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1 **Effect of tectonic inversion on supra-salt fault geometry and reactivation**
2 **histories in the Southern North Sea**

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10 **Abstract**

11 High-resolution 3D seismic and borehole data in the Broad Fourteens Basin, Southern North
12 Sea, are used to investigate the relationship between lithology and fault throw distribution, as
13 well as to understand the reactivation and growth histories of faults developed due to tectonic
14 inversion. Two (2) distinct tiers of faults are identified, and their geometry analysed in detail.
15 Tier 1 faults comprise closely spaced sets of normal faults that resulted from the progressive
16 buckling and stretching of Upper Mesozoic strata during Late Cretaceous to Paleogene tectonic
17 inversion. They have been reactivated but still show net normal throw separations, even though
18 they were formed during a period of regional compression. Tier 2 faults comprise densely
19 spaced sets of normal faults in Paleogene strata with a broad range of strikes, forming a
20 polygonal pattern. These faults relate to early diagenesis but still record the effect of the
21 Paleogene inversion episode. An important characteristic is that Tier 1 faults are highly
22 segmented and show differences in throw distribution between shale-rich and sandy intervals.
23 The faults are more segmented, with relatively small throw maxima of 14 ms (17.7 m) in shale-

24 rich intervals, while sandy intervals are less segmented with larger throw maxima of 32 ms
25 (40.3 m). Discrepancies in fault throw distribution and segmentation increase the chances of
26 compartmentalisation or localised fluid flow through fault linkages, presenting at the same time
27 significant risks when injecting CO₂ in subsurface traps. Recognising the effect of tectonic
28 inversion on supra-salt fault geometry, and reactivation histories, can be crucial to the
29 characterisation of faulted hydrocarbon and carbon capture and storage (CCS) reservoirs in
30 tectonically inverted basins such as the Southern North Sea.

31

32 **Keywords:** Southern North Sea; Tectonic shortening; Mechanical stratigraphy; Lithology;
33 Fault throw; Fault reactivation; Fault linkage.

34

35 **1. Introduction**

36 In layered successions, the mechanical stratigraphy of the host rock affects the nucleation,
37 segmentation, geometry, and displacement distribution of tectonic faults (Peacock and
38 Sanderson, 1991; Mansfield and Cartwright, 1996; Gross et al. 1997; Childs et al. 2009;
39 Gabrielsen et al., 2016; Ferrill et al. 2017). This means that faults tend to localise (and be less
40 segmented) in harder lithologies such as limestone and sandstone, while becoming more widely
41 distributed (and segmented) in weaker lithologies such as claystone and shale (Schöpfer et al.,
42 2006; Libak et al., 2019). In parallel, analogue deformation experiments show that weak
43 intervals can act as detachments that cause stress decoupling at a local scale, preventing the
44 propagation of faults across specific intervals. This results in a preferable horizontal
45 propagation of faults to the detriment of their vertical growth (Bahroudi et al., 2003; Withjack
46 and Callaway 2000; Richardson et al., 2005; Gabrielsen et al., 2016). Such a horizontal shift in
47 fault geometry across an incompetent layer can result in vertical fault segmentation whereby

48 fault segments are hard- or soft-linked (Bahroudi et al. 2003; Mansfield and Cartwright, 1996;
49 Maunde et al., 2021).

50 Late Cretaceous to Paleogene tectonic inversion in the Broad Fourteens Basin, Southern North
51 Sea, contributed to the generation, and subsequent reactivation, of normal faults in supra-salt
52 overburden rocks (Oudmayer and De Jager, 1993; Nalpas et al., 1995; Gerling et al., 1999;
53 Wong et al., 2001; van Verweij and Simmelink, 2002; De Lugt et al., 2003; 2002; Duin et al.,
54 2006). Broad anticlines with outer-arc normal faults were formed in response to the Alpine
55 inversion episodes affecting this part of NW Europe: the Sub-Hercynian, Laramide, Pyrenean
56 and Savian tectonic episodes. This had mostly a positive economic impact, as tectonic
57 movements reactivated older faults and allowed the secondary migration of hydrocarbons into
58 shallower reservoir units (Van Balen et al., 2000; Isaksen, 2004). Nevertheless, to understand
59 the effect of tectonic inversion on the geometry and reactivation histories of faults in the
60 Southern North Sea is key, as these structures add structural complexity to supra-salt reservoir
61 units. Active fracturing provides a pathway for fluids where distinct fault segments interact,
62 with the loci of fault segment linkage across seal units increasing the permeability of host rocks,
63 thus allowing the migration of fluid out of underlying reservoirs (Curewitz and Karson, 1997;
64 Knai and Knipe 1998). Conversely, faults can compartmentalise reservoir units where they
65 form barriers to fluid flow, a character resulting in increasing exploration costs as more wells
66 are needed to retrieve hydrocarbons, or store CO₂ and other gases (Hardman and Booth, 1991;
67 Caine et al. 1996; Cartwright et al., 2007; Bentham et al., 2013).

68 Using 3D seismic and well data, this paper explores the relationship amongst lithology,
69 displacement distribution and the reactivation histories of Upper Mesozoic supra-salt faults in
70 the Broad Fourteens Basin, Southern North Sea (Fig. 1a). The aims of this paper relate to the
71 fact that hydrocarbon traps are much more likely to leak during periods of fault reactivation
72 than when the faults are inactive, all other parameters of seal integrity being the same (Caine

73 et al. 1996; Hooper, 1991; Gartrell et al., 2002; Wiprut and Zoback, 2000, 2002; Cartwright et
74 al., 2007; Bentham et al., 2013; Ward et al., 2016). Hence, this work aims to address the
75 following questions:

- 76 a) What are the geometry and reactivation styles of faults developing during tectonic
77 shortening?
- 78 b) What mode(s) of fault propagation and growth are observed in successions presenting
79 differing lithologies?
- 80 c) What is the effect on reservoirs and seal intervals of faults reactivating during tectonic
81 shortening?

82

83 **2. Data and methods**

84 *2.1. Data*

85 Three-dimensional (3D) seismic and borehole data from the Broad Fourteens Basin, Southern
86 North Sea, are used in this work. The data were acquired in the northern end of the Broad
87 Fourteens Basin, offshore The Netherlands, between 53.1° - 53.3°N and 3.8° - 4.2°E. The
88 interpreted seismic volume covers an area of about 845 km² at a shallow water depth of 37.7
89 m (Fig. 1a).

90 The seismic data are stacked with a 2 ms vertical sampling interval, and a 25 x 25 m bin size,
91 providing a maximum horizontal resolution of 25 m. The resulting seismic volume is zero-
92 phase time migrated and displayed with a normal positive polarity so that an increase in
93 acoustic impedance is represented by a peak (red seismic reflection). A decrease in acoustic
94 impedance is represented by a trough, i.e. a black seismic reflection (SEG European
95 Convention; Brown, 2003). The vertical scale of the seismic data is in two-way travel time
96 (TWTT), up to a recording length of about 4.0 seconds.

97 2.2. *Methods*

98 Seismic horizons and faults were mapped using Schlumberger's Petrel[®]. First, we mapped
99 seven seismic units (Units S1 to S7) bounded by Upper Carboniferous to Miocene
100 unconformities, and tied them to well stratigraphic information published in Penge et al. (1999)
101 and van Verweij and Simmelink (2002) (Fig. 3). We then imaged and interpreted listric faults,
102 and two distinct tiers of normal faults, in Upper Mesozoic to Paleogene strata. Throw data (T)
103 for the interpreted faults were acquired by measuring differences between footwall and
104 hanging-wall horizon cut-offs (Fig. 2a). These measurements were taken along the fault planes
105 on seismic profiles perpendicular, and also oblique, to local fault strike, bearing in mind local
106 changes in fault geometry and strike.

107 Two-dimensional (2D) contour maps and throw-depth (T-Z) profiles were produced to assess
108 the reactivation and vertical growth styles of faults. From the 2D contour maps, throw-distance
109 (T-X) profiles were produced to assess fault growth histories and the role of lithology on fault
110 throw distribution. The measured fault throw values were depth converted from seconds to
111 meters using Equation (1) below.

$$112 \quad V = \frac{2Z}{T} \quad (1)$$

113 where (V) is the interval or average velocity in m/s, (Z) is the depth in meters, and (T) is the
114 two-way travel time in seconds, gathered from borehole data.

115 The vertical seismic resolution for the target intervals in Upper Mesozoic strata is 15.8 m based
116 on a dominant frequency of 40 Hz and an average velocity of 2521.3 m/s. As fault-throw
117 measurements depend on the vertical sampling interval, rather than the vertical seismic
118 resolution (Tao and Alves, 2019), the minimum fault offset resolved on-screen during fault
119 throw analysis varies from 2 ms (1.9 m) to 3 ms (3.8 m). However, uncertainty in the positions

120 of stratal terminations does introduce a minimal error associated with the relative depth of the
121 recorded fault throws (Fig. 2). This is a function of the frequency content of the seismic dataset
122 (Mansfield and Cartwright, 1996). Errors associated with spurious velocity estimates may also
123 affect the throw values when converted to meters. These limitations will affect the absolute
124 value of estimated fault throws.

125 Throw-depth (T-Z) profiles can offer information on multiple parameters such as fault
126 nucleation, growth, segmentation, linkage of individual faults and rock competence (Baudon
127 and Cartwright, 2008; Peacock and Sanderson, 1991; Maunde et al., 2021). Discrepancies in
128 throw gradients often result from mechanical heterogeneities, fault reactivation and fault
129 segmentation (Childs et al., 1996; Baudon and Cartwright, 2008; Laubach et al., 2009).
130 Therefore, our throw-depth (T-Z) analyses aimed to identify fault throw anomalies which will,
131 in this paper, be linked to rock properties and local mechanical stratigraphy.

132

133 **3. Geological and seismic-stratigraphic settings**

134 The Broad Fourteens Basin, part of the larger South Permian Basin, records a complex history
135 of rifting, halokinesis and tectonic inversion (Duin et al., 2006; Nalpas et al., 1995; Van Wijhe,
136 1987; Verweij and Simmelink, 2002; Ziegler, 1990). The basin contains Upper Paleozoic and
137 Mesozoic strata overlain by Cenozoic siliciclastics (Van Wijhe, 1987; Van Adrichem Boogaert
138 and Kouwe, 1993; Gerling et al., 1999; van Verweij and Simmelink, 2002). Structural styles in
139 the Broad Fourteens Basin are dominated by normal faulting, which reflects the predominance
140 of an extensional regime since the Late Paleozoic (Fig. 4). Minor reverse movement is observed
141 along only a few normal faults (Alves and Elliott, 2014) (Fig. 4).

142

143 *3.1. Upper Paleozoic*

144 Towards the end of the Carboniferous a large foreland basin, the Variscan Foreland Basin, was
145 formed in what is now the Southern North Sea (Duin et al., 2006; Oudmayer and De Jager,
146 1993; Van Wijhe, 1987; Ziegler, 1990). Thick lacustrine and deltaic intervals with interbedded
147 coal seams were deposited at this time as part of the Limburg Group (Fig. 3). Included in this
148 unit are the Westphalian Coal Measures, a major source of gas in Northern Europe (Gerling et
149 al., 1999; Van Wijhe, 1987). Oblique-slip normal faulting predominated after the Variscan
150 Orogeny, with the largest faults cutting through the Variscan fold belt and propagating along
151 older NW-SE trending basement faults. In fact, the present-day structural grain of the Southern
152 North Sea follows horst-and-graben structures bounded by the latter basement faults (Duin et
153 al., 2006; Oudmayer and De Jager, 1993; Van Wijhe, 1987; Ziegler, 1990).

154 Sedimentation in the Permian was interrupted by thermal upwelling induced by doleritic
155 magma, which intruded the basement through oblique-slip dextral normal faults. This hiatus is
156 expressed in the form of a Saalian unconformity separating Lower from Upper Rotliegend
157 strata (Van Wees et al., 2000) (Fig. 3). Subsidence was resumed in the Late Permian and,
158 consequently, the South Permian Basin became separated from the North Permian Basin by the
159 Mid North Sea High (Duin et al., 2006). In the study area, Upper Rotliegend terrestrial
160 sandstones of the Slochteren Formation were deposited above the Saalian unconformity to
161 become the major reservoir interval for Permian gas plays (Verweij and Simmelink, 2002) (Fig.
162 3).

163 The Zechstein Sea subsequently flooded the Broad Fourteens Basin in the Late Permian,
164 depositing a thick interval of salt and relatively thin carbonate stringers (van Verweij and
165 Simmelink, 2002; Strozyk et al., 2012) (Unit S2 in Figs. 3, 4 and 5). Zechstein salt caps Upper
166 Rotliegend continental sandstones (Unit S1) and forms an effective seal rock for Permian (and
167 older) strata (Coward, 1995). In the interpreted seismic volume, a high-amplitude seismic

168 reflection separates the Zechstein Group (Unit S2) from Upper Rotliegend reservoirs in Unit
169 S1 (Figs. 4 to 6; Table 1).

170

171 *3.2. Mesozoic*

172 Continental rifting was intensified during the Mesozoic, allowing for differential subsidence to
173 predominate in the Southern North Sea (Alves and Elliott, 2014; Duin et al., 2006) (Fig. 4). In
174 a rapidly subsiding Broad Fourteens Basin, aeolian sands and lacustrine claystones from the
175 Lower and Upper Germanic Trias Group (Unit S3; Fig. 3) were conformably deposited above
176 the Zechstein salt (Van Hulten, 2010). In seismic data, the bright reflection at the base of
177 Germanic Trias Group correlates with a change from the high-velocity Zechstein salt (Unit S2)
178 to the relatively low-velocity aeolian sandstones and lacustrine claystones of the Lower
179 Germanic Trias Group in Unit S3 (Figs. 4 and 5; Table 1). In the study area, the Germanic Trias
180 Group (Unit S3) comprises a package with moderate frequency and moderate- to high-
181 amplitude seismic reflections (Figs. 4 and 6). Aeolian sands and lacustrine claystones of the
182 Lower Germanic Trias Group (Buntsandstein Formation) are a prolific gas reservoir,
183 particularly where Zechstein salt (Unit S2) has been withdrawn and welds have formed
184 between Triassic strata (Unit S3) and the Rotliegend Group in Unit S1 (Van Hulten, 2010).

185 Towards the end of the Triassic, salt tectonics and reactive diapirism became concentrated
186 along extensional boundary faults (Stewart and Coward, 1995; Ziegler, 1992). Rift-raft
187 tectonics led to the further deepening of the Broad Fourteens Basin and the establishment of
188 open marine conditions (Alves and Elliott, 2014; Penge et al., 1993). As a result, the deep-
189 water Altena Shales (Unit S4) were deposited unconformably above the Germanic Trias Group,
190 with the more bituminous Posidonia Shale Formation comprising the source interval for
191 Jurassic oil plays due to a marked segmentation of the Southern North Sea in confined sub-

192 basins (Duin et al., 2006; Nalpas et al., 1995) (Fig. 3). The Altena Shales (Unit S4) comprise
193 argillaceous deposits, calcareous and clastic sediments (van Verweij and Simmelink, 2002),
194 and form a package of high frequency, continuous and moderate- to high-amplitude reflections
195 in seismic data (Figs. 4 and 6; Table 1).

196 Deposition of the Altena Shales stopped in the Middle Jurassic during the Mid-Kimmerian
197 upwarping tectonic event (Fig. 3). This upwarping event is a product of salt tectonics, reactive
198 diapirism and thermal upwelling from dolerite intrusions (Van Wees et al., 2000), which
199 occurred in association with the Jurassic Kimmerian tectonic phase (Fig. 3). In areas with the
200 greater uplift, up to 1500 m of Jurassic strata may have been eroded (Heim et al., 2013). Despite
201 this latter uplift event, continuing NE-SW oriented extension compartmentalised the Broad
202 Fourteens Basin, imposing its present-day NW-SE trend (Fig. 1a). Local erosion of Triassic,
203 Zechstein and Rotliegend sequences above active structural highs generated thick successions
204 of the Delfland Subgroup and Vlieland Sandstone, depositing reservoir and seal intervals for
205 oil that was later sourced from the Posidonia Shales (Van Wijhe, 1987; Verweij and
206 Simmelink, 2002; Duin et al., 2006).

207 The Rijnland Group (Unit S5) comprises coarse clastic intervals, carbonaceous claystones and
208 interbedded sandstones, and was deposited conformably above the Schieland Group (van
209 Verweij and Simmelink, 2002; Van Adrichem Boogaert and Kouwe, 1993) (Fig. 3). Unit S5 is
210 bounded at the top by the Base Tertiary Unconformity (H6), at which level maximum erosion
211 takes place at the crest of a Late Cretaceous anticline (Figs. 4 and 6). In seismic data, Unit S5
212 forms a package of high-amplitude, high-frequency seismic reflections deformed locally by
213 closely spaced normal faults (Figs. 4 and 6; Table 1).

214 The Late Cretaceous records a major episode of sea-level rise, accompanied by post-rift
215 subsidence, and led to the accumulation of the Chalk Group (Van Wijhe, 1987; Verweij and

216 Simmelink, 2002) (Fig. 3). This group (Unit S6) comprises limestones, marls, calcareous
217 claystones and glauconitic sands deposited conformably above the Rijnland Group (van
218 Verweij and Simmelink, 2002) (Figs. 3 and 5). The onset of Alpine compression in the Late
219 Cretaceous interrupted regional subsidence in the Broad Fourteens Basin, with the so called
220 Sub-Hercynian tectonic phase reactivating Variscan faults with a reverse-dextral motion (De
221 Lugt et al., 2003; Nalpas et al., 1995). Maximum erosion of ~ 700 m of strata occurred in the
222 centre of the basin, close to the axis of inversion, herein named Anticline A, affecting the
223 overall thickness of the Chalk Group (Nalpas et al., 1995; De Lugt et al., 2003) (Figs. 4 and 6).
224 Later, the Laramide inversion event in the early Paleocene created a prominent Cretaceous-
225 Tertiary boundary (H6) at the top of Chalk Group (Oudmayer and De Jager, 1993; De Lugt et
226 al., 2003) (Figs. 4 and 6).

227

228 3.3. Cenozoic

229 Cenozoic strata comprise sandstones, clays, silts, locally gravel or peat, and brown coal seams
230 that are part of the North Sea Group, interpreted as Unit S7 in our seismic volume (van Verweij
231 and Simmelink, 2002; Van Adrichem Boogaert and Kouwe, 1993). The North Sea Group
232 directly overlies the Chalk Group (Fig. 5). Where maximum erosion took place around the
233 hinge region of the Late Cretaceous Anticline A, the base of Cenozoic strata directly overlies
234 the Rijnland Group (Unit S5; Figs. 4 and 6). Unit S7 is characterised by a package of high-
235 frequency, continuous and moderate to high-amplitude seismic reflections (Figs. 3 to 5; Table
236 1).

237 Three (3) inversion episodes affected the Broad Fourteens Basin in the Cenozoic – the
238 Laramide, Pyrenean and Savian episodes (Fig. 3). The Laramide inversion (early Paleocene)
239 reactivated Sub-Hercynian faults and created a prominent Base Tertiary Unconformity (De

240 Lugt et al., 2003; Oudmayer and De Jager, 1993) (Horizon H6; Figs. 3 to 9). The Pyrenean
241 inversion (Oligocene) created another unconformity at the base of the Miocene strata,
242 separating the Lower from the Middle North Sea Group (Oudmayer and De Jager, 1993; Wong
243 et al., 2001; Verweij and Simmelink, 2002) (Fig. 3). The boundary between the Middle and
244 Upper North Sea Groups (Savian unconformity) marks a break in sedimentation that resulted
245 from regional uplift during the Alpine Orogeny and a global sea-level lowstand (Oudmayer
246 and De Jager, 1993; Wong et al., 2001) (Fig. 3).

247

248 **4. Principal fault geometries**

249 The seismic data show Upper Mesozoic to Paleogene strata offset by deeply rooted listric
250 faults, and deformed by broad anticlines associated with normal faults (Figs. 4 to 6). The TWTT
251 structural maps in Figs. 10 to 12 highlight the main structures interpreted in the study area.

252

253 *4.1. Listric faults*

254 In the interpreted dataset, listric faults are detached in the Zechstein salt (Unit S2) and
255 accommodated the gravitational gliding of the overburden strata. At the same time, significant
256 subsidence occurred in adjacent hanging-wall blocks (Penge et al., 1999; Alves, 2012; Alves
257 and Elliott, 2014) (Figs. 4, 5 and 8). Variations in thickness between the footwall and the
258 hanging-wall blocks of listric faults reveal that syn-sedimentary growth faults propagated
259 upwards from the Zechstein salt (Unit S2; Figs. 4 to 6).

260 Listric faults offset Units S3, S4 and S5 (Lower and Middle Mesozoic strata), with some
261 propagating vertically into Paleogene strata in Unit S7 (Figs. 5 and 8). They are characterised
262 by a broadly spaced curvilinear pattern in map view, striking in a NW-SE direction that is sub-

263 parallel to the strike of Anticline A (Figs. 10b and 12). Listric faults show trace lengths of 7.2-
264 13.5 km, with a maximum fault throw of 440 m (Figs. 4, 8 and 12).

265

266 *4.2. Tiers of normal faults*

267 Normal faults are closely spaced in Upper Mesozoic and Paleogene strata (Figs. 4 to 6). We
268 grouped these normal faults into two distinct tiers: Tier 1 (Upper Mesozoic) and Tier 2
269 (Paleogene). In the interpreted dataset, periods of fault reactivation below and above the Base
270 Tertiary Unconformity (horizon H6) can be relatively dated. Horizon (H6) forms a high-
271 amplitude, regionally mappable seismic reflector and represents a major change in from the
272 soft Paleogene Lower North Sea clays and silts above (Unit S7) to the harder limestones of the
273 Chalk Group below (Unit S6; Figs. 3 to 5 and 12).

274

275 *4.2.1. Tier 1 faults: Late Mesozoic*

276 Tier 1 faults are closely spaced normal faults formed around the hinge of Anticline A (Figs. 4
277 and 6). These faults predominantly offset Upper Mesozoic strata in Units S5 and S6 (Figs. 4
278 and 6). The upper tips of Tier 1 faults are eroded and truncated by the Base Tertiary
279 Unconformity (horizon H6), with some faults reactivating and extending into Paleogene strata
280 (Figs. 6 to 8). The location of Tier 1 faults around the hinge of Anticline A suggests they are
281 created by outer-arc stretching during buckling and, thus, do not normally accommodate
282 regional extension (see Rowan et al., 1999) (Figs. 4 and 6). Tier 1 faults are grouped into non-
283 reactivated (eroded) and reactivated faults based on their upper tip terminations, as revealed by
284 the seismic sections and throw-depth (T-Z) profiles in Figs. 6, 13 and 14.

285

286 *4.2.1.1. Non-reactivated (eroded) Tier 1 faults*

287 Non-reactivated Tier 1 faults are restricted to the hinge of Anticline A (Figs. 6, 13 and 14).
288 Their upper tip lines are eroded and truncated at the Base Tertiary Unconformity (horizon H6),
289 with no faults propagating upwards into Paleogene strata (Figs. 13 and 14). The relatively large
290 throw values recorded just below horizon H6 confirm the erosion of their upper tips (Figs. 15
291 to 17), suggesting that these faults were active, and offsetting Unit S6, before the erosional
292 event responsible for the Base Tertiary Unconformity (Figs. 3 and 6).

293 Non-reactivated Tier 1 faults are characterised by their closely spaced, linear to curvilinear
294 conjugate pattern and strike predominantly in a NW-SE direction, roughly parallel to the strike
295 of Anticline A (Fig. 10). Thus, their plan-view geometry is controlled by this latter structure
296 (Fig. 10b). Non-reactivated Tier 1 faults show a maximum throw of 34.5 m, a spacing ranging
297 from 560 to 2,300 m, and trace lengths of 1,100-11,250 m (Fig. 10).

298

299 *4.2.1.2. Reactivated Tier 1 faults*

300 Fault reactivation has been described as reflecting the further propagation of pre-existing faults
301 (Holdsworth et al., 1997; Nicol et al., 2005). Tier 1 faults that offset the Base Tertiary
302 Unconformity (horizon H6) and propagate upwards in Paleogene strata are interpreted as
303 reactivated Tier 1 faults (Figs. 6, 13 and 14). Their throws die out upwards into Paleogene
304 strata, contrasting with non-reactivated (eroded) Tier 1 faults that are truncated at level of
305 horizon H6, or just below this latter (Figs. 6, 13 and 14).

306 Reactivated Tier 1 faults are characterised by their linear to curvilinear pattern, and were
307 predominantly reactivated above Anticline A in the southern part of the study area (Fig. 12).
308 The faults have a maximum throw of 40.2 m, a spacing of 840-5,200 m, and trace lengths of

309 1,200-12,250 m (Fig. 12). Some reactivated Tier 1 faults intersect the relatively deep listric
310 faults, thus potentially forming secondary migratory pathways for hydrocarbons into shallower
311 Paleogene units (Figs. 6, 8 and 14).

312

313 *4.2.1. Tier 2 faults: Paleogene*

314 Tier 2 faults comprise densely spaced sets of normal faults with a discrete range of strikes, and
315 reveal an irregular polygonal geometry in map view (Figs. 5, 6, 9 and 11). The upper and lower
316 tip lines of these faults die out in Paleogene strata, with some faults propagating downward and
317 offsetting the Base Tertiary Unconformity (horizon H6) around the hinges of Anticlines B and
318 C, a character particularly observed towards the northern part of the study area (Fig. 12). These
319 faults initially formed as polygonal faults and were reactivated to form new fault segments, or
320 lengthen their sizes, due to later tectonic deformation (Figs. 5, 9 and 11).

321 Tier 2 faults have a maximum throw of 9.8 m, a spacing of 320-680 m, and trace lengths of
322 950-2,000 m. They also accommodate a significant part of the local stretching affecting the
323 Paleogene overburden (Figs. 9 and 11). The geometry of Tier 2 faults likely resulted from near-
324 seafloor extension over growing anticlines, which affected compacting mud-rich strata
325 (Lonergan et al., 1998; Cartwright et al., 2003).

326

327 **5. Effect of lithology on fault throw distribution**

328 The interpreted faults F1 to F6 are characterised by their maximum throw of 32 ms (40.2 m),
329 an average spacing of 560 m, and trace lengths ranging from 1,100-11,250 m. These faults
330 offset a layered succession comprising sands and shales (Figs. 15 to 20). Importantly,

331 differences in fault throw are observed when the fault strands in the sand-rich intervals are
332 compared to fault segments in the shale-rich intervals. In the sand-rich intervals, fault throws
333 are larger (average 32 ms, or 40.3 m) compared to the smaller fault throws (average 13.5 ms,
334 or 17.7 m) documented in the shale rich-intervals (Figs. 15-20).

335 A decrease in fault throw is observed as the faults propagate from sand-rich into shale-rich
336 intervals (Figs. 15 to 20). Hence, the propagation of fault segments, first grown in sand-rich
337 strata, into shale intervals can result in vertically segmented fault arrays, as revealed by the
338 throw-depth (T-Z) data in Figs. 15 to 20. Nevertheless, further propagation of two hard-linked
339 fault segments after their growth can attenuate the throw variations recorded on T-Z profiles,
340 and thus obscure differences in the throw distribution with depth.

341

342 **6. Propagation and growth history of faults**

343 *6.1. Fault nucleation*

344 The relative nucleation of representative faults F1 to F6 in the study area is illustrated with
345 reference to the throw-depth (T-Z) profiles in Figs. 15 to 20. Fault segments with throws
346 between 16 ms and 32 ms (20.2 m and 40.3 m) are early-stage fault segments and represent
347 regions where faults nucleated first in competent sand and limestone intervals (Figs. 15 to 20).
348 Each segment of these early-stage faults propagated outwards until they encountered other fault
349 strands to link with. Linkage points are recorded in less competent shale-rich intervals where
350 throw minima vary between 2 ms and 14 ms (2.5 m to 17.7 m) (Figs. 15 to 20) (Ellis and
351 Dunlap, 1988; Mansfield and Cartwright, 1996). Hence, we interpret regions with local throw
352 maxima in the throw-depth (T-Z) profiles as the first loci of fault growth, which dominantly
353 occurred in competent sand and limestone intervals (Figs. 15b to 20b).

354

355 *6.2. Modes of fault growth*

356 We recognise two (2) distinct modes of fault growth, as revealed by the throw-depth profiles
357 in Figs. 15 to 22. These modes include fault growth via upward propagation and segment
358 linkage. Listric faults that reflect the early-stage deformation of Mesozoic strata grew via the
359 upward propagation from a parent fault above the Zechstein salt (Unit S2; Figs. 4 to 6). These
360 faults exhibit a typical vertical, positive stepped throw gradient (Fault F7; Fig. 21). They show
361 major breaks in throw gradients around the top of Jurassic strata. The fault strands below the
362 top Jurassic marker (horizon H4a) offset Triassic-Jurassic strata and show throw maxima
363 between 42 ms and 85 ms (52.9 m to 129 m) (Fig. 21). The strands above the top Jurassic
364 marker offset Cretaceous strata and reveal abrupt steps in throw profiles, with throws reaching
365 values between 15 ms and 32 ms (18.9 m to 40.3 m) (Fig. 21).

366 The upward decrease in throw values, and the vertical positive step in throw gradients recorded
367 by listric fault F7, are related to fault growth by upward propagation from parent faults above
368 the Zechstein salt (Unit S2; Figs. 4 to 6). The absence of alternating local throw maxima and
369 minima on the throw distribution profiles reflects the growth of listric faults by upward
370 propagation (Fig. 21). Also, thickness variations between the footwall and the hanging-wall
371 blocks of listric faults show these are syn-sedimentary faults that propagated vertically during
372 their growth (Figs. 4 to 6).

373 The representative vertical throw-depth (T-Z) profiles in Figs. 15b to 20b and 22c show a
374 distinct mode of growth dominated by segment linkage. This mode of fault growth is
375 recognised by its stepped vertical throw-depth (T-Z) profiles with breaks in throw gradients
376 (Figs. 15b to 20b and 22c). Sharp changes in throw values are interpreted to be a consequence
377 of reactivation and growth by segment linkage, where two separate faults have propagated

378 towards each other. Segments with local throw maxima are early-stage fault-segments formed
379 in regions where faults nucleated first in more competent (sand-rich) intervals. Each fault
380 segment is separated by a local throw minimum in less competent (shale-rich) intervals, as
381 expected for this type of growth by segment linkage (Figs. 15b to 20b and 22c).

382 Abrupt changes in fault throw are interpreted as a characteristic of fault reactivation and can
383 be attributed to lithological effects during fault propagation through mechanical barriers (Figs.
384 15b to 20b). Contrasts in acoustic impedance of the sediments along the fault planes are
385 sufficient to infer such major change in throw gradients. Fault growth via segment linkage has
386 wider implications for reactivation processes in fault systems, particularly where more
387 competent (strong) mechanical layers favour the nucleation of new faults in distinct mechanical
388 intervals (Peacock and Sanderson, 1992; Childs et al., 1996) (Figs. 15 to 20).

389

390 **7. Discussion**

391 *7.1. Impact of tectonic shortening on the geometry and reactivation of supra-salt faults*

392 Fault reactivation has been described as reflecting the further propagation of pre-existing faults
393 after a significant period of inactivity (Holdsworth et al., 1997; Nicol et al., 2005). The ability
394 for a fault to repeatedly reactivate is directly related to the orientation of the fault planes with
395 respect to the principal stresses (White et al., 1986; Richard and Krantz, 1991), and the
396 mechanical properties of the fault surface or zone itself: a) fault cohesion, faults' coefficient of
397 friction on the fault surface, and c) fluid pressure controlled by regional tectonics (Ward et al.,
398 2016; Ferrill et al., 2017).

399 The Late Cretaceous to Paleogene tectonic inversion episodes (i.e. Sub-Hercynian, Laramide,
400 Pyrenean and Savian episodes; Figs. 3 and 23), have induced a continuum of deformation in

401 the Broad Fourteen Basin, Southern North Sea, and contributed significantly to the formation
402 and subsequent reactivation of Upper Mesozoic to Paleogene supra-salt faults (Figs. 4, 5 and
403 23). In the study area, we recognise two distinct tiers of faults according to their geometry: a)
404 Tier 1 faults (Upper Mesozoic), and b) Tier 2 faults (Paleogene) (Figs. 4 to 6). Tier 1 faults
405 resulted from the progressive buckling and stretching of outer arc Mesozoic strata during the
406 Late Cretaceous inversion episode, i.e. during Sub-Hercynian tectonics (Figs. 3, 4 and 24c,d).

407 The Laramide inversion episode (Early Paleocene) reactivated Sub-Hercynian Tier 1 faults and
408 created a prominent Late Cretaceous-Tertiary unconformity (horizon H6) (De Lugt et al., 2003;
409 Oudmayer and De Jager, 1993). This same horizon H6 is a strong, regionally mappable seismic
410 reflector and represents a major change in rock strength from softer Tertiary clays and silts of
411 the North Sea Group (Unit S7) to stiffer Upper Cretaceous limestones deposits of the Chalk
412 Group below (Unit S6; Figs. 3, 4, 23 and 24e). The upper tip lines for these Tier 1 faults were
413 eroded by the Paleocene Laramide erosional event at the Base Tertiary Unconformity (H6;
414 Figs. 13 and 14), suggesting they were actively offsetting Upper Mesozoic strata before the
415 start of the Laramide erosional event (Fig. 24c and d). Subsequently, the Pyrenean (Oligocene)
416 and Savian (Miocene) inversion episodes reactivated some of these faults upwards into
417 Paleogene strata (Unit S7), where they link with the overlying Tier 2 faults (Figs. 6, 23 and
418 24e).

419 The TWTT structural maps in Fig. 12 highlight the map view of these fault tiers. Tier 1 faults
420 were largely reactivated around the hinge of Late Mesozoic Anticline A, whereas the overlying
421 Tier 2 faults were selectively reactivated around the hinges of Anticline B and C (Fig. 12). This
422 observation suggests that in addition to the fault's orientation and geometry (Richard and
423 Krantz, 1991; Baudon and Cartwright, 2000) other controls, such as the location of the

424 underlying anticlines, affected fault reactivation in the study area, as observed on the TWTT
425 map in Fig. 12.

426 The distinct geometries observed in Tier 1 and 2 faults can be attributed to the mechanical
427 differences in different lithological intervals and deformation mechanisms (Figs. 10 and 11).
428 The tectonic shortening and brittle deformation experienced by the more competent carbonate
429 and sand-rich strata of the Chalk and Rijnland Groups led to more localised linear-curvilinear
430 geometries in Tier 1 faults (Fig. 10), whereas compactional loading (diagenesis) and the
431 relatively ductile deformation of the incompetent mud-rich strata of the Lower North Sea
432 Group resulted in diffuse strain and the generation of a polygonal pattern in Tier 2 faults (Figs.
433 11). The polygonal pattern in Tier 2 faults was likely formed from near-seafloor extensional
434 stresses predominating over growing anticlines, accompanied by the sudden compaction of
435 mud-rich strata and subsequent loss of volume and fluid (Lonergan et al., 1998; Cartwright et
436 al., 2003) (Fig. 11). Nevertheless, some of the Tier 2 faults still record the effect of Miocene
437 inversion episode (Savian phase) which largely reactivated and lengthen some of these latter
438 faults downwards around the hinge of Anticlines B and C (Figs. 5, 9 and 12).

439 According to the analogue sandbox experiments presented in Gabrielsen et al. (2016)
440 incompetent layers, or intervals, with a ductile behaviour can prevent fault propagation or lead
441 to vertical segmentation (decoupling) when fault segments are subjected to various types of
442 linkage across ductile layers. In the study area, we observe vertical fault segmentation in both
443 seismic and throw-depth (T-Z) profiles (Figs. 9, 15b, 16b, 17b and 22c). Several fault segments
444 with relatively small throws are observed in shale-rich intervals, while faults in the sand-rich
445 intervals appear as discrete, isolated faults recording the largest throws (Figs. 15b, 16b, 17b,
446 19c and 22c).

447 The effect of incompetent layers on the segmentation of faults has been studied at outcrop and
448 using seismic data (Soliva et al. 2005; Schöpfer et al. 2006; Libak et al., 2019; Ferrill et al.
449 2017). For instance, Libak et al. (2019) recently interpreted seismic data from the Norwegian
450 Barents Sea to show that fault zones are more segmented and wider in claystones, while faults
451 in sandy intervals are narrower and more localised, thus less segmented. Deformation tends to
452 be more localised (less segmented) to reveal local throw maxima in competent lithologies such
453 as sandstones and carbonates, and more distributed (segmented) in incompetent lithologies
454 such as claystones and shales, where throw minima are recorded (Schöpfer et al. 2006).

455 Research has also shown that faults are often steep in competent lithologies, while faults have
456 more gentle dips in relatively incompetent strata (Peacock 2002; Ferrill et al. 2017). Such
457 differences in fault dip along a fault segment can locally lead to fault refraction, which may
458 generate extensional (dilatational) jogs (Peacock and Sanderson 1991; Ferrill et al. 2017). In
459 the study area, no evidence exists for changes in fault dip geometries, as faults propagate from
460 competent into incompetent intervals. This is often due to intricate fault geometries of a
461 particular area or, instead, a result of the limited resolution of seismic datasets, i.e. the faults
462 are not fully resolved by the seismic data. In the study area, the lack of variation in fault dips
463 is interpreted as reflecting the deformation of the original dip-linkage structures during post-
464 linkage slip of the faults, with any original topological irregularities having been largely
465 eliminated during fault reactivation.

466

467 *7.2. Propagation and growth history of faults in layered successions*

468 Interpreted faults F1 to F6 and F8 to F11 reveal a break in throw gradients, and a progressive
469 decrease in throw towards the fault tips, a characteristic of reactivation and growth during fault
470 propagation through mechanical barriers (Gross et al., 1997; Wilkins and Gross, 2002) (Figs.

471 15b to 20b and 22c). Research has shown that, as strain accumulates in a layered sedimentary
472 sequence, competent (brittle) lithologies such as limestones and sandstones accommodate
473 smaller amounts of pre-failure strain and are able to fracture first, whereas incompetent
474 (ductile) lithologies such as claystones and shales accommodate higher prefailure strain prior
475 to faulting and usually fracture later (Ferrill and Morris, 2003, 2008; Welch et al., 2009).
476 Hence, faults would be expected to nucleate first in competent lithologies with the larger
477 throws, and this study show this to be the case (Figs. 15 to 20).

478 The results in this work show differences between the throw magnitudes of faults in sand-rich
479 intervals (with a throw maximum of 32 ms, or 40.3 m) compared to the shale-rich intervals
480 (with a throw maximum of 14 ms, or 17.7 m) (Figs. 15 to 20). This difference can be related to
481 the predominance of brittle deformation in the competent sand-rich intervals, resulting in a less
482 segmented zones of fault deformation with local throw maxima, while ductile deformation in
483 incompetent shale-rich interval led to a more segmented zone of deformation, with local throw
484 minima (Figs. 15b to 20b and 22c). Thus, fault segments with local throw maxima in the throw-
485 depth (T-Z) profiles are interpreted to be the loci where faults nucleated first, with this
486 occurring predominantly in competent sand-rich intervals (Figs. 15 to 20). These fault
487 segments drove displacement into shale-rich intervals where smaller fault throws are
488 accommodated by more ductile deformation (Figs. 15 to 20).

489 In our throw-depth (T-Z) profiles there is evidence for vertical fault segmentation, where the
490 fault segments with local throw minima in the shale-rich intervals were linked to pre-existing
491 fault segments with local throw maxima in the sand-rich intervals (Figs. 15b to 20b). Thus, the
492 propagation of slip from fault segments with local throw maxima (in the sand-rich intervals)
493 into the shale-rich intervals can describe the vertically segmented fault arrays observed in the
494 throw-depth (T-Z) profiles in Figs. 15b to 20b and 22c. The results of our throw-depth (T-Z)
495 interpretation support the view that vertically segmented fault arrays initially nucleated in the

496 competent, and brittle, lithologies (sandstones and limestones) with less segmented maximum
497 throws, and were later linked by faults in the incompetent, ductile, lithologies (shales) with
498 more segmented, minimum throws (Peacock and Sanderson, 1992; Childs et al., 1996) (Figs.
499 15b to 20b).

500 Differences in the throw distribution provide insights into the recognition of two (2) distinct
501 modes of fault growth: fault growth via upward propagation vs. fault segment linkage. The
502 listric fault F7 (Fig. 21) shows a regular upward decrease in throw values and maintains
503 vertical, positively stepped gradients, revealing the classical model for fault growth by upward
504 propagation from pre-existing faults above thick salt (Richard and Krantz, 1991; Baudon and
505 Cartwright, 2008; Maunde and Alves, 2020) (Fig. 21). The maximum throw value on the throw
506 profile marks the onset of faulting; thus, faulting started above the Permian Zechstein salt (Figs.
507 6 and 21).

508 The interpreted faults F1 to F6 and F8 to F11 present throw-depth (T-Z) profiles with multiple
509 local throw maxima separated by local throw minima, revealing fault growth via segment
510 linkage (Baudon and Cartwright, 2008; Kim and Sanderson, 2005) (Figs. 15b to 20b and 22c).
511 Fault segments with local throw maxima represent the intervals where faults nucleate first in
512 more competent sand-rich intervals. Each of these fault segments propagated outwards until
513 they encountered other pre-existing fault segments to link with. The zone of linkage between
514 two originally individual segments that are linked is recognisable by a zone of local throw
515 minima and steepening of the throw gradients (Cartwright et al., 1995; Lohr et al., 2008). (Figs.
516 15b to 20b). However, further propagation of the two hard-linked fault segments after growth
517 might attenuate the throw variations and obscure differences in the throw distribution (Figs.
518 18b and 20b).

519 The interpreted fault tiers are largely segmented and may present an important limitation for
520 the implementation of carbon capture and storage (CCS) in the Broad Fourteens Basin (Figs.
521 15b to 20b and 22c). For example, the locus of fault segment linkage may increase the
522 permeability of the rocks. Where the fault segments interact, active fracturing provides a
523 pathway for fluids, as well as increasing the chances of compartmentalisation or localised fluid
524 flow through the fault linkages (Curewitz and Karson, 1997; Ward et al., 2016), thus revealing
525 significant risks when injecting CO₂ into the subsurface. In the Broad Fourteens Basin, listric
526 faults control and transmit fluids within, and between Mesozoic strata (Penge et al., 1999;
527 Alves and Elliott, 2014). The reactivated Tier 1 faults intersecting these deeply rooted listric
528 faults potentially allow secondary migration of hydrocarbons into shallower Paleogene
529 reservoirs (Figs. 8 and 24e).

530 The models for the evolution of interpreted faults in Fig. 24 provide insights into the timing of
531 fault activity, with a direct application to hydrocarbon migration and sealing of faults in
532 petroleum reservoirs. For instance, the relative timing of any fault reactivation phases with
533 reference to the filling of hydrocarbon traps would be critical for an evaluation of seal risk
534 (Cartwright et al., 2007). A further understanding of reactivation processes will greatly improve
535 petroleum prediction of seal integrity, trap geometry and fluid migration into shallow reservoirs
536 in the Broad Fourteens Basin, Southern North Sea.

537

538 **8. Conclusions**

539 Detailed mapping and geometric analyses of normal faults using high-quality 3D seismic and
540 borehole data from the Broad Fourteens Basin, offshore The Netherlands, provided important
541 insights into the geometry and reactivation histories of Upper Mesozoic to Paleogene supra-
542 salt faults. The key conclusions of this study are as follows:

543

- 544 1. In the Broad Fourteen Basin, Southern North Sea, the Late Cretaceous to Paleogene
545 tectonic inversion episodes induced a continuum of internal deformation and contributed
546 significantly to the formation and subsequent reactivation of supra-salt faults. Such a
547 phenomenon had a positive economic impact, as reactivated faults potentially allowed the
548 secondary migration of hydrocarbons into shallower reservoir units.
- 549 2. Two distinct tiers of fault geometry are recognised in the study area: a) Tier 1 faults (Late
550 Mesozoic) resulting from local buckling and stretching of outer arc Mesozoic strata during
551 the Late Cretaceous-Paleogene tectonic inversion episodes (i.e. Sub-Hercynian, Laramide,
552 Pyrenean and Savian phases), b) Tier 2 faults (Paleogene) relating to early diagenesis but
553 still recording the effect of a Paleogene inversion episode. All in all, the geometry and
554 location of underlying anticlinal structures affected the selection of reactivation and growth
555 histories of the interpreted fault tiers.
- 556 3. The truncation and lack of near-zero throw values at the Base Tertiary Unconformity,
557 revealed by Tier 1 faults, confirm the erosion of the upper fault tips by a Paleocene-
558 Laramide erosional event. This truncation suggests that Tier 1 faults were active in the
559 Upper Cretaceous Chalk Group before the onset of a Paleocene erosional event in the
560 Southern North Sea.
- 561 4. Notable differences in fault throw values are observed between sand- and shale-rich
562 intervals. In sand-rich intervals, fault throws are larger (32 ms or 40.3 m) compared to
563 shale-rich intervals (14 ms or 17.7 m). Hence, families of vertically segmented fault arrays
564 are observed in the throw-depth profiles, as faults propagated through alternating sand-
565 shale intervals.
- 566 5. The interpreted fault tiers are segmented, increasing the chances of compartmentalisation,
567 or localised fluid flow, through fault linkage points. In the Broad Fourteens Basin, listric

568 faults provide significant pathways for fluid migrating from pre-Zechstein salt units into
569 Mesozoic strata. Consequently, Tier 1 faults intersecting these deeply rooted listric faults
570 will potentially allow the secondary migration of hydrocarbons into shallower reservoir
571 units.

572

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578

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759

760 **Figure captions**

761 **Fig. 1.** a) Map of the Southern North Sea highlighting its Dutch offshore sector and the location
762 of the study area in the northern end of the Broad Fourteens Basin (BFB), offshore The
763 Netherlands, b) TWTT structural map of the Base Tertiary Unconformity (H6) showing the
764 location of exploration wells and key seismic lines.

765 **Fig. 2.** Schematic cross-section showing the points of fault throw-depth (T-Z) measurements
766 (a) and corresponding throw-depth (T-Z) plot (b). Local throw maxima in the throw-depth plot
767 represent the interval where fault nucleated first..

768 **Fig. 3.** Simplified seismic-stratigraphic correlation between interpreted seismic units and the
769 formal stratigraphic units recognised in the Dutch Sector of the Southern North Sea. Main
770 stratigraphic groups, tectonic phases and unconformities related to regional tectonic events are
771 based on Penge et al. (1999) and van Verweij and Simmelink (2002). Horizons H1-H6, and
772 Units S1-S7 refer to interpreted seismic horizons and units, respectively. The location of the
773 seismic line is shown in Figs. 1b, 10, 11 and 12.

774 **Fig. 4.** a) Uninterpreted and b) interpreted seismic profiles revealing the distinct geometry of
775 Upper Mesozoic (Tier 1) and Paleogene (Tier 2) faults formed over Anticline A. These fault
776 tiers are separated by the Base Tertiary Unconformity (horizons H6). Tier 1 faults responded
777 to Late Cretaceous to Paleogene tectonic inversion episodes, whereas Tier 2 faults resulted
778 from: i) near-seafloor extension over growing anticlines, and ii) sudden compaction of mud-
779 rich strata with subsequent loss of volume and fluid, forming polygonal fault geometries. The
780 location of the seismic line is shown in Figs. 1b, 10, 11 and 12.

781 **Fig. 5.** a) Uninterpreted and b) interpreted seismic profiles showing the distinct geometry of
782 Late Mesozoic (Tier 1) and Paleogene (Tier 2) faults over Anticlines B and C. These two fault
783 tiers are separated by the Base Tertiary Unconformity (horizon H6). However, some of the
784 Tier 2 faults propagate downwards and offset horizon H6. The location of the seismic line is
785 shown in Figs. 1b, 10, 11 and 12.

786 **Fig. 6.** a) Uninterpreted and b) interpreted seismic profiles revealing the geometry of Upper
787 Mesozoic (Tier 1) and Paleogene (Tier 2) faults over Anticline A. Tier 1 faults were generated
788 by the local buckling and stretching of the anticline's outer-arc strata during the Late
789 Cretaceous-Paleogene tectonic inversion episodes. These faults were eroded and truncated at
790 the Base of Tertiary Unconformity (horizon H6), with some reactivating upwards into
791 Paleogene strata (Unit S7), linking with the overlying Tier 2 faults. The location of the seismic
792 line is shown in Figs. 1b, 10, 11 and 12.

793 **Fig. 7.** a) Uninterpreted and b) interpreted seismic profiles highlighting the geometry of Upper
794 Mesozoic (Tier 1) and Paleogene (Tier 2) faults over Anticline A. The imaged fault tiers are
795 separated by the Base of Tertiary Unconformity (horizon H6), with some of the Tier 1 faults
796 reactivating upwards into Paleogene strata (Unit S7), linking with Tier 2 faults. The location
797 of the seismic line is shown in Figs. 1b, 10, 11 and 12.

798 **Fig. 8.** a) Uninterpreted and b) interpreted seismic profiles highlighting the geometry of Upper
799 Mesozoic (Tier 1) and Paleogene (Tier 2) faults over Anticline A. Distinct fault tiers are
800 separated by the Base Tertiary Unconformity (H6), but with some of the Tier 1 faults
801 reactivating upwards into Paleogene strata (S7) to link with Tier 2 faults. A deeply rooted listric
802 fault that detaches on top Zechstein salt (H2) propagates vertically into Paleogene strata (S7).
803 Some of the Tiers 1 and 2 faults intersect this listric fault. The location of the seismic line is
804 shown in Figs. 1b, 10, 11 and 12.

805 **Fig. 9.** a) Uninterpreted and b) Interpreted inline seismic sections revealing the geometry of
806 Tier 2 faults in Paleogene strata (Unit S7: Lower North Sea Group), c) Uninterpreted and d)
807 Interpreted cross-line seismic sections also highlighting the geometry of Tier 2 faults in
808 Paleogene strata. These faults are closely spaced, with some also segmented. They result from
809 near-seafloor extension over growing anticlines and sudden compaction of mud-rich strata
810 (with subsequent loss of volume and fluid), forming polygonal fault geometries. The location
811 of the seismic lines are shown in Figs. 1b, 10, 11 and 12.

812 **Fig. 10.** a) TWTT structural map of a representative interval in Upper Mesozoic strata (H4a)
813 highlighting the geometry of Tier 1 faults, the location of exploration wells and key seismic
814 lines, b) Interpreted sketch highlighting the map view geometry of Tier 1 faults over the NW-
815 SE trending Anticline A. These faults show linear to curvilinear geometries in map view. A,
816 B and C are anticlines responding to the effect of tectonic inversion in the Southern North Sea.

817 **Fig. 11.** a) TWTT structural map for representative interval in Paleogene strata highlighting
818 the geometry of Tier 2 faults, the location of exploration wells and key seismic lines, b)
819 Interpreted sketch highlighting the geometry of Tier 2 faults. A, B and C are anticlines
820 responding to the effect of tectonic inversion in the Southern North Sea.

821 **Fig. 12.** a) TWTT structural map of the Base Tertiary Unconformity (horizon H6) highlighting
822 the location of exploration wells and key seismic lines. A, B and C are anticlines responding
823 to the effect of tectonic inversion in the Southern North Sea, b) Interpreted sketch highlighting
824 the geometry of reactivated fault families affecting the Base Tertiary Unconformity (horizon
825 H6). Reactivated Tier 1 faults show linear to curvilinear geometries around Anticline A. Tier
826 2 faults show irregular polygonal geometries over Anticlines B and C.

827 **Fig. 13.** a) Uninterpreted and b) interpreted seismic profiles revealing the geometry of
828 representative Upper Mesozoic (Tier 1) faults over Anticline A. These faults were eroded and

829 truncated at the Base of Tertiary Unconformity (non-reactivated Tier 1 faults), with some
830 reactivating and propagating upwards into Paleogene strata (Reactivated Tier 1 faults). The
831 location of the seismic line is shown in Figs. 1b, 10, 11 and 12.

832 **Fig. 14.** a) Uninterpreted and b) interpreted seismic profiles revealing the geometry of
833 representative Upper Mesozoic (Tier 1) faults over Anticline A. These faults were eroded and
834 truncated at the Base of Tertiary Unconformity (non-reactivated Tier 1 faults), with some
835 reactivating and propagating upward into Paleogene strata (Reactivated Tier 1 faults). Some of
836 the Tier 1 faults intersect a deeply rooted listric fault that detaches on the top of Zechstein salt.

837 **Fig. 15.** Representative throw-depth (T-Z) profiles stressing the influence of mechanical
838 stratigraphy and lithology on throw distribution and growth in fault F1. a) Interpreted seismic
839 section and well log. b) Representative throw-depth (T-Z) profiles revealing fault reactivation
840 and growth by segment linkage. Here, two separate pre-existing faults with throw maxima in
841 sand-rich competent intervals have propagated towards each other and linked in shale-rich
842 intervals, where local fault throw minima are recorded. c) Throw-depth contour map showing
843 anomalous throw distributions and, d) Throw-distance (T-X) plots through the contour map.
844 See Fig. 13 for a full seismic section of the interpreted fault F1.

845 **Fig. 16.** Representative throw-depth (T-Z) profiles revealing the effect of mechanical
846 stratigraphy and lithology on throw distribution and growth in fault F2. a) Interpreted seismic
847 section and well log. b) Representative throw-depth (T-Z) profiles showing fault reactivation
848 and growth by segment linkage. Two separate faults with local throw maxima between 15 and
849 30 ms (18.2-37.8 m) in sand-rich (competent) intervals have propagated towards each other
850 and linked in shale-rich (incompetent) intervals, where local throw minima between 2 and 15
851 ms (2.5-19.2 m) are recorded. c) Throw-depth contour map showing anomalous throw

852 distributions. d) Throw-distance (T-X) plots through the contour map stressing fault growth
853 via segment linkage. See Fig. 13 for a full seismic section of the interpreted fault F2.

854 **Fig. 17.** Representative throw-depth (T-Z) profiles revealing the effect of mechanical
855 stratigraphy and lithology on throw distribution and growth in fault F3. In sand-rich intervals,
856 fault throws are usually larger - between 14 and 30 ms (17.7-37.8 m) - compared to the smaller
857 fault throws between 2 and 14 ms (2.5-17.7 m) recorded in shale rich-intervals. These changes
858 in throw values are interpreted to be a consequence of mechanical stratigraphy and lithological
859 changes in the host rock. a) Interpreted seismic section and well log. b) Representative throw-
860 depth (T-Z) profiles showing fault reactivation and growth by segment linkage. c) Throw-depth
861 contour map showing throw distributions. d) Throw-distance (T-X) plots through the contour
862 map. See Fig. 13 for a full seismic section of the interpreted fault F3.

863 **Fig. 18.** Representative throw-depth (T-Z) profiles stressing the influence of mechanical
864 stratigraphy and lithology on throw distribution and growth in fault F4. A reduction in throw
865 values is observed as faults propagate from sand-rich intervals into shale-rich intervals. a)
866 Interpreted seismic section and well log. b) Representative throw-depth (T-Z) profiles
867 highlighting the fault reactivation and growth by segment linkage, where two separate pre-
868 existing faults with throw maxima in sand-rich competent intervals have propagated towards
869 each other and linked in shale-rich intervals, where local fault throw minima are recorded. c)
870 Throw-depth contour map showing throw distributions. d) Throw-distance (T-X) plots through
871 the contour map. See Fig. 14 for a full seismic section of the interpreted fault F4.

872 **Fig. 19.** Representative throw-depth (T-Z) profiles revealing the effect of mechanical
873 stratigraphy and lithology on throw distribution and growth in fault F5. a) Interpreted seismic
874 section and well log. b) Representative throw-depth (T-Z) profiles highlighting fault
875 reactivation and growth by segment linkage. c) Throw-depth contour map showing anomalous

876 throw distributions. d) Throw-distance (T-X) plots through the contour map stressing fault
877 growth via segment linkage. See Fig. 14 for a full seismic section of the interpreted fault F5.

878 **Fig. 20.** Representative throw-depth (T-Z) profiles revealing the effect of mechanical
879 stratigraphy and lithology on throw distribution and growth on fault F6. a) Interpreted seismic
880 section and well log. b) Representative throw-depth (T-Z) profiles highlighting fault
881 reactivation and growth by segment linkage. Here, two separate pre-existing faults with throw
882 maxima in more competent intervals have propagated towards each other and linked in less
883 competent intervals. c) Throw-depth contour map showing throw distributions. d) Throw-
884 distance (T-X) plots through the contour map. See Figs. 6 and 7 for a full seismic section of
885 the interpreted fault F6.

886 **Fig. 21.** Representative throw-depth (T-Z) profiles for a listric fault showing typical growth by
887 upwards propagation i.e. a vertical, positive stepped throw gradient. The decrease and vertical
888 positive step in throw gradients recorded by the listric fault can be related to the effects of
889 reactivation by upwards propagation from parent faults above a detachment surface, i.e.
890 Zechstein salt in Fig. 6.

891 **Fig. 22.** a) Uninterpreted and b) interpreted seismic profiles showing the geometry of Tier 2
892 faults in Paleogene strata (Unit S7; Lower North Sea Group). c) Representative throw-depth
893 (T-Z) profiles highlighting the reactivation and growth history of Tier 2 faults. The sharp
894 changes in throw values are interpreted to relate to fault reactivation and growth by segment
895 linkage, where multiple throw maxima are separated by throw minima.

896 **Fig. 23.** Schematic illustration of the relative age and time-span of representative distinct fault
897 tiers mapped over the NW-SE striking Anticline A. Plotted in the diagram is the number of
898 reflections affected by faults above and below the Base Tertiary Unconformity (H6). Tier 1
899 faults dominantly offset Upper Mesozoic strata and truncated/eroded at the Base Tertiary

900 Unconformity (Non-reactivated Tier 1 faults), with some faults reactivating upwards into
901 Paleogene strata (Reactivated Tier 1 faults). Tier 2 faults dominantly offset Paleogene strata.
902 They are related to early diagenesis but still record the effect of the Paleogene inversion
903 episode. Main stratigraphic groups, tectonic phases and unconformities related to regional
904 tectonic events are based on Penge et al. (1999) and van Verweij and Simmelink (2002).

905 **Fig. 24.** Schematic model for the geological evolution of the study area highlighting the age
906 and reactivation of main fault families. Listric faults were active during the Jurassic syn-rift
907 phase in association with rift-raft tectonics, b). c) Tier 1 faults occurred during Late Cretaceous
908 Sub-Hercynian inversion, i.e. the time of the formation of major anticlines and deposition of
909 the Chalk Group. d) Period of reactivation of Sub-Hercynian faults (Tier 1 faults) and erosion
910 of their upper fault tips by the Paleocene-Laramide erosional event, creating a prominent Late
911 Cretaceous-Tertiary Unconformity (horizon H6). e) Phase of reactivation of some Tier 1 faults
912 into the Paleogene strata during Oligocene-Pyrenian inversion and formation of Tier 2 faults
913 in Paleogene strata. The present-day, post-inversion phase comprises two distinct fault tiers:
914 Tier 1 (Late Mesozoic) and Tier 2 (Paleogene) faults.

List of Figures

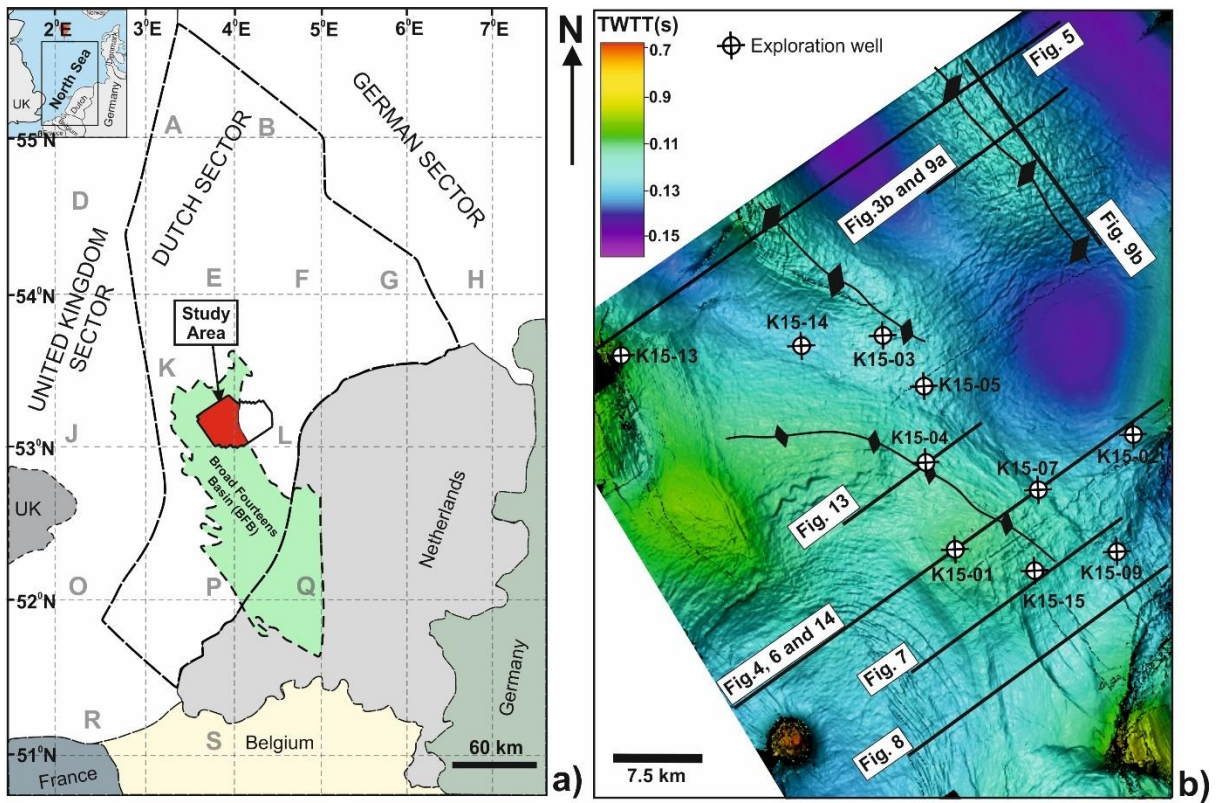


Fig. 1

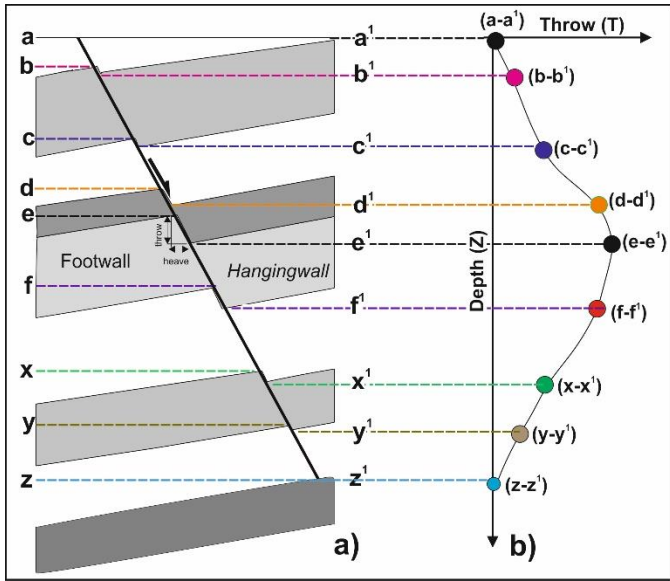


Fig. 2

Time (Ma)	Era	Period	Epoch/Series	Stratigraphy Groups	Seismic units	Velocity m/s	Tectonic Phases	
0	CENOZOIC	Quaternary	Pliocene	North Sea Group	Upper	Unit S7	Savian Pyrenean Laramide Sub-Hercynian Austrian Late Kimmerian Mid-Kimmerian Early-Kimmerian Hardegsen Saalian Asturian Sudetan	
20			Miocene					Middle
40		Paleogene	Oligocene	Lower				
60			Eocene					
80			Paleocene					
100		MESOZOIC	Cretaceous	Late	Chalk Group	Unit S6		3907.6
120				Early	Rijnland Group	Unit S5		2521.3
140	Jurassic		Late	Schieland Group	Unit S4	2067.2		
160			Middle	Schieland Group				
180			Early	Altana Group				
220	Triassic		Late	Germanic Trias Group	Unit S3	3045.6		
240			Middle		Unit S2	4305.7		
260		Early	Unit S1		2873.3			
280	PALEOZOIC	Permian	Late	Zechstein Group (ZE)	H2			
300			Middle	Rotliegend Group	H1			
320		Carboniferous	Silesian	Limburg Group				

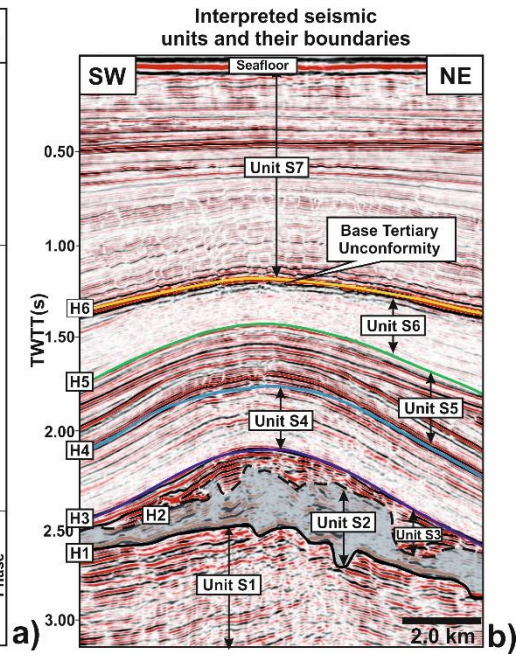


Fig. 3

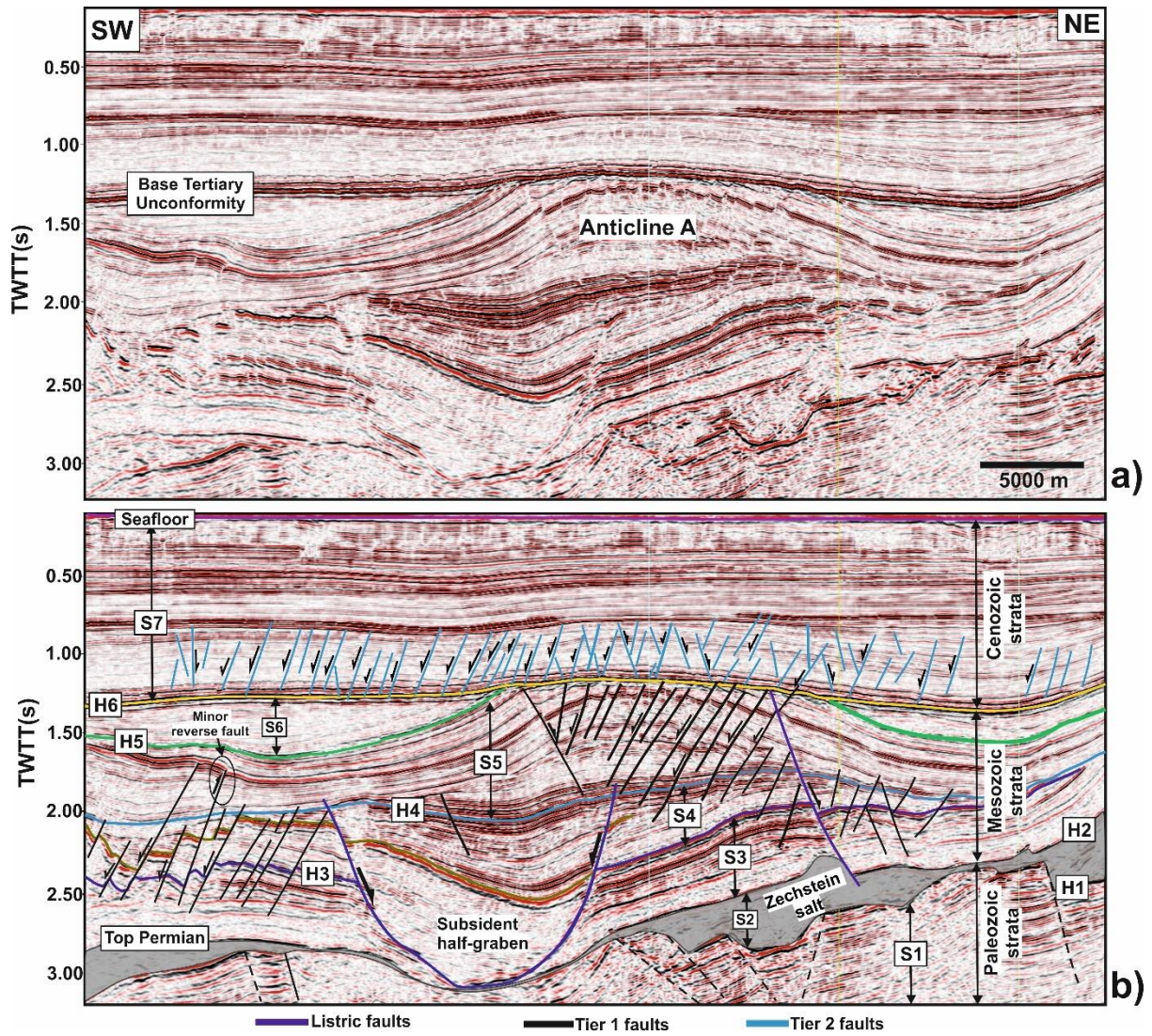


Fig. 4

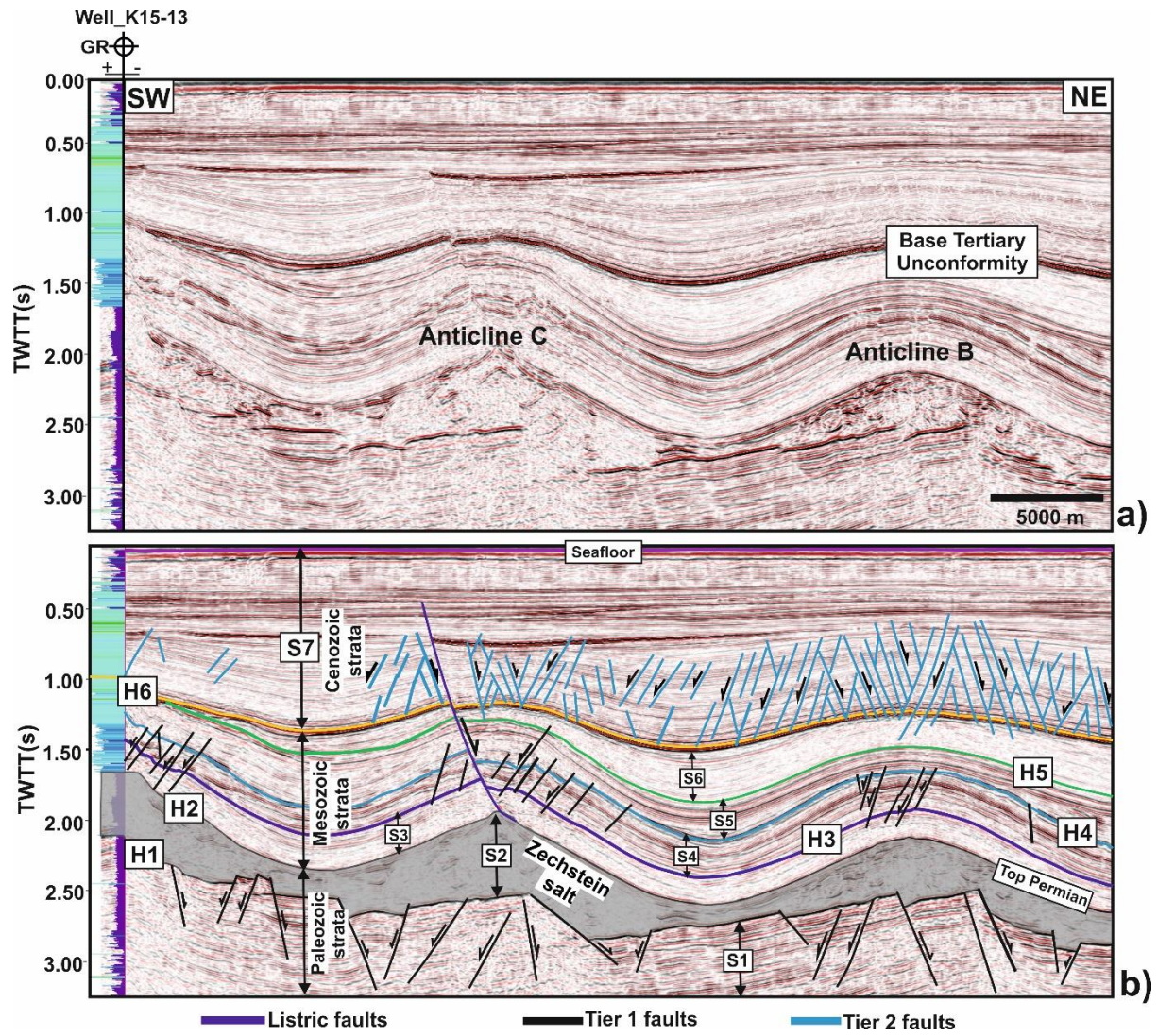


Fig. 5

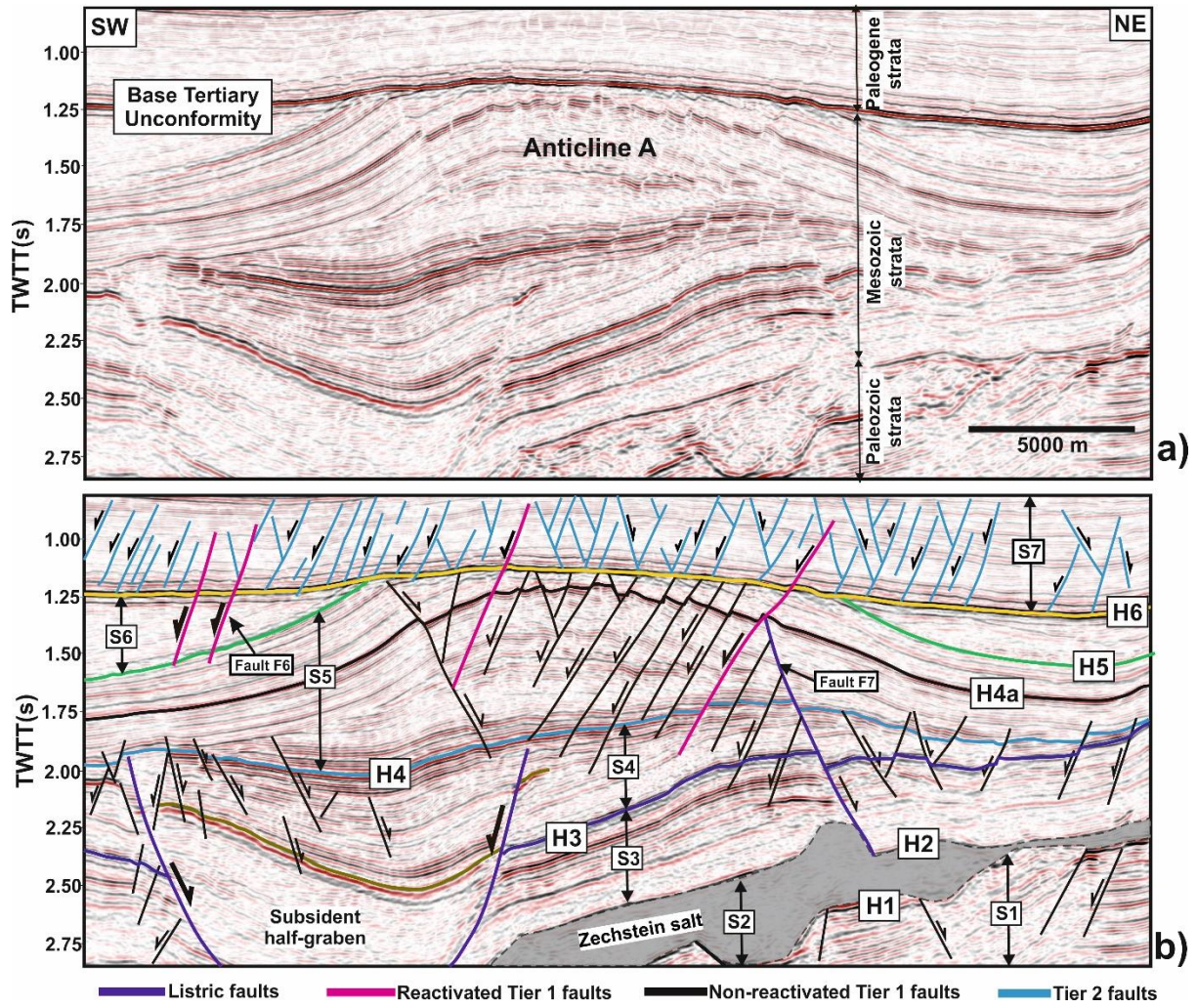


Fig. 6

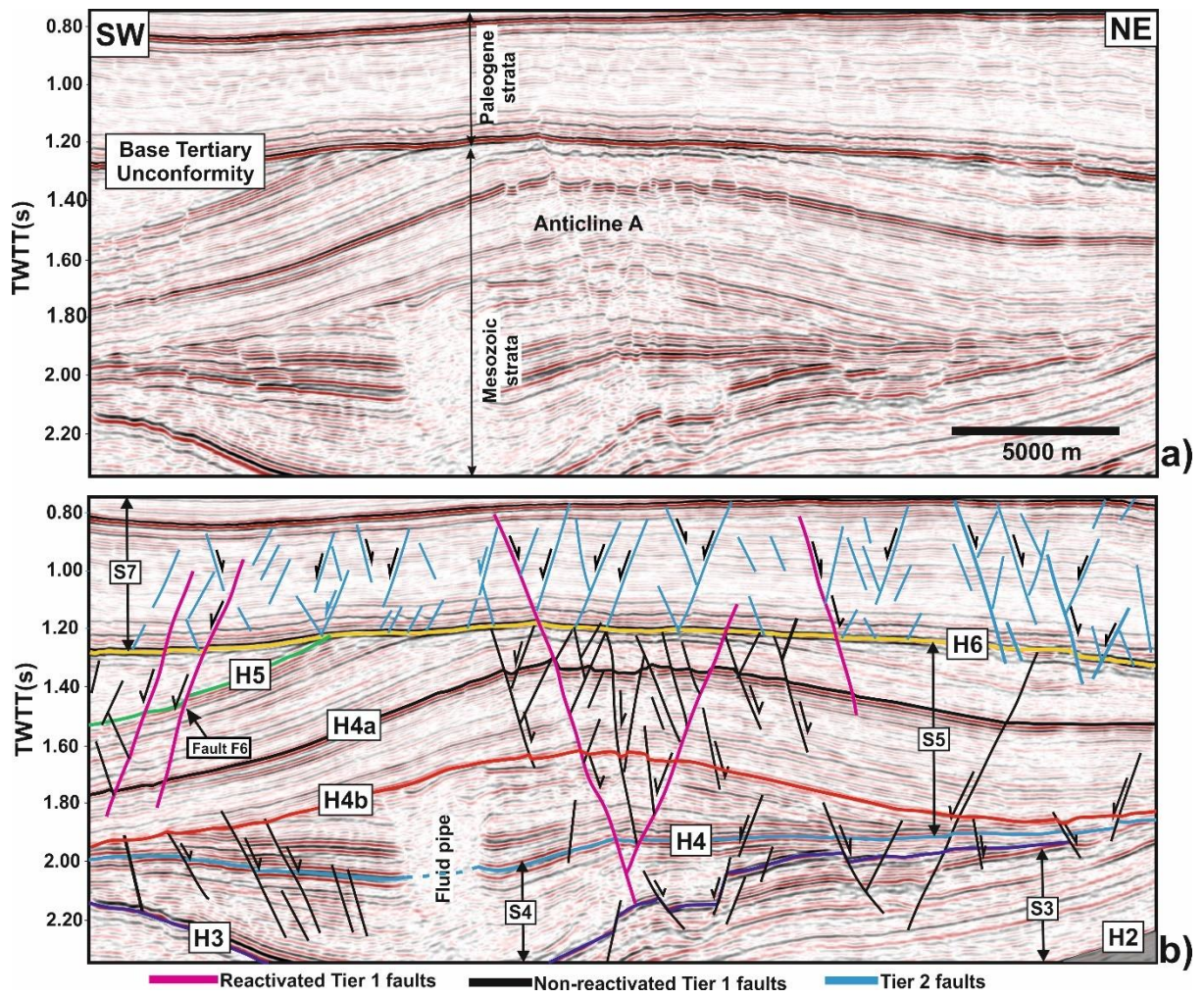


Fig. 7

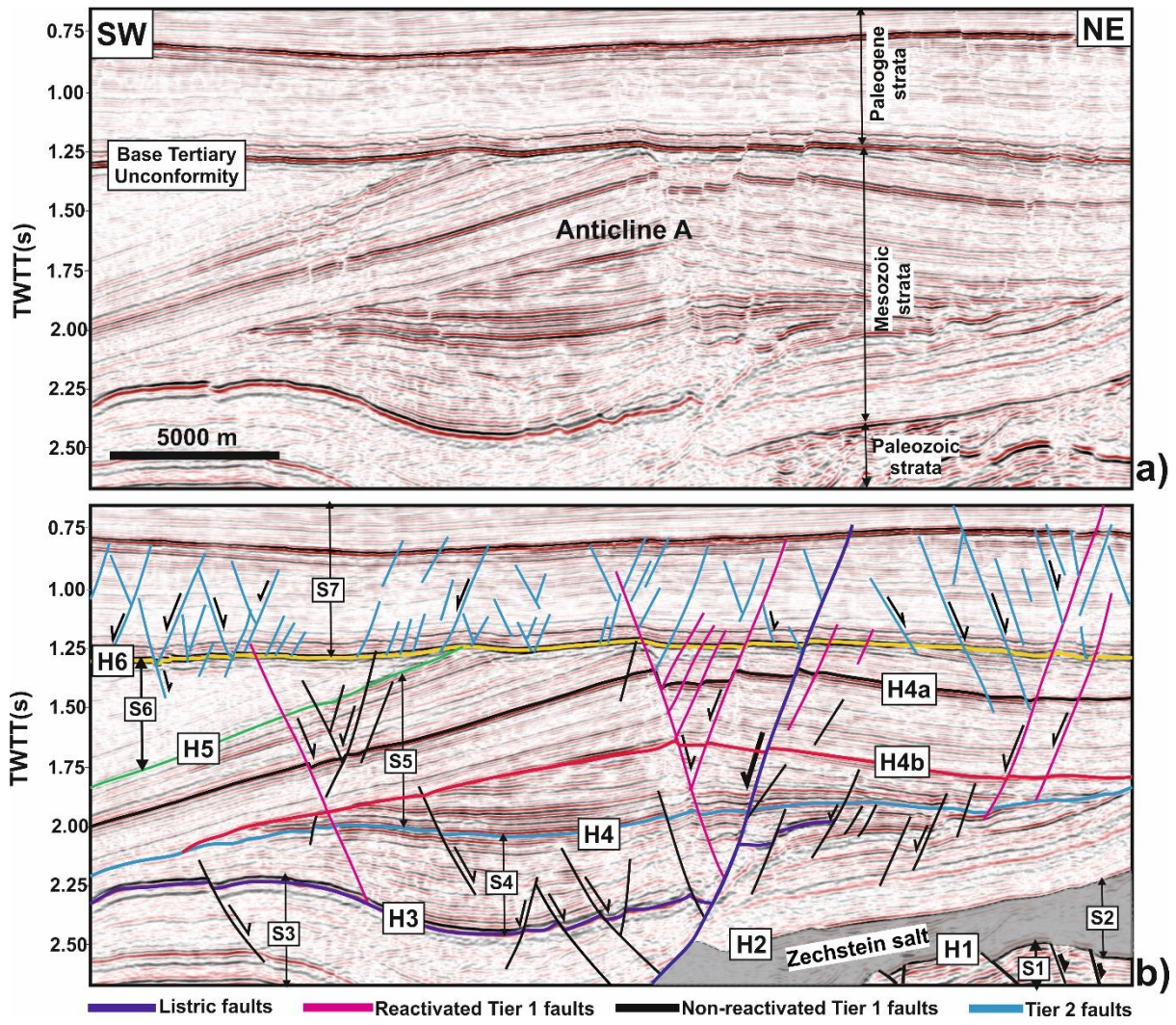


Fig. 8

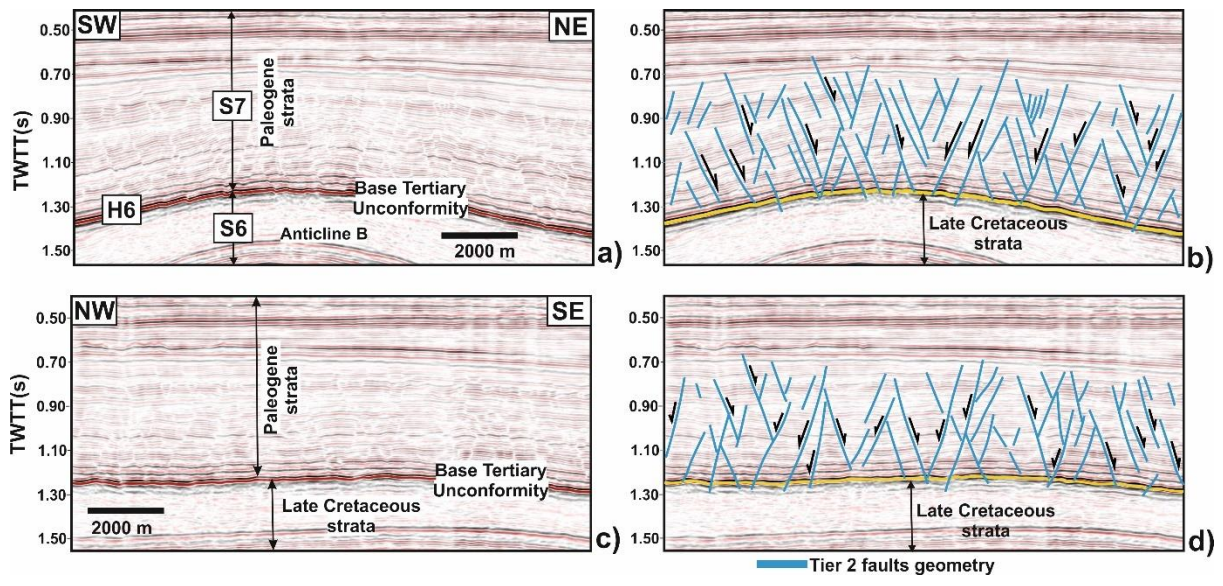


Fig. 9

Map view of Upper Mesozoic (Tier 1) faults

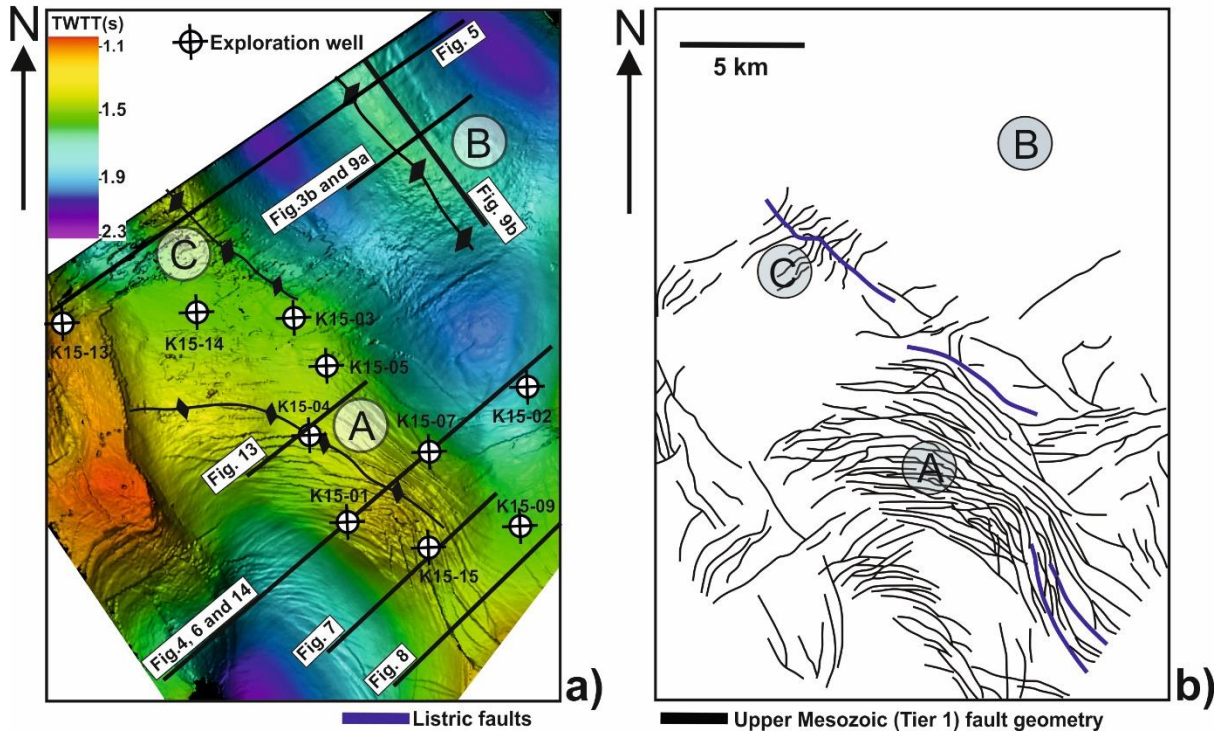


Fig. 10

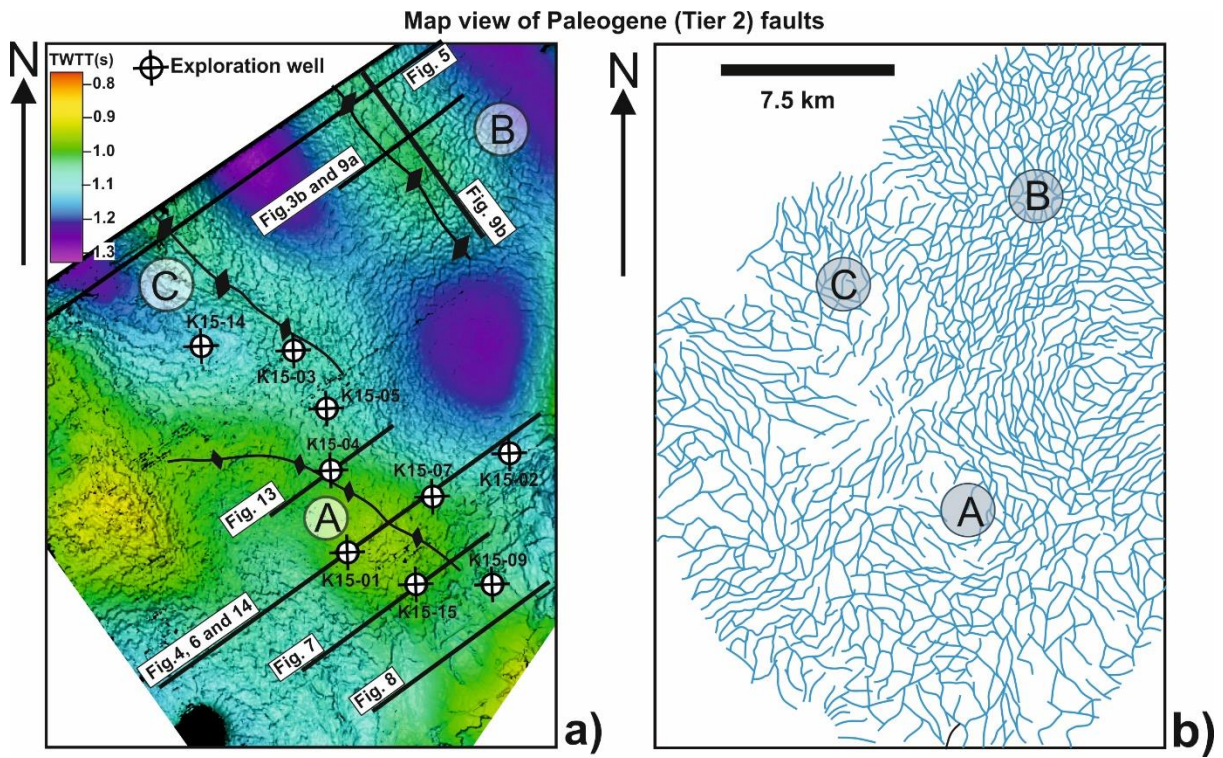


Fig. 11

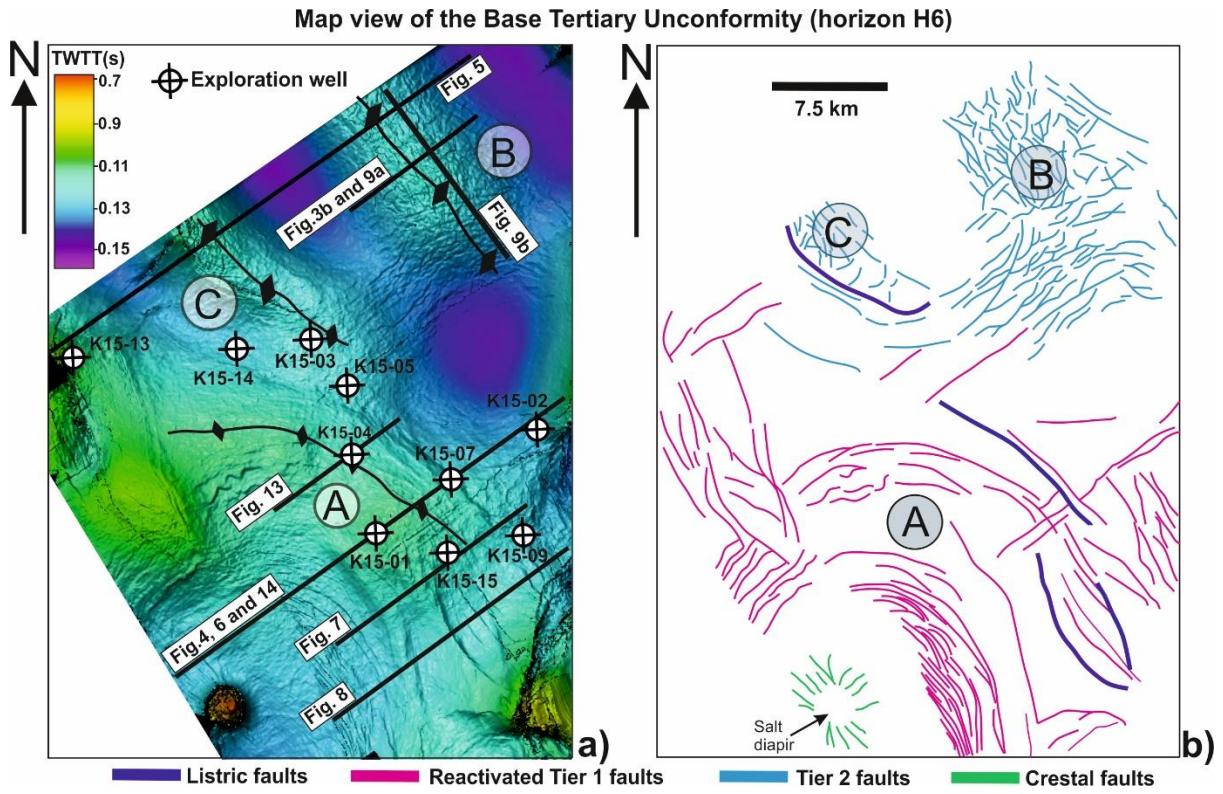


Fig. 12

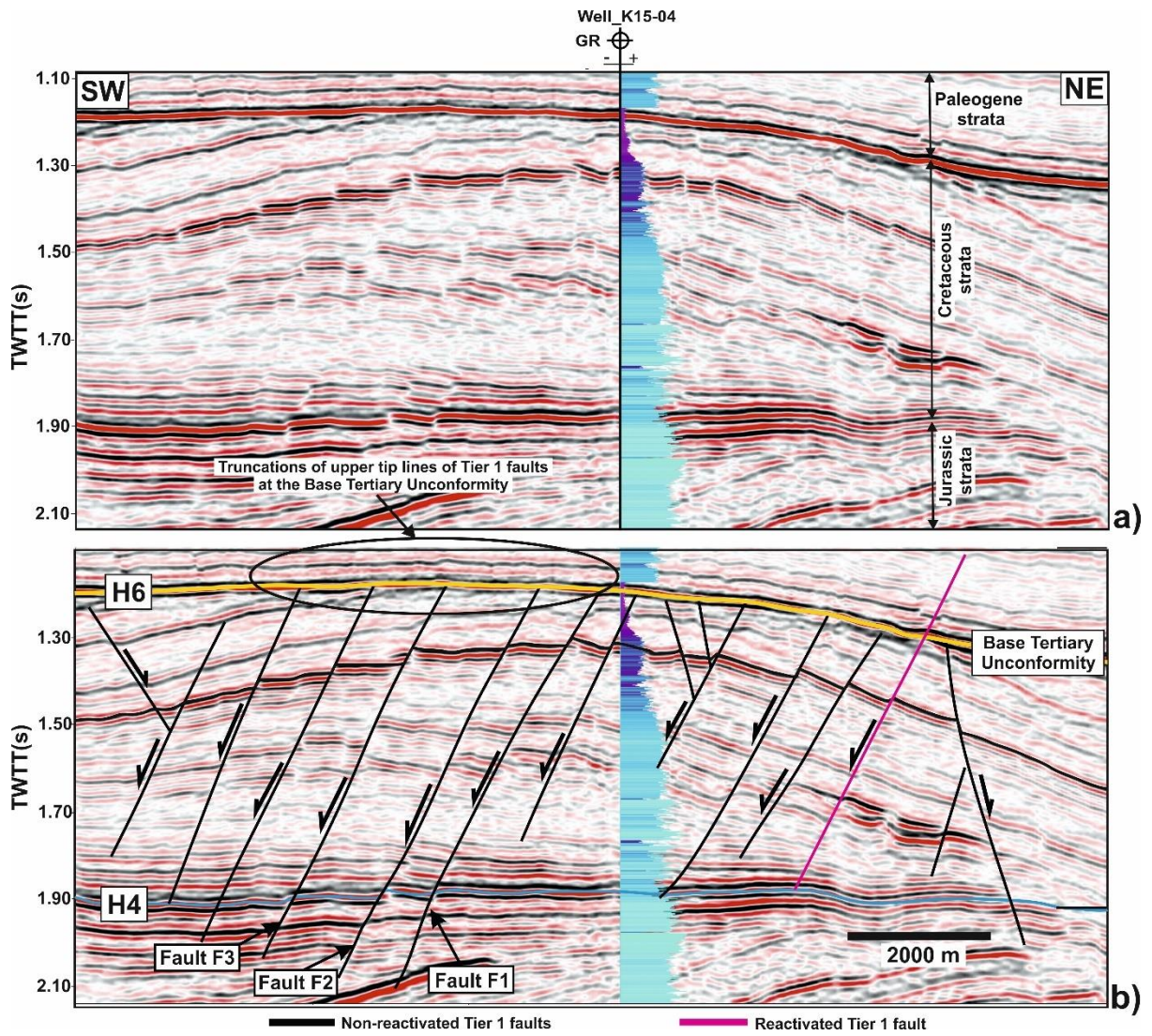


Fig. 13

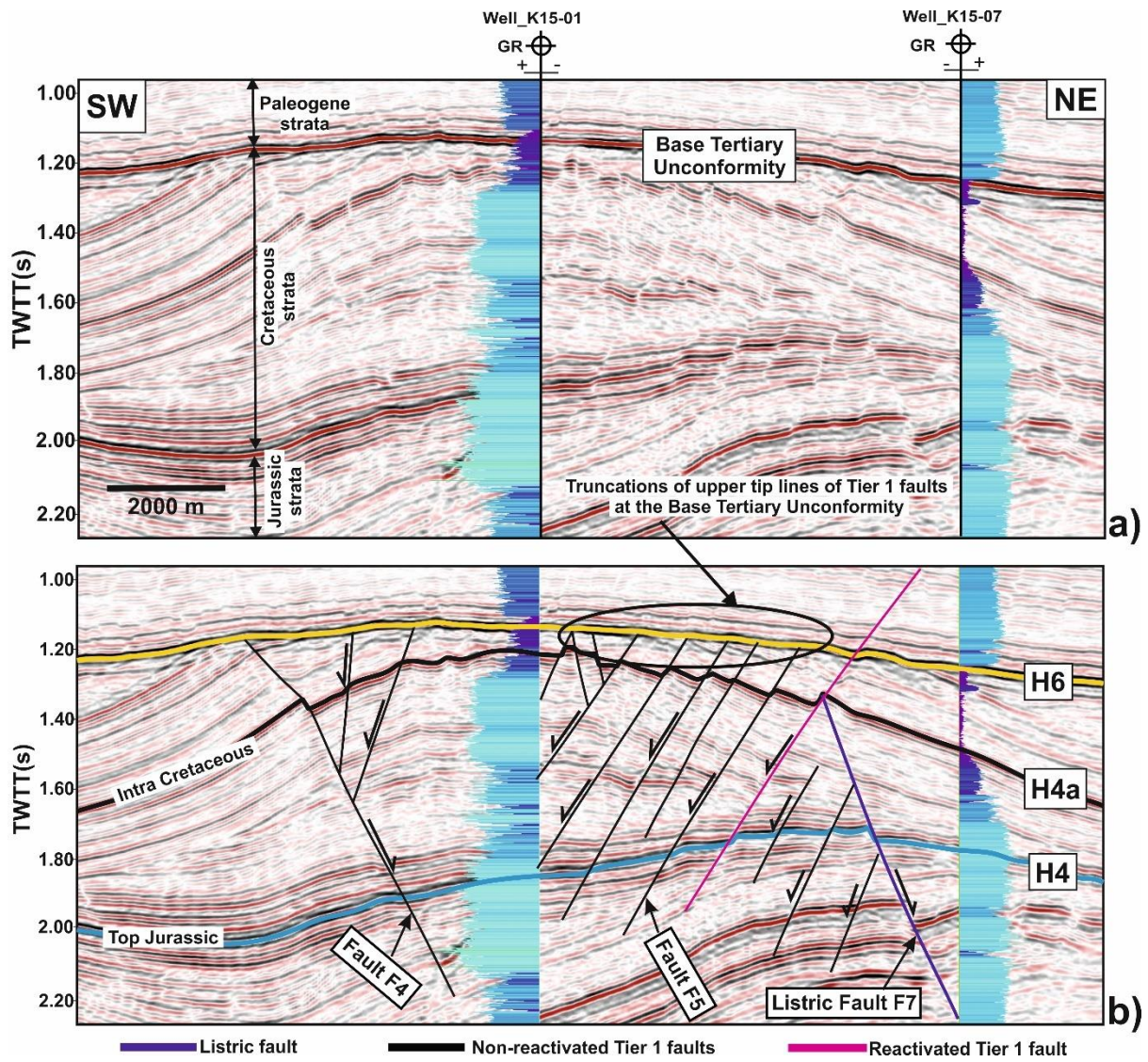


Fig. 14

Correlation panel amongst fault throw distribution, lithology, and growth history for fault F1

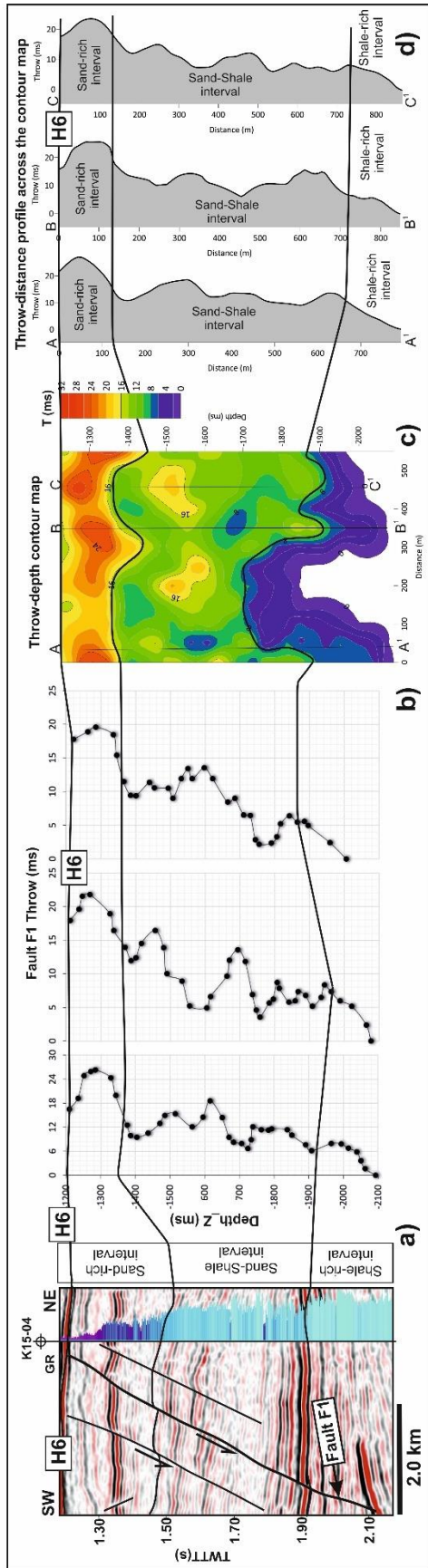


Fig. 15

Correlation panel amongst fault throw distribution, lithology, and growth history for fault F2

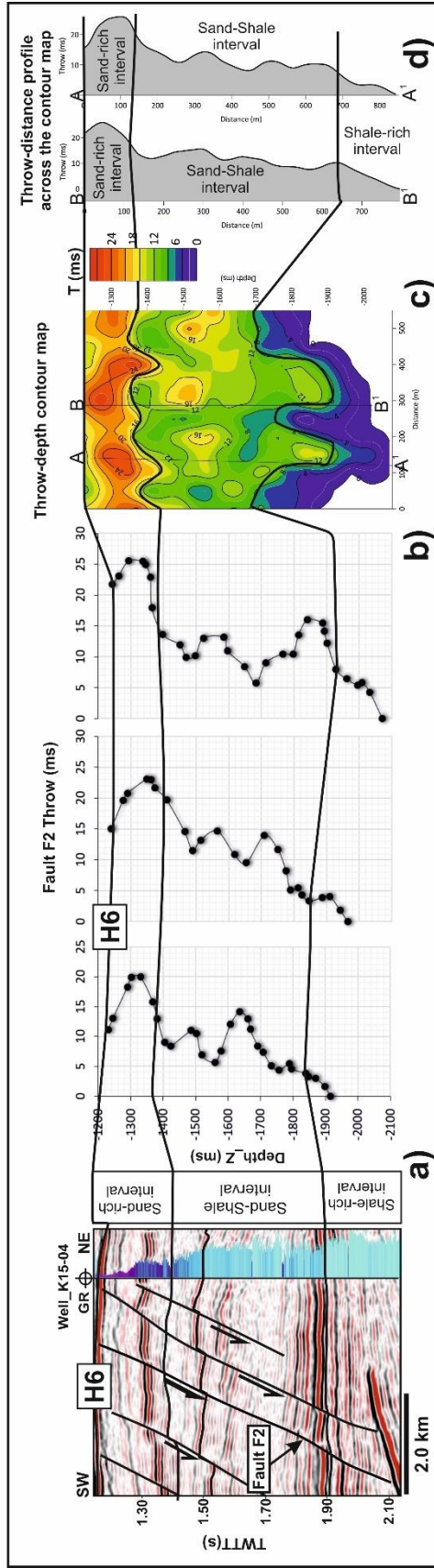


Fig. 16

Correlation panel amongst fault throw distribution, lithology, and growth history for fault F3

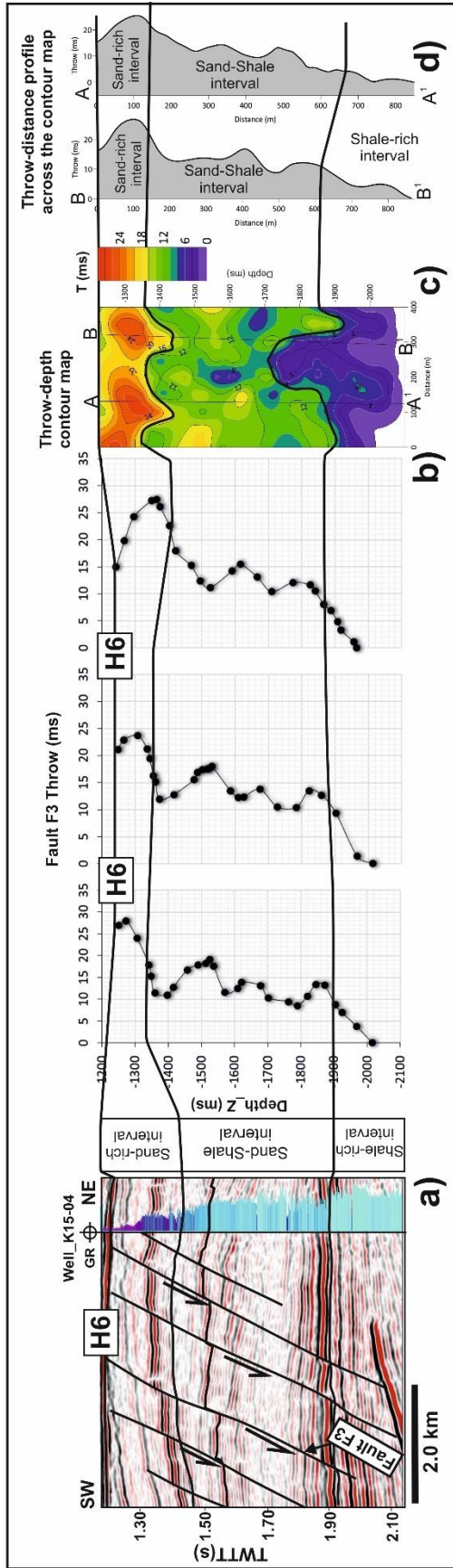


Fig. 17

Correlation panel amongst fault throw distribution, lithology, and growth history for fault F4

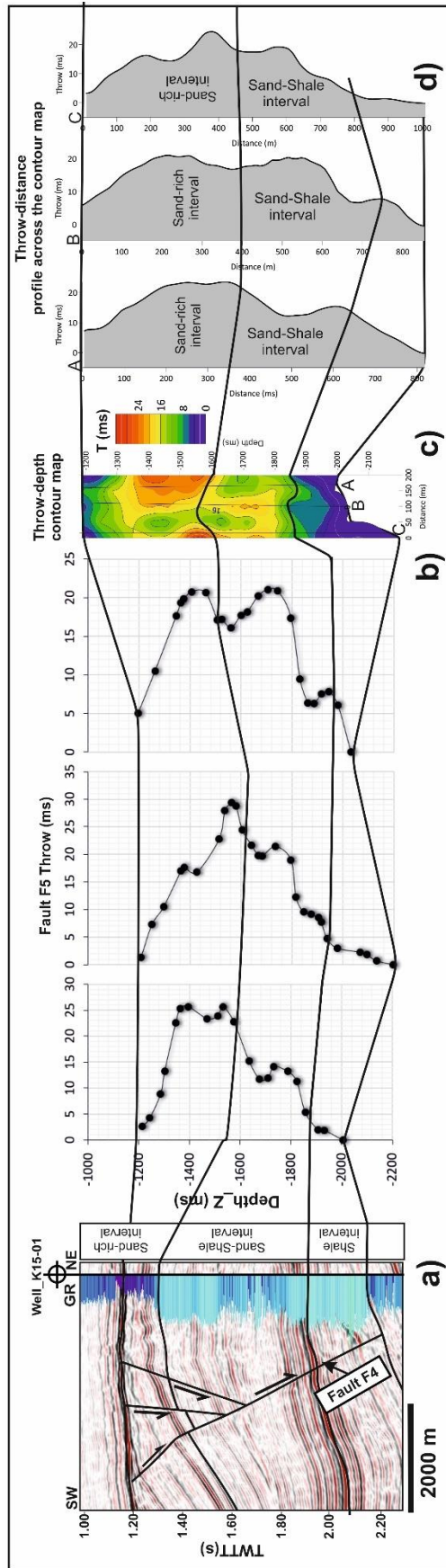


Fig. 18

Correlation panel amongst fault throw distribution, lithology, and growth history for fault F5

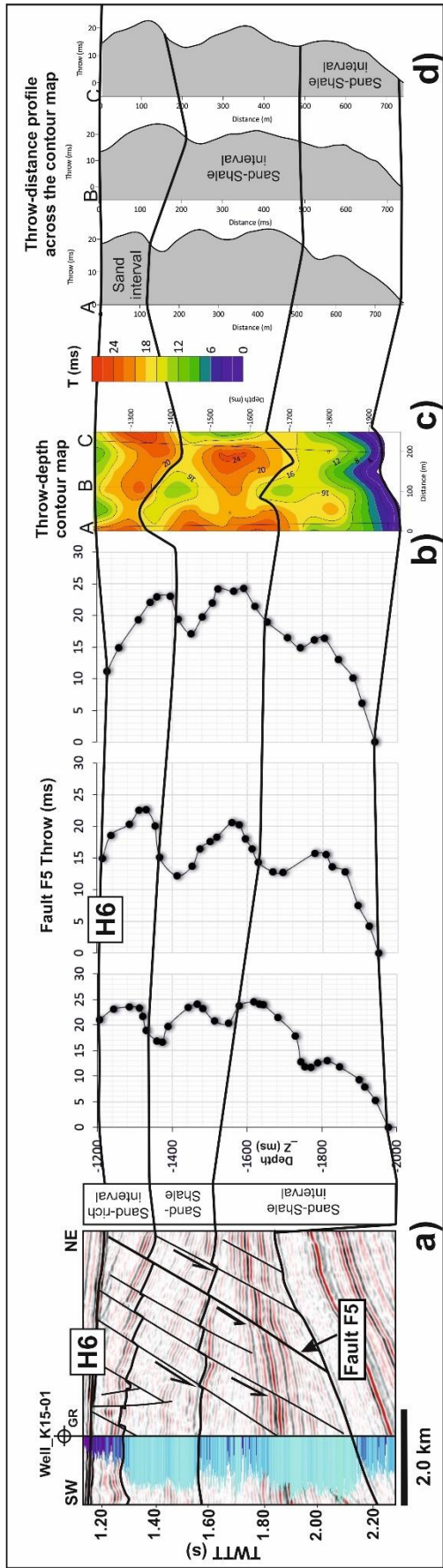


Fig. 19

Correlation panel amongst fault throw distribution, lithology, and growth history for fault F6

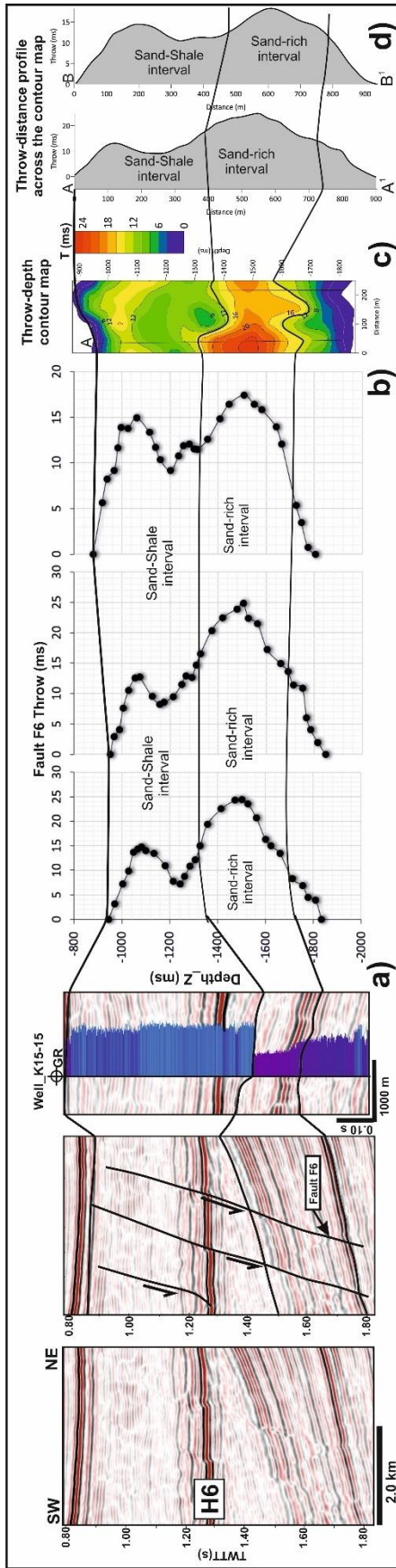


Fig. 20

Reactivation and growth history of listric fault F7

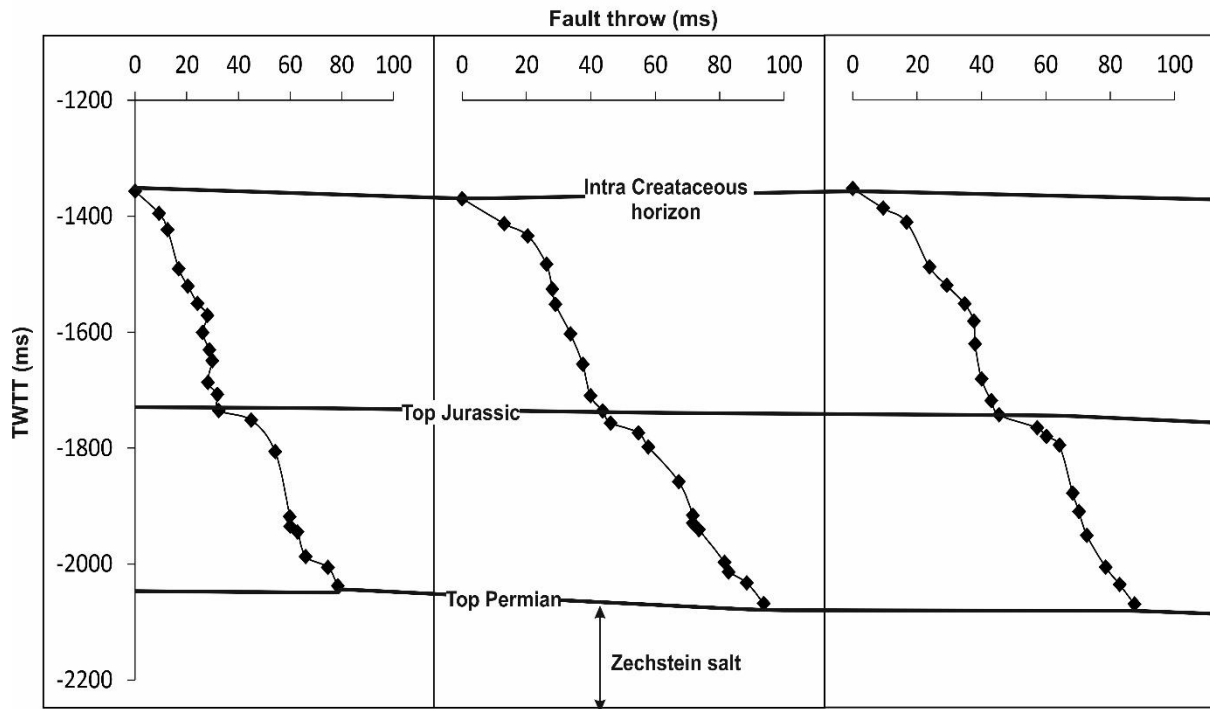
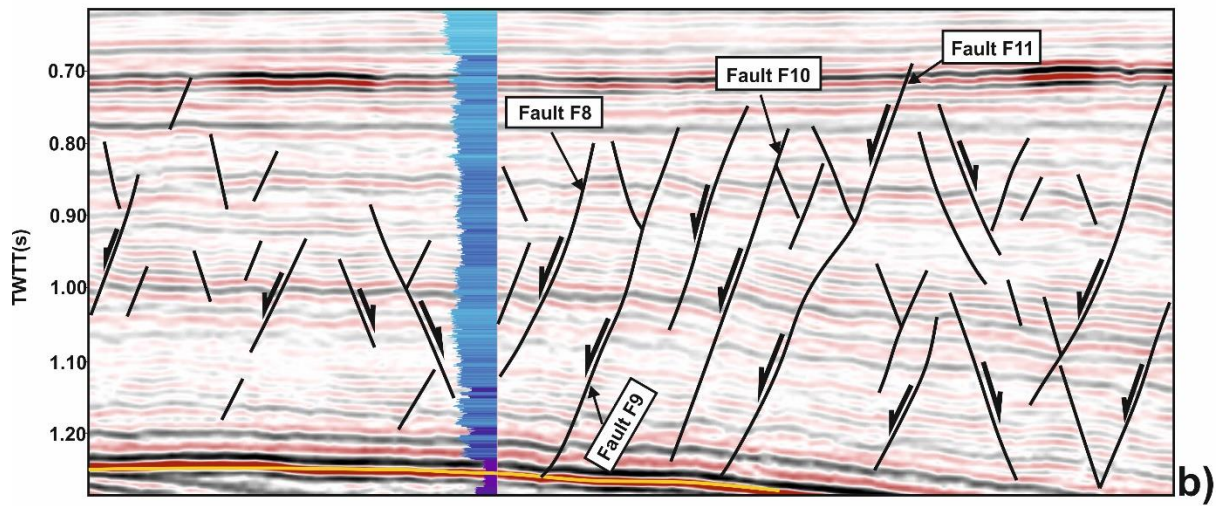
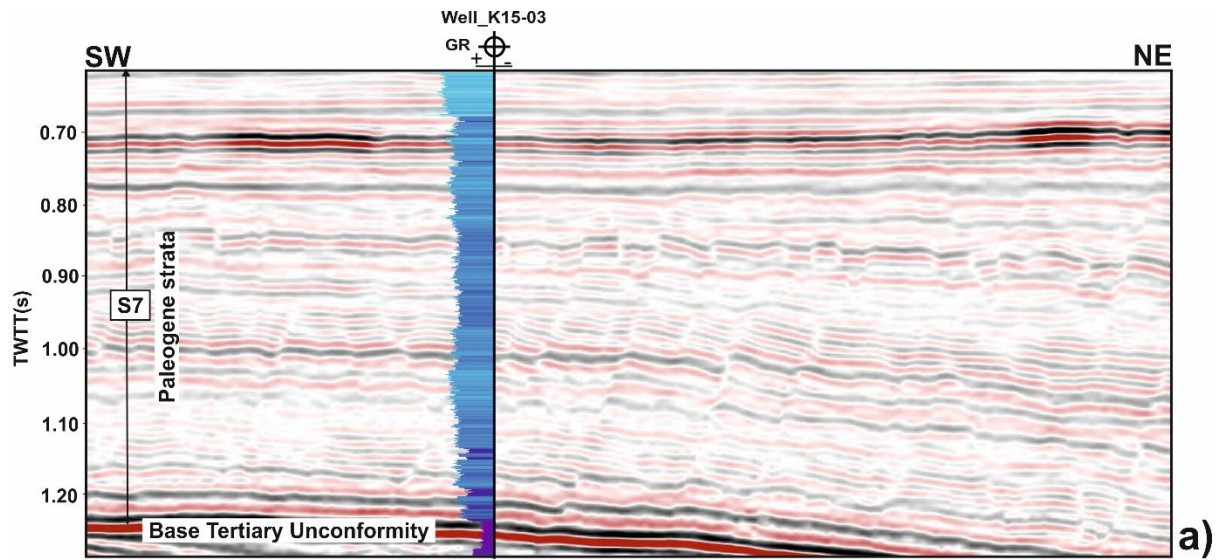


Fig. 21



Reactivation and growth history of Paleogene Tier 2 faults

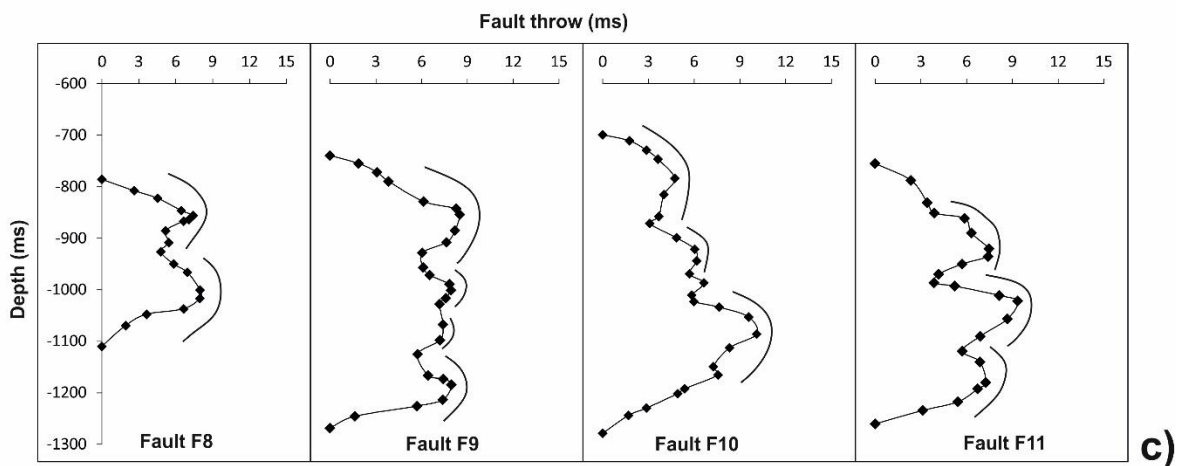


Fig. 22

Relative age of Tier 1 and Tier 2 faults

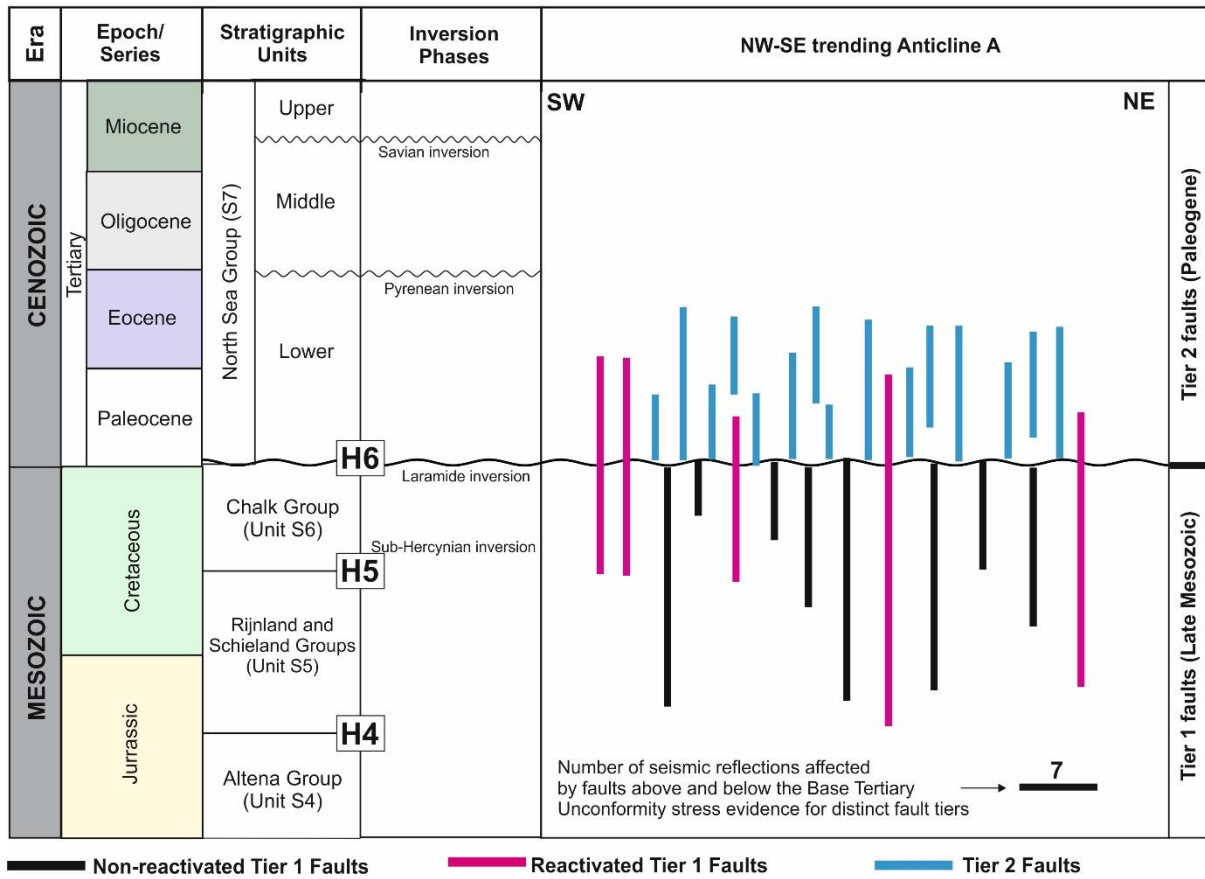


Fig. 23

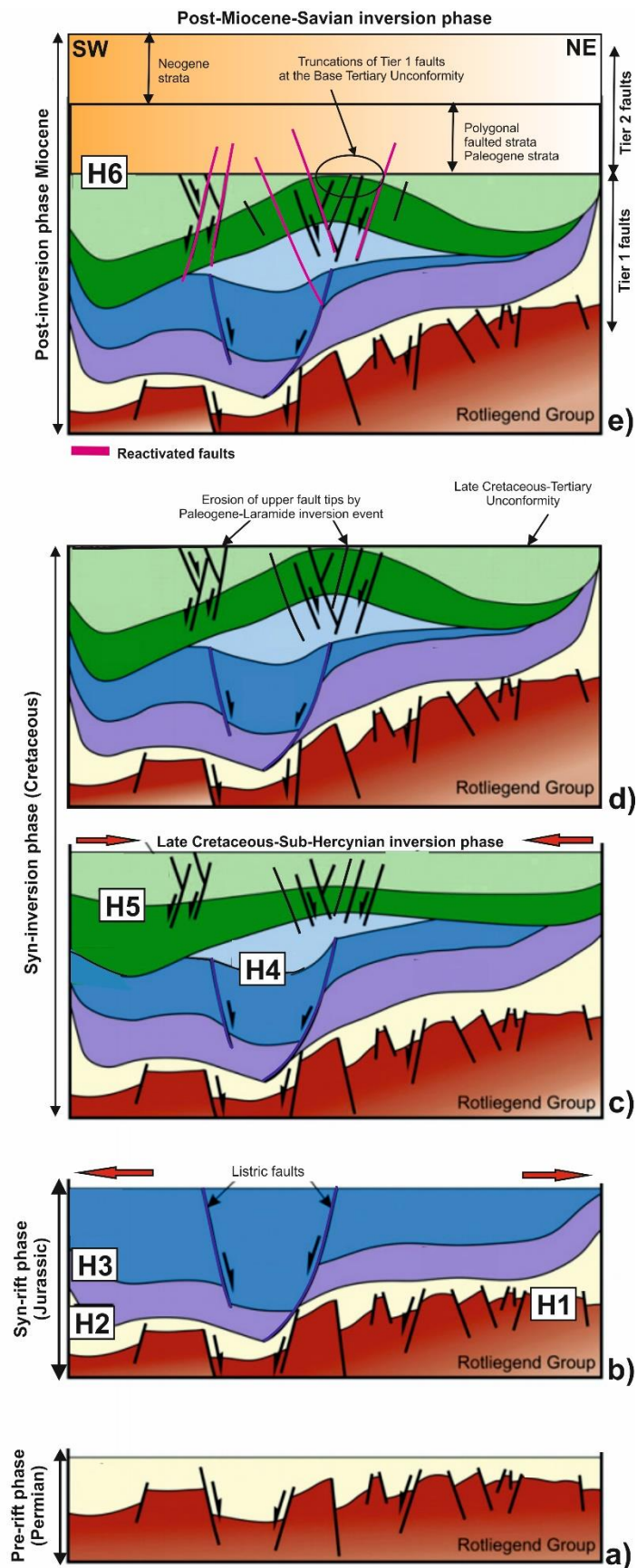
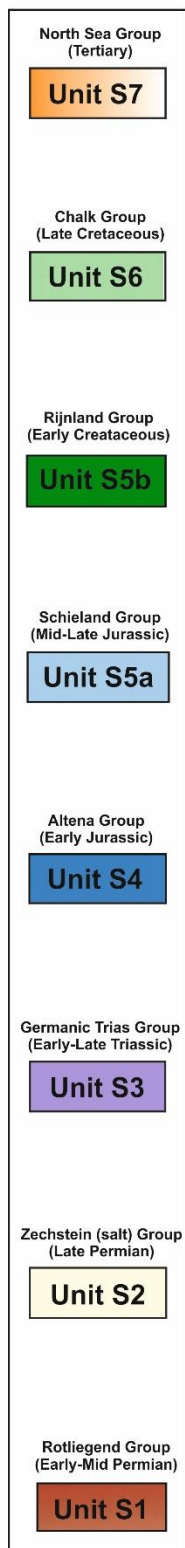


Fig. 24

Table 1: Summary of principal features in the seismostratigraphic units of the Broad Fourteens Basin, Southern North Sea.

Seismic units	Stratigraphic Groups	Age of seismic units	Estimated Thickness (m)	Internal character of seismic units	Dominant lithologies (van Verweij and Simmelink, 2002)
Unit S7	North Sea Group	Paleocene to Recent	1,201	Characterised by a package of high-frequency, continuous and moderate to high-amplitude seismic reflections. Deformed by closely spaced polygonal normal faults.	Clays, sandstones, silts, locally gravel or peat, and brown coal seams.
Unit S6	Chalk Group	Late Cretaceous	684	Low amplitude and chaotic internal reflections. Erosion during the Laramide inversion event created a prominent Cretaceous-Tertiary boundary at the top of Chalk Group (H6). This boundary generated a strong, regionally mappable seismic reflector.	Limestones, marls, calcareous claystones and glauconitic sands
Unit S5	Rijnland and Schieland Groups	Late Jurassic to Early Cretaceous	505	Forms a package of high-amplitude, high-frequency seismic reflections. Deformed locally by closely spaced normal faults around the hinge region of Anticline A.	Carbonaceous claystones, marls and thick-bedded sandstones
Unit S4	Altena Group	Late Triassic to Middle Jurassic	259	Forms a package of high frequency, continuous and moderate to high-amplitude seismic reflections.	Argillaceous deposits, calcareous and clastic sediments. Bituminous Posidonia Shale Formation comprise the source interval for Jurassic oil plays
Unit S3	Germanic Trias Group	Early to Late Triassic	335	Forms a package with moderate frequency and moderate to high-amplitude seismic reflections. On seismic profiles, the bright reflection at the base of Germanic Trias Group (Unit S3) indicates a change from the high-velocity Zechstein salt (Unit S2) to the relatively low-velocity aeolian sandstones and lacustrine claystones of the Lower Germanic Trias Group.	Marine carbonates, evaporites. aeolian sands and lacustrine claystones. Aeolian sands and lacustrine claystones of the Lower Germanic Trias Group (the Buntsandstein Formation) form a prolific gas reservoir in the study area, particularly where Zechstein salt (Unit S2) has been withdrawn and welds have formed between Triassic (Unit S3) and the Rotliegend Group (Unit S1).
Unit S2	Zechstein Group	Late Permian	668	Low amplitude, chaotic internal reflections. The bright reflection at the top (H2) indicates a change from high-velocity Zechstein salt to relatively low-velocity aeolian sandstones and lacustrine claystones.	Thick layers of salt separated by cyclic carbonate intervals. Some of which are fragmented and deformed ('Stringers')
Unit S1	Rotliegend and Limburg Groups	Early to Middle Permian	690	Forms a package of moderate frequency and moderate amplitude seismic reflections. The base of the unit is hard to identify because the overlying salt dims the internal reflections of Rotliegend strata.	Terrestrial coarse grained sandstones (e.g. Slochteren Formation) and finer grained desert lake deposits (e.g. Silverpit Formation). Thick lacustrine and deltaic intervals with interbedded coal seams were deposited as part of the Limburg Group. Westphalian Coal Measures.