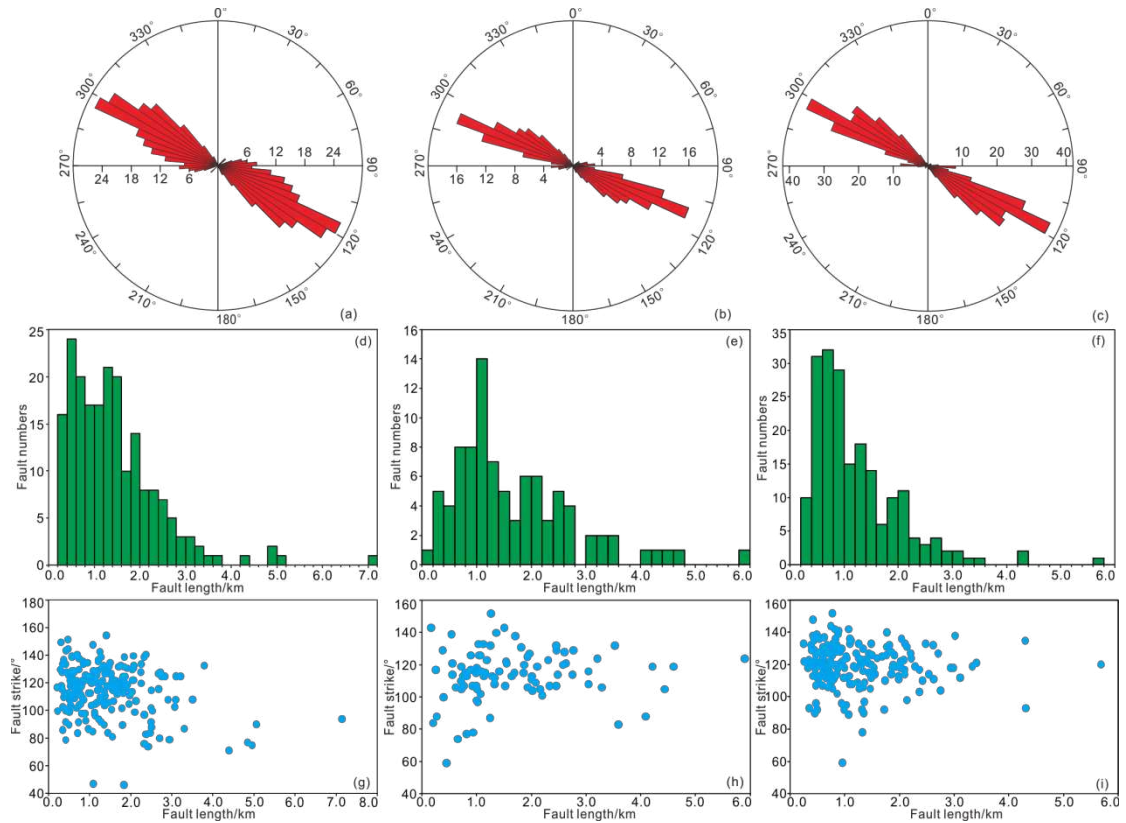


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Figure 10

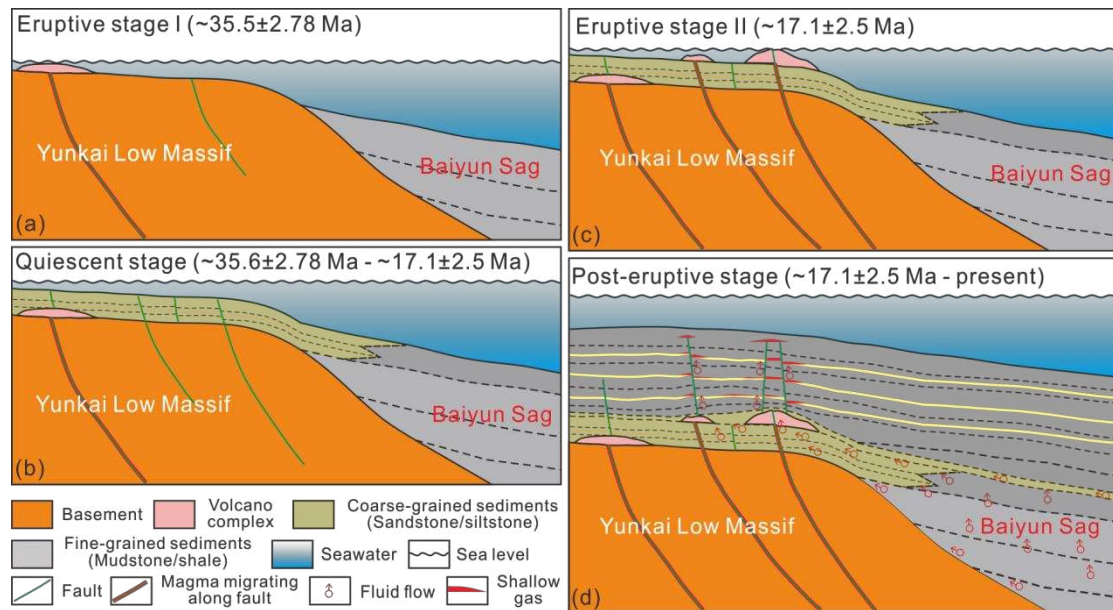


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