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1 **Terrane boundary reactivation, barriers to lateral**

2 **fault propagation and reactivated fabrics - Rifting**

3 **across the Median Batholith Zone, Great South**

4 **Basin, New Zealand**

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8 **Key points**

- 9 • We document multiple styles of structural inheritance that influence various aspects of rift
10 physiography in the Great South Basin, New Zealand
- 11 • The southern boundary of the Median Batholith Zone terrane is reactivated as a large
12 extensional shear zone and detachment
- 13 • Faults splay, segment and eventually terminate as they approach stronger material associated
14 with a granitic laccolith.

15

16 **Abstract**

17 Prominent pre-existing structural heterogeneities within the lithosphere may localise or partition
18 deformation during tectonic events. The NE-trending Great South Basin, offshore New Zealand,
19 formed perpendicular to a series of underlying crustal terranes, including the dominantly granitic
20 Median Batholith Zone, which along with the boundaries between individual terranes, exert a strong
21 control on rift physiography and kinematics. We find that the crustal-to-lithospheric scale southern
22 terrane boundary of the Median Batholith Zone is associated with a crustal-scale shear zone that was
23 reactivated during Late Cretaceous extension between Zealandia and Australia. This reactivated
24 terrane boundary is oriented at a high-angle to the faults defining the Great South Basin. We identify a
25 large granitic laccolith along the southern margin of the Median Batholith, expressed as sub-
26 horizontal packages of reflectivity and acoustically transparent areas on seismic reflection data. The
27 presence of this strong granitic body inhibits the lateral south-westward propagation of NE-trending
28 faults, which segment into a series of splays that rotate to align along the margin as they approach.
29 Further, we also identify two E-W and NE-SW oriented basement fabrics, likely corresponding to
30 prominent foliations, which are exploited by small-scale faults across the basin. We show that
31 different mechanisms of structural inheritance are able to operate simultaneously, and somewhat
32 independently, within rift systems at different scales of observation. The presence of structural
33 heterogeneities across all scales need to be incorporated into our understanding of the structural
34 evolution of complex rift systems.

35

37 **1. Introduction**

38 Continental crust is highly heterogeneous. It is comprised of distinct crustal units, including island
39 arcs, exotic terranes and igneous plutons, the boundaries between which may represent pronounced
40 rheological and lithological contrasts, forming crustal-to-lithospheric scale structures. Individual
41 crustal units likely contain numerous pre-existing structural heterogeneities reflective of their own
42 unique histories prior to amalgamation into the continental crust as well as structures formed during
43 subsequent tectonic events (Howell 1980; McWilliams & Howell 1982; Bishop et al. 1985; Mortimer
44 2004; Lundmark et al. 2013; Peace et al. 2017; Johnston 2019). Accordingly, a range of pre-existing
45 heterogeneities are present throughout the crust across all scales, and may exert a considerable
46 influence over multiple aspects of rift physiography during continental extension.

47 Lithosphere-scale structures often localise strain, as indicated by tectonic events repeatedly localising
48 in highly deformed orogenic belts surrounding more stable cratonic continental interiors. These belts
49 may control the location of rift systems and, to some extent, continental breakup (e.g. Wilson 1966;
50 Ring 1994; Dore et al. 1997; Tommasi & Vauchez 2001; Thomas 2006; Paton et al. 2016; Wenker &
51 Beaumont 2016; Phillips et al. 2018; Thomas 2018; Heron et al. 2019). The distribution of different
52 crustal rheologies and their associated strength variations, such as between distinct crustal terranes or
53 between igneous batholiths and adjacent terranes, may inhibit fault nucleation and propagation in
54 some areas whilst promoting it in others (Critchley 1984; Koopmann et al. 2014; Magee et al. 2014;
55 Peace et al. 2017; Howell et al. 2019). Pre-existing structures in the crust may also localise
56 deformation and control the geometry and evolution of fault and rift systems (e.g. Daly et al. 1989;
57 Fossen et al. 2016; Mortimer et al. 2016; Phillips et al. 2016; Fazlikhani et al. 2017; Morley 2017;
58 Peace et al. 2017; Dawson et al. 2018; Rotevatn et al. 2018b; Vasconcelos et al. 2019). In addition,
59 pre-existing structures and fabrics at outcrop scale may be exploited by and control the geometry of
60 later faults and fractures (Morley et al. 2004; Paton & Underhill 2004; De Paola et al. 2005; Morley
61 2010; Chattopadhyay & Chakra 2013; Kirkpatrick et al. 2013; Duffy et al. 2015; Dichiarante et al.

62 2016; Mortimer et al. 2016; Phillips et al. 2017). Equally, pre-existing structures do not always
63 influence rift physiography; some may remain passive during subsequent tectonic events, whilst
64 certain structures may only be selectively reactivated (e.g. Roberts & Holdsworth 1999; Reeve et al.
65 2013). Numerous examples of interactions between pre-existing structures and rift-related faults have
66 been documented in rift systems worldwide; however, we often lack an in-depth understanding of the
67 mechanics of these interactions, as well as how different scales of pre-existing structure may influence
68 different aspects of rift geometry and development.

69 In this study, we focus on the Great South Basin, a NE-trending rift system located offshore of the
70 South Island of New Zealand. Basement beneath the basin comprises a series of volcano-sedimentary
71 terranes, which accreted along the southern margin of Gondwana during protracted Cambrian-
72 Cretaceous subduction (Mortimer et al. 1999; Tulloch et al. 1999; Mortimer 2004, 2014; Robertson et
73 al. 2019; Robertson & Palamakumbura 2019; Tulloch et al. 2019). These terranes are separated by W-
74 to WNW-trending crustal-to-lithospheric scale boundaries that are oriented perpendicular to the
75 overlying basin (Muir et al. 2000; Mortimer et al. 2002). The presence of prominent terrane
76 boundaries, strength variations between different terranes and various heterogeneities within
77 individual terranes, make this the ideal location to analyse multiple structural heterogeneities and their
78 interactions with rift-related faults, across a range of spatial scales. We focus on the evolution of the
79 basin atop the Median Batholith Zone, a Carboniferous-Early Cretaceous Cordilleran-style magmatic
80 arc, and its boundaries with the Western Province terranes to the south and the Brook Street and
81 Murihiku Terranes to the north (Figure 1) (Bishop et al. 1985; Tulloch et al. 1999; Mortimer et al.
82 2002; Jongens 2006; Tulloch et al. 2019).

83 Using borehole-constrained 2D and 3D seismic reflection data, we document multiple structural
84 heterogeneities beneath the Great South Basin, and determine how they influence rift physiography
85 and kinematics. . The styles of structural inheritance established in this study and their associated
86 characteristic fault geometries; may be indicative of similar styles of structural inheritance present in
87 other rift systems worldwide.

90 **2. Regional geological setting and evolution**

91 The Great South Basin is a NE-trending Late Cretaceous rift basin located offshore of the east coast of
92 the South Island of New Zealand. It contains a maximum sedimentary thickness of 8.6 km, which
93 includes up to 4 km of Upper Cretaceous strata (Beggs 1993; Sahoo et al. 2014; Morley et al. 2017)
94 (Figure 1, 3). The Great South Basin, along with the adjacent Canterbury Basin and Bounty Trough, is
95 situated within the Campbell Plateau, a submerged (<1000 m water depth) area of thinned continental
96 crust (22-32 km) that extends ~1000 km southeast of the South Island (Figure 1) (Beggs 1993;
97 Mortimer et al. 2002; Grobys et al. 2009; Uruski 2010; Higgs et al. 2019). Here, we focus on a 21,000
98 km² area covering the southern part of the Great South Basin, located to the southeast of Stewart
99 Island (Figure 1).

100 The basement geology of New Zealand comprises a series of crustal to lithospheric terranes that
101 accreted to the southern margin of Gondwana during protracted subduction from the Cambrian-Early
102 Cretaceous (e.g. Bishop et al. 1985; Bradshaw 1989; Muir et al. 2000; Mortimer 2014; Mortimer et al.
103 2014). Subduction ceased during the Early Cretaceous (~105 Ma) as the buoyant Hikurangi Plateau
104 collided along the margin (Davy et al. 2008; Uruski 2015). Since the Cenozoic, these terranes have
105 been offset along the Alpine Fault, a major plate boundary and strike-slip fault located along the spine
106 of the South Island that has accommodated >450 km, and potentially >700 km, offset (Wellman 1953;
107 Cooper et al. 1987; Sutherland et al. 2000; Lamb et al. 2016). Due to this offset, the basement terranes
108 of the South Island are also present beneath the North Island (Figure 1) (Muir et al. 2000; Mortimer et
109 al. 2002; Collanega et al. 2018). The basement terranes, which together comprise the Austral
110 Superprovince, are divided into Eastern and Western provinces separated by the Median Batholith
111 Zone (Mortimer et al. 2014). The timing of accretion along the Gondwana margin becomes younger
112 eastwards, with those terranes of the Western Province terranes accreting to the margin of Gondwana
113 earlier than those in the Eastern Province and occupying a more proximal position with respect to the
114 continental interior. Here, we focus on terranes that underlie the Great South Basin; i.e. the Western

115 Province Terranes, the Median Batholith Zone and the Brook Street and Murihiku terranes of the
116 Eastern Province (Figure 1).

117 The Western Province comprises the Buller and Takaka terranes, dominantly (meta)-sedimentary
118 Gondwana-derived continental fragments that accreted along the margin during the Cambrian-
119 Devonian (Bradshaw 1989; Mortimer 2004; Bache et al. 2014; Tulloch et al. 2019). The Eastern
120 Province terranes largely originated within the Panthalassa Ocean as a series of volcanic and
121 magmatic arcs and associated sedimentary basins (Bishop et al. 1985; Mortimer et al. 1997; Mortimer
122 et al. 2002; Mortimer 2004). The Brook Street terrane is immediately north of the Median Batholith
123 and comprises a Permian volcanic and volcanioclastic sequence that initially formed as an intra-oceanic
124 arc (Landis et al. 1999; Mortimer 2004). Further north, the Murihiku terrane is composed of gently
125 folded Jurassic-aged sandstones and volcanioclastic rocks that were initially part of a forearc
126 sedimentary basin (Campbell et al. 2003; Mortimer 2004). Between the Western and Eastern Province
127 terranes is the Median Batholith Zone, a Cordilleran-style magmatic arc that represented the site of
128 subduction-related magmatism from 375-110 Ma (Mortimer et al. 1999; Mortimer 2004). Although
129 previously interpreted as a highly tectonised allochthonous zone, recent studies have demonstrated that
130 the majority of plutonic material is autochthonous, with only relatively minor reworking and
131 tectonism identified, and is therefore referred to as the Median Batholith Zone in this study (Mortimer
132 et al. 1999). The Median Batholith Zone comprises numerous plutonic intrusions that can be divided
133 into various suites based on the age of emplacement and composition (Tulloch 1988; Allibone &
134 Tulloch 2004). Based on well information and onshore exposures at Stewart Island, an overall
135 southwards younging trend occurs across the batholith, with the Cretaceous-aged Separation Point
136 Batholith suite located along the southern margin and older batholith suites further north (Mortimer et
137 al. 1999; Muir et al. 2000; Allibone & Tulloch 2004; Tulloch et al. 2019).

138 The Great South Basin formed via two phases of Late Cretaceous extension related to the breakup of
139 Gondwana. Extensional activity may have begun in the Jurassic-Early Cretaceous in a back-arc
140 setting along the southern margin of Gondwana, with Jurassic strata identified in the deepwater
141 Taranaki Basin and potentially in the Great South Basin (Grobys et al. 2007; Uruski et al. 2007;

142 Uruski 2010). Initial NE-SW oriented extension occurred between Australia and the contiguous
143 Zealandia and Western Antarctica at ~101-89 Ma related to the opening of the Tasman Sea and the
144 northwards propagation of the Tasman ridge (Kula et al. 2007; Kula et al. 2009; Sahoo et al. 2014;
145 Tulloch et al. 2019). A second rift phase, related to the breakup of Zealandia and Western Antarctica
146 and associated with the eventual formation of the Pacific-Antarctic ridge, occurred from 90-80 Ma
147 (Kula et al. 2007; Tulloch et al. 2019). The regional extension direction was oriented NW-SE, roughly
148 parallel to the underlying basement terrane boundaries, and resulted in the formation of the NE-
149 trending Great South Basin (Figure 1). Late Cretaceous extension, forming the Great South and
150 Canterbury basins and the Bounty Trough reduced crustal thickness to 22-32 km across the area
151 (Mortimer et al. 2002). In the Great South Basin, faults related to this activity have been proposed to
152 sole out onto a mid-crustal detachment (Uruski et al. 2007; Sahoo et al. 2014).

153 The onset of subduction in the Tonga-Kermadec region in the Oligo-Miocene and the formation of the
154 Alpine Fault resulted in a regional compressional regime across New Zealand (Cooper et al. 1987;
155 Sutherland et al. 2000; Sutherland et al. 2010; Bache et al. 2012). The Great South Basin was
156 relatively far-removed from the compressional stresses associated with the formation of this new plate
157 boundary, with regional compression expressed as low-amplitude, long wavelength folding (Uruski
158 2010).

159

160 **3. Data and Methods**

161 **3.1 Seismic interpretation**

162 We use borehole-constrained 2D and 3D seismic reflection data, covering an area of 21,000 km²
163 offshore of the South Island of New Zealand. A 3D seismic reflection volume (GSB-3D) was acquired
164 in the south of this area and covers ~1,400 km² (Figure 1). Seismic reflection data follow the SEG
165 normal polarity convention; that is, a downwards increase in acoustic impedance (i.e. the seabed) is
166 represented by a peak, whereas a downwards decrease in acoustic impedance is represented by a

167 trough (see seabed inset in Figure 2b). 2D seismic reflection data record to 6-8 s TWT and display
168 variable image quality between individual surveys. Typical spacing between individual 2D seismic
169 sections outside of the 3D volume is ~3 km, although this increases to ~9 km south of the 3D volume.
170 The 3D seismic volume records to 8 s TWT and displays excellent image quality throughout. Using a
171 velocity of ~2800 m/s (based on interval velocities derived from the Pukaki-1 well) and a frequency
172 of 20 Hz, we calculate a vertical resolution (wavelength (λ)/4) of ~35 m across the 3D volume within
173 the Cretaceous interval. This represents roughly a minimum vertical resolution within this interval.

174 We mapped a series of prominent seismic reflections throughout the dataset and linked them to the
175 regional stratigraphy (Figure 2). The ages of regional stratigraphic horizons were constrained by the
176 nearby Pukaki-1, Pakaha-1, Tara-1, Toroa-1 and Rakiura-1 boreholes (Figure 1). A seismic-well tie
177 was performed on the Pukaki-1 well to link the seismic interpretations to the well data (Figure 2). Top
178 Acoustic Basement and intra-Upper Cretaceous horizons form the main surfaces referred to
179 throughout this study, as they were the most affected by rift activity (Figure 2). Top Acoustic
180 Basement typically represents top crystalline basement across the area (Figure 1), although in some
181 instances coherent reflectivity suggestive of sedimentary layering is observed beneath this surface,
182 potentially related to earlier, likely Jurassic, rifting (Uruski et al. 2007) (Figure 3). The intra-Upper
183 Cretaceous horizon was interpreted throughout the 3D seismic volume and across the main basin
184 depocentre to map syn-rift fault geometries in more detail (Figure 1, 3). Seismic interpretations were
185 carried out, and are presented, in the time domain (seconds Two-way-travel time; s TWT). Key
186 structural measurements were converted to the depth domain based on regional checkshot information
187 (see supplementary material for checkshot data).

188 Crystalline basement in the area is mostly associated with the underlying Median Batholith (Figure 1).
189 Based on U-Pb zircon ages, the Pakaha-1 well penetrates a Carboniferous granitic basement (323 Ma)
190 (Tulloch et al. 2019), and the Pukaki-1 well penetrates a Cretaceous-aged granitic basement to the
191 southeast (Figure 1). The Pukaki-1 granite is dated at 107 Ma and can be confidently correlated with
192 the Separation Point Batholith suite (Tulloch et al. 2009; Tulloch et al. 2019). The Separation Point
193 Batholith suite is also identified in the same structural setting, to the south of the Median Batholith

194 Zone, along its boundary with the Western Province terranes, in the North Island (Muir et al. 2000),
195 suggesting it occupies a similar structural setting along the length of the batholith.

196 **3.2 Quantitative fault analysis**

197 We performed quantitative analyses, in the form of throw-length plots, on a series of faults within the
198 basin to quantify their geometric and kinematic evolution. The geometry of each fault analysed,
199 including horizon cutoffs and any tip lines were carefully constrained throughout the data to minimise
200 any interpretation-related artefacts (Walsh et al. 2003; Duffy et al. 2015). We measure fault throw as
201 opposed to displacement to avoid errors associated with depth conversion during the measurement of
202 displacement. Based on our fault interpretations we calculated throw-length plots for individual fault
203 segments at both the Acoustic Basement and intra-Upper Cretaceous stratigraphic horizons. To
204 accurately constrain the kinematic evolution of a fault we need to record all fault slip-related strain,
205 including both brittle faulting and ductile folding such as that associated with fault propagation
206 folding. Therefore, where necessary, horizon cut-offs were projected to the fault plane from an area
207 unaffected by local fault parallel folding (e.g. Walsh et al. 1996; Long & Imber 2012; Whipp et al.
208 2014; Duffy et al. 2015; Coleman et al. 2018). Throw measurements were taken for each fault along a
209 series of parallel seismic sections within the 3D volume, oriented orthogonal to the main fault trend
210 and each separated by ~340 m. Analyses of individual faults were then projected onto a single plane
211 representing a strike projection of the overall fault system. This allowed us to calculate the cumulative
212 throw accrued across the fault system and to analyse how strain was accommodated along its length.

213

214 **4. Rift physiography and basement structure**

215 **4.1 Regional rift geometry**

216 The Great South Basin is characterised by NE-trending, predominantly SE-dipping faults. NW-
217 dipping faults are also present and help define a series of NE-trending basement ridges in the east of

218 the area (Figure 1). The centre of the basin reaches 3-4 s TWT (~4.5 km) depth and shallows
219 eastwards onto the continental shelf (~1.5 s TWT, ~1.3 km) (Figure 1, 3). The basin deepens to
220 around 5 s TWT (~9 km) in the north and the south (Figure 1).

221 Upper Cretaceous strata display divergent wedges and thicken towards the hanging walls of major
222 NE-trending faults (Figure 3), indicating Late Cretaceous fault activity. We also recognise a
223 potentially earlier phase of activity, with apparent syn-rift strata present below the acoustic basement
224 surface in the hangingwalls of some structures (Figure 3). Although we are unable to assign an age to
225 these strata, we suggest that, based on regional considerations, they are likely Late Jurassic-
226 Cretaceous in age (Uruski et al. 2007; Uruski 2010). Palaeocene to recent strata comprise the post-rift
227 basin fill and display a slight westwards thickening related to increased sediment input and clinoform
228 progradation from the mainland (Figure 3). This large clinoform sequence forms a major bathymetric
229 escarpment to the west (Figure 3). E-dipping faults along the western margin of the basin appear to
230 potentially merge at depth (Figure 3). In the east of the area, the Pakaha-1 well penetrates granitic
231 basement atop a ~10 km wide NE-trending horst termed the Pakaha Ridge (Figure 1, 3). Basement
232 beneath this ridge is highly reflective and appears to dip westwards. A series of W-dipping faults
233 define the western margin of the Pakaha ridge and merge with the basement reflectivity at ~5-6 s
234 TWT (~10.5 km) (Figure 3). A ~65 km long, SSW-dipping fault is located in the south of the study
235 area (Figure 1). This fault is co-located along the along-strike projection of the boundary between the
236 Median Batholith and Western Province terranes (Figure 1), and is therefore termed the Terrane
237 Boundary Fault.

238

239 **4.2 Basement structures**

240 The Terrane Boundary Fault records >1 s TWT (>2 km) throw across the Acoustic Basement surface
241 (Figure 4, 5). This fault corresponds to a prominent reflection on seismic data, with a package of high-
242 amplitude fault-parallel reflections present in basement in its immediate footwall (Figure 4, 5). This
243 reflection package is truncated by the top Basement surface and extends to lower crustal depths (8 s

244 TWT; ~20 km) (Figure 4, 5). Individual reflections are remarkably continuous within the package,
245 continuing down-dip across depth intervals of >2.5 s TWT (Figure 4). The width of the reflection
246 package increases at shallower depths, from ~2 km wide at 6-7 s TWT (~15 km), to ~5 km wide at 2-
247 3 s TWT (~2.7 km) (Figure 4, 5). A reflection corresponding to the lower boundary of this package
248 can be traced to the top Acoustic Basement surface, where the package delineates a 5-7 km wide
249 subcrop at the top Acoustic Basement surface (Figure 4). A series of faults in the hanging wall of the
250 Terrane Boundary Fault merge with said fault downdip, defining a series of fault blocks, with those at
251 greater depths showing larger offset than those at shallow depths (Figure 4). The timing of activity
252 along these hanging wall faults appears to occur later updip along the Terrane Boundary Fault, with
253 deeper faults showing earlier activity than those at shallow depths (Figure 4). High amplitude
254 reflections are present in the sedimentary sequence in the hangingwall of the Terrane Boundary Fault,
255 and are likely related to coal intervals within the Upper Cretaceous Hoiho Group (Figure 4) (Killops
256 et al. 1997).

257 In addition to the fault-parallel reflection package associated with the Terrane Boundary Fault, we
258 observe further high-amplitude basement reflectivity at mid-crustal depths (4-6 s TWT; 6-12 km) in
259 the footwall of the Terrane Boundary Fault, corresponding to Median Batholith Zone basement
260 (Figure 4, 5). These reflection packages are typically sub-horizontal, although they dip slightly
261 northwards further to the north. The reflection packages define areas of high- and low-reflectivity
262 within crystalline basement. In the west, beneath the basin margin, the reflection packages extend
263 from 3-6 s TWT (3.5-12.5 km) and reach close to the top basement surface (Figure 4). Beneath the
264 basin further to the east, the packages do not extend to as shallow depths and are present from 5-7 s
265 TWT (9-16.5 km) (Figure 5).

266 Based on its geometry and seismic reflection character, we interpret the fault-parallel reflection
267 package in the footwall of the Terrane Boundary Fault as the seismic expression of a crustal-scale
268 shear zone (here termed the Terrane Boundary Shear Zone). The reflection package resembles the
269 characteristic seismic expression of shear zones, which arises through constructive interference
270 between highly strained mylonite zones and intervening relatively undeformed material (Jones & Nur

271 1984; Carreras 2001; Reeve et al. 2013; Rennie et al. 2013; Phillips et al. 2016). Elsewhere, similar
272 reflection packages have been confidently linked to onshore shear zones (Freeman et al. 1988; Wang
273 et al. 1989; Fossen & Hurich 2005; Bird et al. 2014; Phillips et al. 2016; Fazlkhani et al. 2017;
274 Lenhart et al. 2019) or those encountered in boreholes (Hedin et al. 2016).

275 We suggest the sub-horizontal reflection packages in the footwall of the Terrane Boundary Shear
276 Zone represent a series of stacked igneous laccoliths. Granitic rocks are abundant across the Median
277 Batholith Zone in this area (Mortimer et al. 1999; Tulloch et al. 2019), as indicated by granitic
278 basement penetrated nearby boreholes (Figure 2) and exposed onshore Stewart Island (Figure 1).
279 Basement penetrated by the Pukaki-1 well is correlated to the Separation Point Batholith Suite, which
280 occupies a similar location along the southern margin of the Median Batholith to the structures
281 interpreted here (Figure 5) (Allibone & Tulloch 2004; Tulloch et al. 2019). Similarly, the Pakaha-1
282 borehole penetrates granitic basement belonging to a Carboniferous-aged batholith suite (Figure 1)
283 (Tulloch et al. 2019).

284 In addition, the reflection patterns identified here, of stacked sub-horizontal packages of high- and
285 low-amplitude reflectivity, resemble those observed from the Lake District Batholith, where
286 prominent reflections are generated between stacked granite laccolith sheets (Figure 4) (Evans et al.
287 1993; Evans et al. 1994). The interpreted lenticular geometries of the reflection packages here are also
288 consistent with those expected from granitic laccoliths (McCaffrey & Petford 1997; Petford et al.
289 2000). Based on the regional distribution and dominantly granitic nature of basement rocks in this
290 area, we prefer an igneous origin for these packages of reflectivity rather than one related to
291 metamorphic basement lithologies (Lenhart et al. 2019). Although we have no direct constrains on the
292 lithology of these reflection packages, based on their geometry and seismic character, in conjunction
293 with the regional setting and nature of crystalline basement in this area, we interpret the reflection
294 packages to represent a series of stacked, likely granitic, laccoliths.

295 As well as the shear zone and granite-related reflectivity in the footwall of the Terrane Boundary
296 Fault, two seismic fabrics within basement are also pervasive throughout the area (Figure 4, 5). These
297 fabrics are characterised by widespread relatively linear reflections and are often truncated at a high

298 angle by the top Acoustic Basement surface. They fabrics often appear to display mutually cross-
299 cutting relationships in cross-section, and are often associated with low-displacement faults at the top
300 Acoustic Basement surface (Figure 4, 5).

301 **5 Detailed rift geometry – 3D seismic volume**

302 Two horizons mapped through the 3D seismic volume provide additional detail on fault geometries
303 and rift physiography in the footwall of the Terrane Boundary Fault (Figure 6).

304 A WNW-trending structural high is present in the immediate footwall of the Terrane Boundary Fault,
305 which we henceforth refer to as the Terrane Boundary Fault (TBF) Footwall Block (Figure 6a). The
306 Terrane Boundary Fault is not clearly expressed at the Intra-upper Cretaceous structural level;
307 although some minor, WNW-trending and SSW-dipping faults are present along the southern margin
308 of the TBF Footwall Block (Figure 6b). The TBF Footwall Block is underpinned by the interpreted
309 granitic laccoliths and may link with the Pakaha ridge to the east (Figure 1). Only a few, low-
310 displacement WNW- and NE-trending faults are present across the TBF Footwall Block (Figure 6a).

311 The northern margin of the TBF Footwall Block is largely parallel to the Terrane Boundary Fault,
312 whilst a series of embayments are present along its southern margin (Figure 6a, 7). These embayments
313 are 5-8 km wide, ~0.5 s TWT deep and incise about ~6 km back into the TBF Footwall Block (Figure
314 7).

315 A NE-trending fault is expressed at both the Acoustic Basement and intra-Upper Cretaceous surfaces
316 to the northeast of the area (Figure 6). This fault forms a single structure in the northeast that splay
317 into series of smaller segments to the southwest and is hereby referred to as the ‘Splaying Fault
318 System’. Individual segments of the Splaying Fault System dip southeast and northwest, resulting in
319 complex plan-view geometries across the Acoustic Basement and Intra-upper Cretaceous surfaces,
320 and often non-resolvable relationships at depth (Figure 3, 6). Some NE-striking, SE-dipping faults are
321 present in the southwest of the area, defining NE-trending structural highs superimposed onto the TBF
322 Footwall Block (Figure 6). Reflectivity associated with the Splaying Fault System cross-cuts

323 reflectivity in the footwall of the Terrane Boundary Fault, indicating that the Splaying Fault System
324 formed after the Terrane Boundary Shear Zone and granitic material (Figure 6, 7).

325 **5.1 Geometry and kinematics of the Splaying Fault System**

326 By measuring throw across individual fault segments within the Splaying Fault System at both the
327 Acoustic Basement and Intra-Upper Cretaceous structural levels, we are able to quantitatively analyse
328 how strain is accommodated along the fault system (Figure 8, 9). Individual fault segments are better
329 resolved across the Intra-Upper Cretaceous surface, meaning that they may provide a more complete
330 record of strain distribution along the fault system, although not all faults offset this surface (Figure
331 9b).

332 In the northeast of the area the Splaying Fault System is represented by a single fault (Figure 8a),
333 which accommodates ~800 ms (~1.8 km) and ~250 ms (~200 m) throw across the Acoustic Basement
334 and Intra-Upper Cretaceous surfaces respectively (Figure 9). Two throw minima are present along the
335 profile of this single fault plane (Fault 1), corresponding to bends in the fault trace formed by
336 breached relay ramps along the fault (Fault 1; Figure 9). Sub-horizontal layered reflectivity beneath
337 the Acoustic Basement surface in this area is interpreted as originating from sedimentary bedding,
338 with some cross-cutting reflections interpreted as faults (Figure 8a). Any pre-Acoustic Basement
339 strata is likely to be Jurassic to Early Cretaceous in age, potentially relating to earlier rift phases in
340 the basin's formation (Uruski et al. 2007; Uruski 2010).

341 To the southwest, the Splaying Fault System begins to segment into a series of SE- and NW-dipping
342 faults synthetic and antithetic to the main fault (Fault 1) respectively (Figure 6b, 8b). Fault
343 segmentation is initially accommodated by dissection of the footwall into four fault segments that
344 form a single plane at depth, and by the formation of antithetic hangingwall faults that appear to abut
345 against the main fault structure at depth (Figure 8b). Additional NW-dipping faults in the footwall dip
346 away from the main fault and further bisect the footwall (Figure 8b). This segmentation is
347 accompanied by a decrease in throw along the main fault, as extension is accommodated by smaller
348 fault segments in the footwall and hangingwall, with each segment accommodating 100-200 ms throw

349 (~200 m) at the Acoustic Basement surface (Figure 9a) and ~40 ms TWT at the Intra-Upper
350 Cretaceous (Figure 9b). A key observation is that as the fault begins to splay, the cumulative throw
351 across the whole system remains relatively constant. A slight minimum in the cumulative throw
352 profile is present at ~24 km at the Acoustic Basement structural level (Figure 9a). However, as such a
353 minimum is not observed at the Intra-Upper Cretaceous surface (Figure 9b), this may be related to a
354 lack of imaging of faults in this area rather than a property of the system itself.

355 As the fault begins to splays at the intra-Upper Cretaceous surface, a new fault (F2; Figure 9b) forms
356 in the hangingwall of Fault 1 and initially accommodates around ~150 ms (~200 m) throw compared
357 to 25-50 ms (~50 m) throw across Fault 1 in the same location. In the northeast, Fault 1 appears to
358 have been associated with a period of fault propagation folding prior to the brittle offset of the intra-
359 upper Cretaceous surface, which is incorporated into the throw measurements for Fault 1 (Figure 8a).
360 Therefore, when F2 forms in the hangingwall of Fault 1, the ductile deformation is incorporated into
361 the throw measurements of F2 rather than Fault 1, which is now located in the footwall of F2 (Figure
362 9b).

363 Further southwest along the Splaying Fault System the footwall becomes highly deformed by both
364 SE- and NW-dipping faults such that no dominant fault or overall hangingwall and footwall can be
365 identified (Figure 8c). Here, extension is accommodated by multiple fault segments across a ~15 km
366 wide zone (Figure 8c). Pre-acoustic basement sedimentary strata are again present in this area,
367 although no divergent stratal wedges are identified in the hangingwalls of fault segments, indicating a
368 lack of activity at that time (Figure 8c). Closer to the TBF Footwall Block the dominant fault appears
369 to switch polarity, with a NW-dipping fault cross-cutting the SE-dipping fault that is dominant along-
370 strike to the northeast (Figure 8d). Along the WNW-trending northern margin of the TBF Footwall
371 Block segments of the Splaying Fault System begin to rotate around vertical axes to a WNW-striking
372 orientation, dipping northeast, with horsetail splay geometries also identified across the Intra-Upper
373 Cretaceous surface in some locations (Figure 6b). The rotation of individual fault segments in this
374 area appears to be at least partially accommodated by their upwards splaying and bifurcation (Figure
375 8d). Individual fault segments tend to rotate and terminate along the northern margin of the TBF

376 Footwall Block, although some minor low-displacement faults (~20 ms TWT throw at the intra-Upper
377 Cretaceous surface; Figure 10) continue further southwest (Figure 6, 9).

378 A series of NW-dipping faults to the east of the Splaying Fault System merge into a package of
379 reflectivity at depth and join with an additional fault to the east that forms the border to a basement
380 ridge (Figure 6, 8d). The geometry and structural style of these faults resemble those along the
381 western border of the Pakaha ridge, where multiple faults root onto the margin of a granitic basement
382 ridge (Figure 3, 8d).

383

384 **6 Styles of structural inheritance**

385 Having described and interpreted multiple structural heterogeneities located beneath the study area,
386 we now document a number of different styles of interaction between these pre-existing structures and
387 the later-formed rift-related faults. We examine how these structures are expressed within the rift
388 system and how they influenced different aspects of the overall rift physiography.

389 **6.1 Terrane boundary reactivation**

390 The boundary between the Median Batholith and Western Province terranes in the study area is
391 characterised by a major crustal-scale shear zone and associated upper-crustal fault system, the
392 Terrane Boundary Shear Zone and Terrane Boundary Fault, as well as a series of granitic laccoliths
393 that underpin the TBF Footwall Block. Regional seismic data indicates that the boundaries between
394 individual terranes extend throughout the crust, and likely the lithosphere (Muir et al. 2000; Mortimer
395 et al. 2002).

396 In the study area, the boundary between the Western Province terranes and the Median Batholith
397 appears to have been exploited by the intrusion of the granitic laccoliths that underpin the TBF
398 Footwall Block. In the North Island, the boundary between Median Batholith and Western Province
399 terranes beneath the Taranaki Basin was exploited by the intrusion of Separation Point Batholith suite

400 (Muir et al. 2000; Collanega et al. 2018). This batholith suite is of similar affinity to the granitic
401 basement sampled by the Pukaki-1 well along-strike of the terrane boundary in this location (Tulloch
402 et al. 2019).

403 The Terrane Boundary Shear Zone localised along the margin of the granitic laccoliths, between the
404 Median Batholith Zone and the Western Province terranes. This shear zone was then reactivated,
405 forming the brittle Terrane Boundary Fault, during Late Cretaceous rifting associated with the
406 breakup of Gondwana (Kula et al. 2007). This fault is associated with a series of fault blocks in its
407 hangingwall and multiple embayments that incise into the footwall (Figure 4, 5, 7). Similarly in the
408 North Island, the boundary between the Median Batholith and Western Province terranes was also
409 reactivated, forming the Cape Egmont Fault Zone (Muir et al. 2000; Collanega et al. 2018).

410 The boundary between the Median Batholith and Western Province terranes in this area represents a
411 crustal-scale structure that has localised strain and been repeatedly exploited and reactivated
412 throughout its history. We suggest that differential stresses arising from the prominent rheological and
413 lithological contrasts between the dominantly plutonic Median Batholith, , and the dominantly
414 sedimentary Western Province terranes created a crustal-scale weakness that localised strain during
415 subsequent tectonic events, leading to the repeated reactivation of the terrane boundary.

416

417 **6.2 Strong crustal blocks as barriers to fault propagation**

418 The Splaying Fault System splays towards the southwest before individual segments rotate and
419 eventually terminate at the northern boundary of the TBF Footwall Block (Figure 6). As the fault
420 segments and throw across any individual fault segment decreases, the cumulative throw remains
421 relatively constant (Figure 9). A large throw gradient is present at the southwestern termination of the
422 Splaying Fault System at both Acoustic Basement and Intra-Upper Cretaceous structural levels, at the
423 northern margin of the TBF Footwall Block. Cumulative throw across the system decreases from
424 ~150 ms to ~50 ms over a distance of 1-2 km at the Acoustic Basement surface, and it decreases from
425 ~150 ms to ~50 ms over a similar distance at the intra-Upper Cretaceous surface. (Figure 9).

426 The relatively constant cumulative throw along the system suggests that the amount of extension
427 accommodated by the fault is constant along its length. We propose that the TBF Footwall Block,
428 underpinned by granitic material, represents an area of strong, relatively homogeneous crust, causing
429 it to inhibit fault nucleation and act as a barrier to the lateral propagation of faults into the block from
430 adjacent, relatively weaker crustal material.

431 Complex fault geometries occur at the southwestern termination of the Splaying Fault System along
432 the northern margin of the TBF Footwall Block (Figure 10). Horsetail splay style geometries are
433 situated at the terminations of Faults 15 and 16 across the Intra-Upper Cretaceous surface (Figure 10)
434 (e.g. McGrath & Davison 1995; Kim et al. 2004). In these locations, NE-trending faults rotate sharply
435 to NW and S/SE orientations at the boundary of the TBF Footwall Block, whilst also splaying into a
436 series of segments that define small-scale graben structures (Figure 10). The graben structures are
437 oriented parallel to the northern margin of the TBF Footwall Block and seemingly parallel to the
438 regional NW-SE oriented extension direction (Figure 10). The grabens are only expressed across the
439 Intra-upper Cretaceous surface. We suggest that these graben form as a consequence of the fault
440 trying to reduce throw and terminate, in the presence of the stronger TBF Footwall Block to the
441 southwest. Local stress perturbations proximal to the WNW-ESE oriented margin of the granitic TBF
442 Footwall Block may have influenced the nearby faults, causing them to rotate to a more WNW-ESE
443 orientation (Figure 10) (cf. Morley 2010; Rotevatn et al. 2018b; Samsu et al. 2019). Some NE-
444 trending faults are identified to the south west of the horsetail splay faults (i.e. Faults 17 and 20 in
445 Figure 10), forming E-W to NE-SW trending grabens within the TBF Footwall Block (Figure 4). We
446 suggest that these relatively low-displacement faults broke through the initial barrier to propagation
447 following an initial period of retardation at the northern margin of the TBF Footwall Block (Figure
448 10).

449 This stronger unit of crustal material appears more resistant to faulting than adjacent areas. As faults
450 in these relatively weak adjacent areas propagate towards this stronger area, they begin to splay and
451 segment, before eventually rotating and aligning along the actual boundary between the two units.

452 **6.3 Reactivation of basement fabrics**

453 Two prominent seismic fabrics are identified in crystalline basement across the study area, dipping
454 towards the south (Figure 11) and to the east (Figure 12). These basement fabrics are most
455 pronounced across the TBF Footwall Block, where they are shown to be associated with an E-W
456 trending and a NE-SW trending fault population across the Acoustic Basement surface (Figure 6a).
457 The different fabrics appear to display mutually cross-cutting relationships, with no interactions
458 providing conclusive evidence for the relative timing of their formation (Figure 4, 5).

459 The E-W fabric aligns with and shares a similar S-dipping geometry as the Terrane Boundary Fault
460 and shear zone. This fabric does not appear to be related to the NE-trending faults within the basin,
461 including the Splaying Fault system, which cross-cut the fabric (Figure 11). The NE-SW fabric is
462 aligned with, and displays a similar dip to, the NE-trending fault population. In cross-section, we
463 observe that the fabrics associated with the NE-trending faults offset the E-W striking fabrics
464 associated with the shear zone (Figure 7), indicating that the NE-SW fabric postdates the E-W fabric.

465 Prominent fabrics on seismic reflection data may be related to a number of different features including
466 sedimentary strata, fault plane reflections, highly foliated basement rocks and shear zones (e.g.
467 Phillips et al. 2016; Fazlkhani et al. 2017; Lenhart et al. 2019), and dyke swarms (e.g. Abdelmalak et
468 al. 2015; Phillips et al. 2017). The E-W fabric appears related to the Terrane Boundary Fault and
469 shear zone, appearing to link with the structure to the south (Figure 11). We suggest this basement
470 fabric may represent a continuation of the TBF shear zone-related fabric through the TBF Footwall
471 Block. The fabric in this location is exploited by multiple low-displacement faults (Figure 11). The
472 generation of this fabric may relate to the initial phase of rift activity in the Great South Basin, related
473 to the Late Cretaceous separation of Zealandia and Australia (Kula et al. 2007; Tulloch et al. 2019).

474 The NE-SW fabric appears to be related to the NE-trending faults that characterise the Great South
475 Basin (Figure 1, 12). These faults formed due to NW-SE oriented extension between Zealandia and
476 Western Antarctica (Kula et al. 2007; Sahoo et al. 2014; Tulloch et al. 2019), and faults associated
477 with this extension are proposed to be listric and link to a detachment at mid-crustal depths (Uruski et

478 al. 2007). The NE-SW fabric may possibly relate to this NW-SE oriented extension. Flexure in the
479 hangingwalls of the larger, listric faults may have led to the reactivation of the fabric, which now
480 hosts distributed minor faults (Figure 12).

481

482 **7 Discussion**

483 **7.1 The regional evolution of the Great South Basin**

484 The WNW-trending Terrane Boundary Fault is oriented at a high angle to the NE-trending faults of
485 the Great South Basin (Figure 1). Whilst it is possible that local stress perturbations relating to pre-
486 existing structures led to the development of non-optimally oriented structures such as the TBF (e.g.
487 Morley 2010; Philippon et al. 2015; Phillips et al. 2016; Rotevatn et al. 2018b; Samsu et al. 2019), we
488 do not think that this is the case due to the sub-perpendicular geometric relationship between the
489 Terrane Boundary Fault and other NE-trending faults. Based on geometric relationships between the
490 NE- and E-trending basement fabrics (Figure 7, 13c), we suggest that the WNW-trending structures
491 formed prior to the NE-trending faults and fabrics. We propose that these non-collinear structures
492 formed during multiple phases of extension relating to the multiphase breakup of Gondwana in the
493 Late Cretaceous. An initial phase of extension occurred at 100-90 Ma, related to the breakup between
494 Australia and the contiguous Zealandia and Western Antarctica. Offshore of the southeast South
495 Island, the extension direction was oriented roughly NE-SW, perpendicular to the orientation of the
496 basement terranes (Tulloch et al. 2019). The boundaries between basement terranes represented
497 crustal-scale weaknesses that were optimally oriented to be reactivated during this rift phase. We
498 suggest that this initial phase of extension reactivated the boundary between the Median Batholith and
499 Western Province terranes, forming the Terrane Boundary Shear Zone and Terrane Boundary Fault.

500 The Terrane Boundary Shear Zone is aligned with the Gutter Shear zone and the Freshwater and
501 Escarpment fault systems within the Median Batholith Zone, which show dextral transpressional
502 activity during the Early Cretaceous (Allibone & Tulloch 2004, 2008). While some oblique slip is

503 possible along the Terrane Boundary Fault, we do not believe this to be the case based on the
504 orientation of the embayments and the southwards dipping fault blocks within (Figure 6, 7). We
505 suggest that the geometry of the Terrane Boundary Shear zone was primarily controlled by the
506 boundary of the granitic laccoliths

507

508 Following breakup between Australia and Zealandia, a second phase of rifting occurred from ~90-80
509 Ma related to the breakup of Zealandia and Western Antarctica, leaving Zealandia as an isolated
510 continent. The NE- to ENE-trending Sisters Shear Zone along the southern coast of Stewart Island is
511 aligned with the northern margin of the Great South Basin and records extensional activity at this time
512 (Kula et al. 2009). The NW-SE extension direction during this rift phase resulted in the formation of
513 NE-trending faults across the Great South Basin (Beggs 1993; Uruski et al. 2007; Grobys et al. 2009;
514 Sahoo et al. 2014). As the extension direction was oriented at a high angle to the WNW-trending
515 Terrane boundary, this structure does not appear to have been active during this rift phase. However,
516 the presence of the Terrane boundary Shear Zone, and the granitic laccoliths beneath the TBF
517 Footwall Block, blocked the lateral propagation of faults forming at this time and acted to segment the
518 overall rift (Figure 13b) (Dore et al. 1997; Corti 2008; Koopmann et al. 2014; Henstra et al. 2015;
519 Peace et al. 2017; Heilman et al. 2019).

520 **7.2 3D geometry and seismic expression of a granitic batholith**

521 Although the Median Batholith represents a large area of igneous material, it is by no means a
522 homogeneous body. The batholith is a composite structure formed during a protracted period of
523 magmatism and comprises multiple generations of plutonic material with complex overprinting
524 relationships as observed onshore (Mortimer et al. 1999; Allibone & Tulloch 2004). The Median
525 Batholith as a whole represents a strong crustal unit relative to adjacent terranes. However, individual
526 plutons within the composite structure, such as the granitic laccoliths interpreted here as part of the
527 Separation Point Batholith suite, may represent relatively young, undeformed and therefore strong
528 crustal units relative to adjacent older batholith suites which may have experienced more deformation

529 and therefore may contain more heterogeneities upon which strain may localise. The large, composite
530 nature of the Median Batholith resembles other batholiths worldwide, such as the Cordillera Blanca
531 batholith of the Peruvian Andes (Petford & Atherton 1992) and the North American Sierra Nevada
532 Batholith (Schwartz et al. 2014).

533 We suggest the granitic body underpinning the TBF Footwall Block belongs to the Cretaceous-aged
534 Separation Point Batholith Suite. Intrusions displaying Separation Point affinity have been identified
535 along the same terrane boundary in the Taranaki Basin (Mortimer et al. 1997; Muir et al. 2000), and
536 form the basement of the Pukaki-1 well, which is also situated along the footwall of the Terrane
537 Boundary Fault (Figure 1) (Tulloch et al. 2019). Late Early Cretaceous batholiths along-strike to the
538 northwest on Stewart Island are largely confined to the south of the Gutter Shear zone, towards the
539 boundary with the Western Province terranes (Mortimer et al. 1999; Allibone & Tulloch 2004). The
540 Separation Point suite was intruded into Carboniferous-aged plutons, such as those penetrated in the
541 Pakaha-1 well (Figure 1) (Tulloch et al. 2019). The spatial relationships between the granitic bodies
542 offshore resembles those observed onshore Stewart Island (Allibone & Tulloch 2004).

543 Due to their relatively homogeneous nature, granitic bodies do not generate prominent impedance
544 contrasts and often appear acoustically transparent on seismic reflection data. However, reflections
545 can be generated at contacts between the granitic body and surrounding country rock, giving us
546 insights into the gross morphology of the granitic body. Seismic reflections have previously been
547 identified originating from the top and base of granitic bodies (Lynn et al. 1981; McLean et al. 2017;
548 Howell et al. 2019), as well as from internal fracture zones (Mair & Green 1981) and layered granitic
549 laccoliths (Evans et al. 1993; Evans et al. 1994). When observed in seismic data, granitic intrusions
550 typically display a laccolith-style geometry, consisting of stacked, lenticular bodies similar to those
551 observed here (Figure 4, 5, 13a) (Lynn et al. 1981; Evans et al. 1994; McCaffrey & Petford 1997;
552 Petford et al. 2000). Across the TBF Footwall Block we identify some areas displaying relatively
553 acoustically transparent seismic facies, which may correspond to the interpreted granitic laccoliths
554 (Figure 11, 12). These acoustically transparent areas are cross-cut by shear zone-related reflectivity in
555 some areas, representing faults and fractures within the granitic body itself (Figure 11).

556 Granitic material is often found beneath basement structural highs, such as the Utsira High in the
557 North Sea (Slagstad et al. 2011; Lundmark et al. 2013); the Alston Block in the UK (Critchley 1984;
558 Howell et al. 2019) and the Sierra Nevada Batholith in the USA (Ducea & Saleeby 1996; Van Buer et
559 al. 2009). Previous studies have proposed that the reduced density and increased rigidity of granite
560 compared to adjacent basement rocks makes them less susceptible to rifting when exposed to
561 extensional stresses (Bott et al. 1958; de Castro et al. 2007). Whilst this increased buoyancy plays an
562 important role in the formation of granite-cored structural highs, isostatic forces relating to initial
563 granite emplacement also play an important role (Howell et al. 2019). These granitic bodies show a
564 partitioning of strain and deformation around their margins rather than internally. One potential
565 mechanism for the lack of faulting across granite-cored structural highs may be the absence of
566 prominent heterogeneities within these relatively homogeneous bodies upon which strain can initially
567 localise (Mair & Green 1981; Howell et al. 2019).

568 The geometry of the interpreted granite body shows some variability along-strike and is not at a
569 constant depth beneath the top Acoustic Basement surface. In the west, the body extends up to ~3 s
570 TWT (Figure 4). In the east, it displays a more domal geometry that extends up to ~5 s TWT, and
571 stops at greater depths beneath the Acoustic Basement (Figure 5). Relief on the top surface of granitic
572 bodies has been identified in the Lake District and North Pennine batholiths onshore UK (Howell et
573 al. 2019). We propose that the relief atop the granite and its depth beneath the top Acoustic Basement
574 surface is expressed in the rift physiography, controlling the location of embayments along the
575 footwall of the Terrane Boundary Fault (Figure 14). In areas where the granitic body extends to
576 shallow depths beneath the top Acoustic Basement surface, we identify a steep shear zone with a
577 series of fault blocks detaching along its margin (Figure 4, 14). However, where the granite sits at
578 greater depths beneath the top Acoustic Basement surface, the upper part of the shear zone rotates to
579 shallower dips across the top of the granite and incises backwards into the TBF Footwall Block,
580 creating embayments that contain ‘perched’ fault blocks atop a sub-horizontal detachment (Figure 5,
581 14). This indicates that the shallow relatively unfaulted areas of the TBF Footwall Block represent
582 areas where the granite reaches shallow depths within basement and that the overall physiography of

583 the TBF Footwall Block may act as a proxy for that of the underlying granite (Figure 6a, 14). This
584 relief across the top of the granitic body may explain why the Terrane Boundary Shear zone localised
585 along its margin thins with depth (Figure 4, 5). At deeper levels the shear zone is pinned along the
586 margin of the granite, whereas at shallower depths, where the granite may be situated at deeper levels,
587 the shear zone is less confined.

588

589 **7.3 Strain accommodation along a laterally inhibited fault system**

590 The Splaying Fault System segments as it approaches the granitic TBF Footwall Block (Figure 6).
591 Cumulative fault throw remains relatively constant across the system as it approaches the block, with
592 a large displacement gradient present towards the boundary with the block itself (Figure 9). The
593 relatively constant cumulative throw along the fault indicates a large degree of kinematic coherence
594 within the system, with individual fault segments behaving as a singular system (Walsh & Watterson
595 1991; Walsh et al. 2002; Walsh et al. 2003; Childs et al. 2017; Jackson et al. 2017; Rotevatn et al.
596 2018a). In cross-section, some faults also appear linked at depth, forming a single structure indicative
597 of some degree of geometric coherence (Figure 8) (Walsh & Watterson 1991; Walsh et al. 2003; Giba
598 et al. 2012; Jackson et al. 2017). However, whilst the NW-dipping fault segments splaying from the
599 footwall block of the main structure display kinematic coherence with the main system they are not
600 geometrically linked (Figure 8).

601 Although a steep gradient is present for cumulative throw on the Splaying Fault System at the
602 boundary with the TBF Footwall Block, such a gradient is not apparent for the individual segments
603 themselves, which display more typical throw profiles (Figure 9) (Childs et al. 2017). As the Splaying
604 Fault System approaches this mechanically strong barrier to lateral fault propagation, it splays into a
605 series of lower displacement segments. These segments display lower throw gradients and are able to
606 terminate easier than a single large structure (Figure 13b). Similar splaying fault geometries are
607 present at fault terminations across all scales. Deformation along the Alpine Fault onshore New
608 Zealand is accommodated by splays of the Marlborough fault system to the northwest, where the fault

609 starts to interact with the Hikurangi subduction zone further east (Norris & Cooper 2001;
610 Wannamaker et al. 2009). Similarly, the eastern branch of the East African Rift forms a series of rift
611 segments in the south, termed the North Tanzania Divergence Zone, where strain is accommodated
612 over a wider area as rifting propagates toward and eventually terminates in the cratonic lithosphere of
613 the Tanzania Craton (Ebinger et al. 1997; Foster et al. 1997; Ring et al. 2005). At smaller scales,
614 geometrically similar structures, such as horsetail splays and damage zones are commonly associated
615 with the lateral terminations of fault systems (Kim & Sanderson 2006; Mouslopoulou et al. 2007;
616 Perrin et al. 2016; Nicol et al. 2017).

617 A key question is whether the fault propagated towards the TBF Footwall Block or whether the fault
618 reached close to its full length geologically instantaneously (i.e. following the constant length fault
619 model) (Walsh et al. 2002; Childs et al. 2017; Nicol et al. 2017) but displayed different structural
620 styles along its length. Furthermore, it is also unclear why the fault splayed at this particular location,
621 outboard of the TBF Footwall Block, rather than at the boundary itself. Nixon et al. (2014) document
622 a transition from localised to distributed extension within a kinematically coherent fault system in the
623 Whakatane Graben, which they link to progressive strain localisation along the system. However, the
624 segmentation in this instance occurs over a relatively short distance and does not resemble the gradual
625 increase in segmentation and the area over which strain is accommodated observed in the Splaying
626 Fault System (Figure 6, 13b). If the entire fault length did form geologically instantaneously, rather
627 than propagate to the southwest, why the fault changed structural style in that specific location would
628 still require an explanation, as the boundary with the TBF Footwall Block is located to the southwest
629 of the initial splay point, with no major change in underlying structure at the point of initial splaying.
630 Damage zones relating to granite emplacement may have locally altered lithological properties of
631 basement rocks; however, this would only affect a limited area. In addition, local rotation and
632 alignment of fault segments are only identified along the margin of the TBF Footwall Block (Figure 6,
633 10), and are not present where the fault begins to splay. Based on the gradational splaying of the fault
634 system and the apparent lack of change in basement physiography at the initial site of segmentation,

635 we suggest that the fault propagated towards the granitic block, although the timescale of this
636 propagation is shorter than the temporal resolution provided by our seismic data.

637 As the faults rotate at the margin of the TBF Footwall Block, they appear to detach from the granite,
638 as they do along the Pakaha Ridge (Figure 3, 8d). One implication of this is that the northern margin
639 of the granitic body dips to the north. Based on the information outlined above we propose the
640 following model for why the fault splay where it does. Surrounding the TBF Footwall Block, the
641 dipping margin of the stronger granitic material restricts the maximum fault height, such that where
642 the faults interact with the granite boundary at depth is located north of and offset from the boundary
643 at the surface (Figure 13b). The initial site of fault splaying would therefore correspond to the area
644 where the deeper levels of the fault start to interact with the granitic body. As the fault approaches, its
645 maximum height is reduced, causing the fault to splay into multiple segments (Figure 13b). Although
646 this model could potentially explain the Splaying Fault System, we are unable to determine this
647 scenario in our data.

648 As previously stated, individual fault segments rotate along the margin of the TBF Footwall Block
649 (Figure 10, 13b). This may be related to local stress perturbations along the margin of the block
650 (Morley 2010; Philippon et al. 2015; Morley 2017; Rotevatn et al. 2018b), or alternatively to a change
651 in structural style along the faults from dip- to strike-slip following a 90° change in orientation
652 (Mouslopoulou et al. 2007). The horsetail splay geometries identified across the intra-Upper
653 Cretaceous surface (Figure 10) describe two WNW-trending grabens, which would not appear to be
654 compatible with strike-slip motion. The grabens are not present at the top Acoustic Basement horizon
655 and the individual faults may link together at depth, indicating that they could be related to oblique
656 activity on a deeper fault. However, in other areas faults align along the margin of the TBF Footwall
657 Block and show no evidence of strike-slip activity (Figure 6b). The rooting of faults onto the granitic
658 body underpinning the TBF Footwall Block may also explain the switch in polarity along the
659 Splaying Fault System, from SE-dipping in the northeast, to NW-dipping further southwest. In the
660 southwest, the NW-dipping faults appear to detach onto the granitic body at depth, preferentially
661 exploiting this pre-existing heterogeneity (Figure 8d).

662

663 **5. Conclusions**

664 In this study, we have analysed the detailed structural evolution of the southern section of the Great
665 South Basin and examined how it has been influenced by various structural heterogeneities relating to
666 the underlying Median Batholith Zone. We have documented a range of styles of structural
667 inheritance, which exert variable influences over rift physiography throughout multiple tectonic
668 events. We find that:

- 669 • The offshore extension of the boundary between the Median Batholith Zone and Western
670 Province terranes, trends WNW across the Great South Basin. This terrane boundary is
671 associated with a crustal-to-lithospheric scale shear zone and a series of faults in the upper
672 crust that segment the Great South Basin. The terrane boundary was initially exploited by the
673 intrusion of igneous plutonic material, before being reactivated in response to NE-SW
674 oriented extension related to the separation of Australia and New Zealand.
- 675 • We postulate a granitic body forms a structural high in the footwall of the reactivated terrane
676 boundary. Based on seismic interpretation, regional context and nearby well information, we
677 interpret that the granitic body displays a laccolith-style geometry and is part of the
678 Cretaceous Separation Point Batholith suite. This batholith suite may have exploited the
679 original lithosphere-scale terrane boundary along the southern margin of the Median Batholith
680 and later appeared to localise the shear zone along its southern margin.
- 681 • We infer details of the 3D geometry of the granitic body from the overlying rift physiography.
682 Where the body reaches shallow depths, it controls the shallow geometry of the Terrane
683 Boundary shear zone, which tracks along the margin and is associated with hangingwall fault
684 blocks; where the granitic body top sits at greater depths, the shear zone shallows atop the
685 structure and forms shallow embayments that incise into the footwall. These features act as a
686 proxy for the relief of the top of the granitic body.

- 687 • The granitic body underpinning the TBF Footwall Block acts as a barrier to the lateral
688 propagation of NE-trending faults within the Median Batholith. These faults form a series of
689 splays that eventually rotate into parallelism as they approach the mechanically strong
690 granitic body, with relatively few faults present across the high itself. NE-trending faults
691 formed in response to NW-SE directed extension related to the separation and breakup of
692 New Zealand and West Antarctica.
- 693 • Individual segments within the splaying fault system display kinematic and geometric
694 coherence along the fault system and accommodate similar values of extension along-strike.
695 The initial site of splaying along the fault system is offset from the boundary of the granitic
696 body, perhaps relating to a N-dipping margin.
- 697 • Two generations of seismic fabrics are developed within basement beneath the basin, trending
698 E-W and NE-SW. These fabrics are proposed to be related to the reactivation of the terrane
699 boundary and the NW-SE directed rifting respectively. They are exploited by numerous
700 small, low-displacement faults, which are particularly well developed atop the basement high.

701

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711 **Figure captions**

712 **Figure 1** – Map showing the top Acoustic Basement structure surface (in two way travel time – TWT)
713 across the study area of the Great South Basin in relation to the underlying basement terranes. Terrane
714 boundaries after Ghisetti (2010) and Mortimer et al. (2002). The locations of wells in the area are
715 shown by grey filled circles, red lines indicate the locations of seismic sections referred to in this
716 study, and the blue polygon shows the outline of the 3D seismic volume. Major depocentre-bounding
717 faults are highlighted by white lines. NE-trending faults are present throughout the basin, with a large
718 WNW-trending fault present along its southern margin. Inset – regional map of New Zealand showing
719 basement terranes offset along the Alpine Fault. Also shown are the locations of the Great South and
720 Canterbury basins offshore the South Island, as well as bathymetric features including the Campbell
721 Plateau, Chatham Rise and Bounty Trough.

722 **Figure 2** – A) Stratigraphic columns showing New Zealand and International units. Regional
723 stratigraphic ages referred to in this study are shown in bold, with the location of the Intra-upper
724 Cretaceous surface also marked. B) Seismic well tie to the Pukaki-1 borehole. Gamma Ray, Sonic and
725 Density logs are shown along with the synthetic and observed seismic traces. The input wavelet used
726 for the generation of the synthetic seismic and a seismic trace from the seabed are shown below. The
727 ages of stratigraphic horizons interpreted in this study are defined and placed into the regional
728 framework of Mortimer et al. (2014). TVD – True Vertical Depth; TWT – Two-way-travel time. See
729 Figure 1 for well location.

730 **Figure 3** – Uninterpreted and interpreted E-W oriented seismic section across the centre of the Great
731 South Basin. See Figure 1 for location. Key stratigraphic horizons are linked to the Pakaha-1 well.
732 The Acoustic Basement is shown by the red line. In the east, some NE-dipping faults merge along the
733 margin of the granitic Pakaha ridge. A complex series of cross-cutting faults are present in the centre
734 of the basin.

735 **Figure 4** – Uninterpreted and interpreted N-S oriented seismic section across the western platform of
736 the study area. See Figure 1 for location. The boundary between the Median Batholith and Western
737 Province terranes is marked by the thick blue line and is associated with a shear zone and fault
738 system, termed the Terrane Boundary Shear Zone and Fault respectively. Divergent syn-rift strata are

739 marked by dark green wedges. A large shear zone is co-located with the boundary between the
740 terranes.

741 **Figure 5** – uninterpreted and interpreted N-S oriented seismic section across the centre of the study
742 area. See Figure 1 for location. The boundary between the Median Batholith and Western Province
743 terranes is marked by the thick blue line. A large area of complex faulting is present in the footwall of
744 the Terrane Boundary Fault.

745 **Figure 6** – A) TWT structure map of the top Acoustic Basement surface based on 3D seismic volume
746 across the centre of the basin, see Figure 1 for location. The basin is dominated by NE-trending faults
747 with the SSW-dipping Terrane Boundary Fault along the southern margin of the basin. A WNW-
748 trending, relatively unfaulted structural high is located in the footwall of the Terrane Boundary Fault,
749 termed the TBF Footwall Block. B) TWT structure map of a key surface within the Upper Cretaceous
750 interval (see Figure 3). A SE-dipping fault, the Splaying Fault System, becomes segmented towards
751 the southwest and forms a series of splays as it approaches the TBF Footwall Block.

752

753 **Figure 7** – uninterpreted and interpreted SW-NE oriented seismic section across the TBF Footwall
754 Block and a prominent footwall embayment. See Figure 4 for location. Basement reflectivity is shown
755 associated with the Terrane Boundary Shear Zone, with additional reflectivity at deeper levels related
756 to granitic laccoliths. These fabrics are cross-cut by fabrics associated with the NE-trending faults.

757 **Figure 8** – Uninterpreted and interpreted seismic sections along-strike of the Splaying Fault System.
758 See Figure 4 for locations. A) Section across the north-eastern extent of the Splaying Fault System,
759 where strain is accommodated by a single fault. Sub-Acoustic Basement reflectivity is present, likely
760 relating to an earlier phase of activity of undetermined age. B) Towards the southwest the fault begins
761 to splay into a series of segments. Synthetic fault segments form in response to dissection of the
762 footwall as antithetic faults form in the hangingwall and merge with the main fault plane. C) The
763 footwall of the fault is now highly deformed with extension accommodated by a wide zone of
764 deformation consisting of SE- and NW-dipping faults. D) Extension is accommodated by a wide zone

765 of deformation, with the dominant faults now dipping to the NW and detaching onto the margin of a
766 granitic ridge. Rotation of the faults to a WNW-ESE strike is accommodated by the formation of
767 shallow synthetic and antithetic faults in the footwall and hangingwall of the faults respectively.

768 **Figure 9** – Throw-length profiles calculated across the Acoustic Basement (A) and Intra-Upper
769 Cretaceous (B) surfaces for individual segments of the Splaying Fault System. Individual profiles are
770 colour-coded to the faults on the surface to the right. Cumulative throw across the whole of the
771 system, calculated by summing throw on individual segments across a lines perpendicular to the strike
772 projection of the main fault, is shown by the black dashed lines. Note that the cumulative throw is
773 relatively consistent across the system regardless of the degree of segmentation, before a steep
774 displacement gradient towards the boundary of the TBF Footwall Block. Also shown are the locations
775 of the sections shown in Figure 8.

776 **Figure 10** – Uninterpreted TWT structure map and detailed interpretations of horsetail-splay style
777 fault geometries across the Intra-Upper Cretaceous surface. See Figure 4b for location. Fault numbers
778 refer to those in Figure 10. Inset – Two seismic sections across the area corresponding to the blue and
779 purple lines on the figure.

780 **Figure 11** – Uninterpreted and interpreted NNE-SSW oriented seismic sections across the TBF
781 Footwall Block, highlighting the E-W oriented basement fabrics. See Figures 4 and 14 for location.
782 Shear-zone related reflectivity is shown by the thick dashed black lines, whilst the basement fabrics
783 are represented by the dark blue lines. NE-trending faults post-date and cross-cut the shear zone
784 related reflectivity.

785 **Figure 12** – Uninterpreted and interpreted E-W oriented seismic section across the TBF Footwall
786 Block, highlighting the NE-trending basement fabric. See Figures 4 and 14 for location. The basement
787 fabric displays a similar dip to the NE-trending faults and is often associated with low-displacement
788 faults across the top Acoustic Basement surface.

789 **Figure 13** – Schematic cartoons showing the different styles of structural inheritance identified in the
790 Great South Basin across different scales. A) Shear zone and associated fault localise along the

791 Terrane boundary and the margin of the continuation of the Separation Point Batholith Suite between
792 the Median Batholith and Western Province. Inset shows the localisation of the shear zone along the
793 granite margin. B) The stronger material in the footwall to the Terrane Boundary Fault forms a barrier
794 to lateral fault propagation, causing faults to splay as they approach and strain to be accommodated
795 across multiple low-displacement segments. Inset – The dipping boundary of the strong barrier
796 restricts fault height away from the boundary at the surface, causing the initial site of fault splaying to
797 be offset from the boundary at shallower depths. C) Exploitation of prominent basement fabrics by
798 relatively low-displacement faults. Differently oriented fabrics may be exploited at different times and
799 during different tectonic events, resulting in multiple generations of faults. Inset – Cross-sectional
800 view showing the reactivation and cross-cutting relationships between different fabrics.

801 **Figure 14** – Conceptual 3D model showing the relationship between the Terrane Boundary Shear
802 Zone and the relief of the top of the granitic body. The shear zone localises along the margin of the
803 granite body. Where the granitic body is situated at shallower depths the shear zone tracks along the
804 margin and is associated with a series of detaching fault blocks; where the shear zone is situated at
805 greater depths, it shallows atop the body and forms embayments that cut back into the footwall.

806

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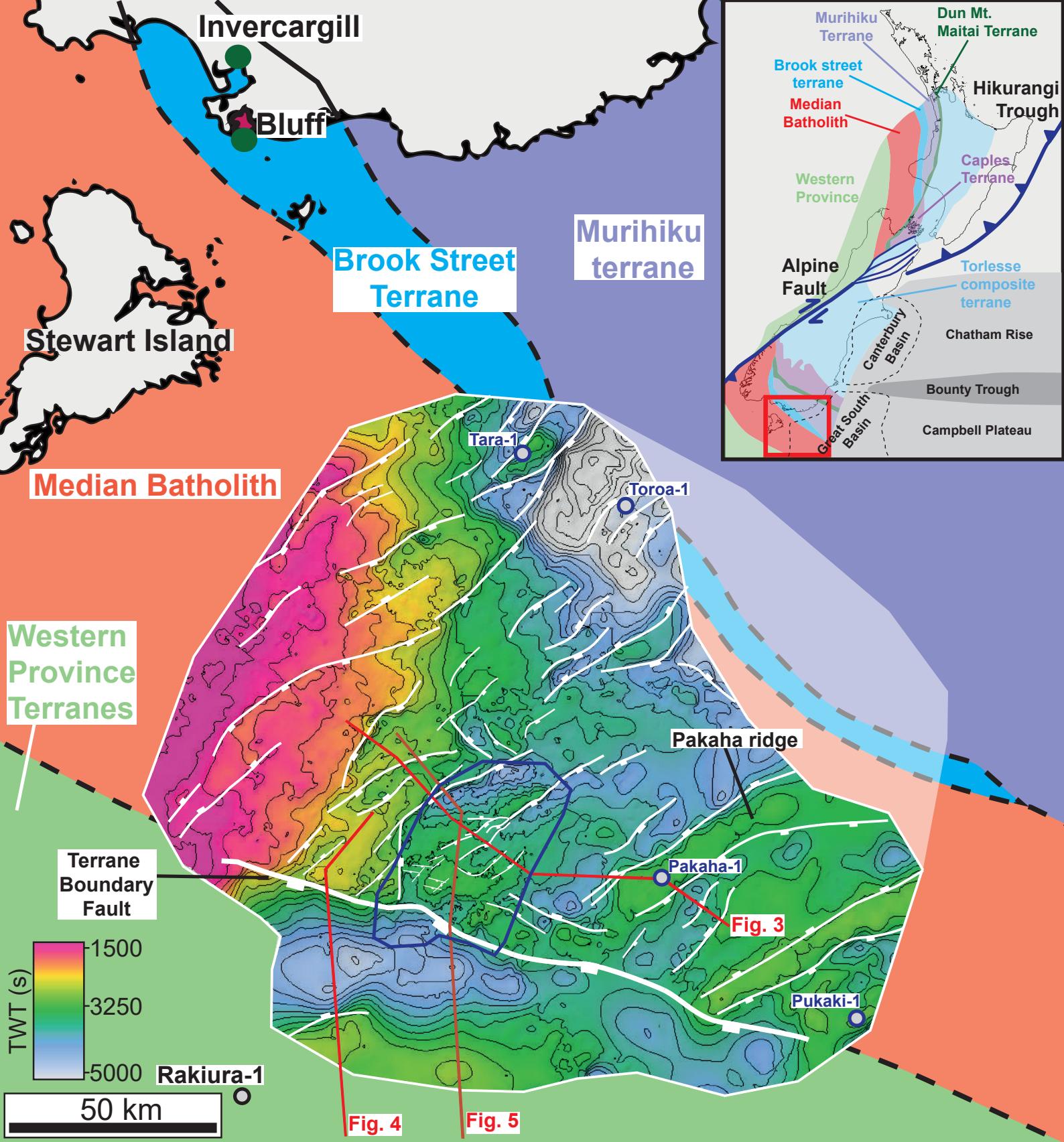
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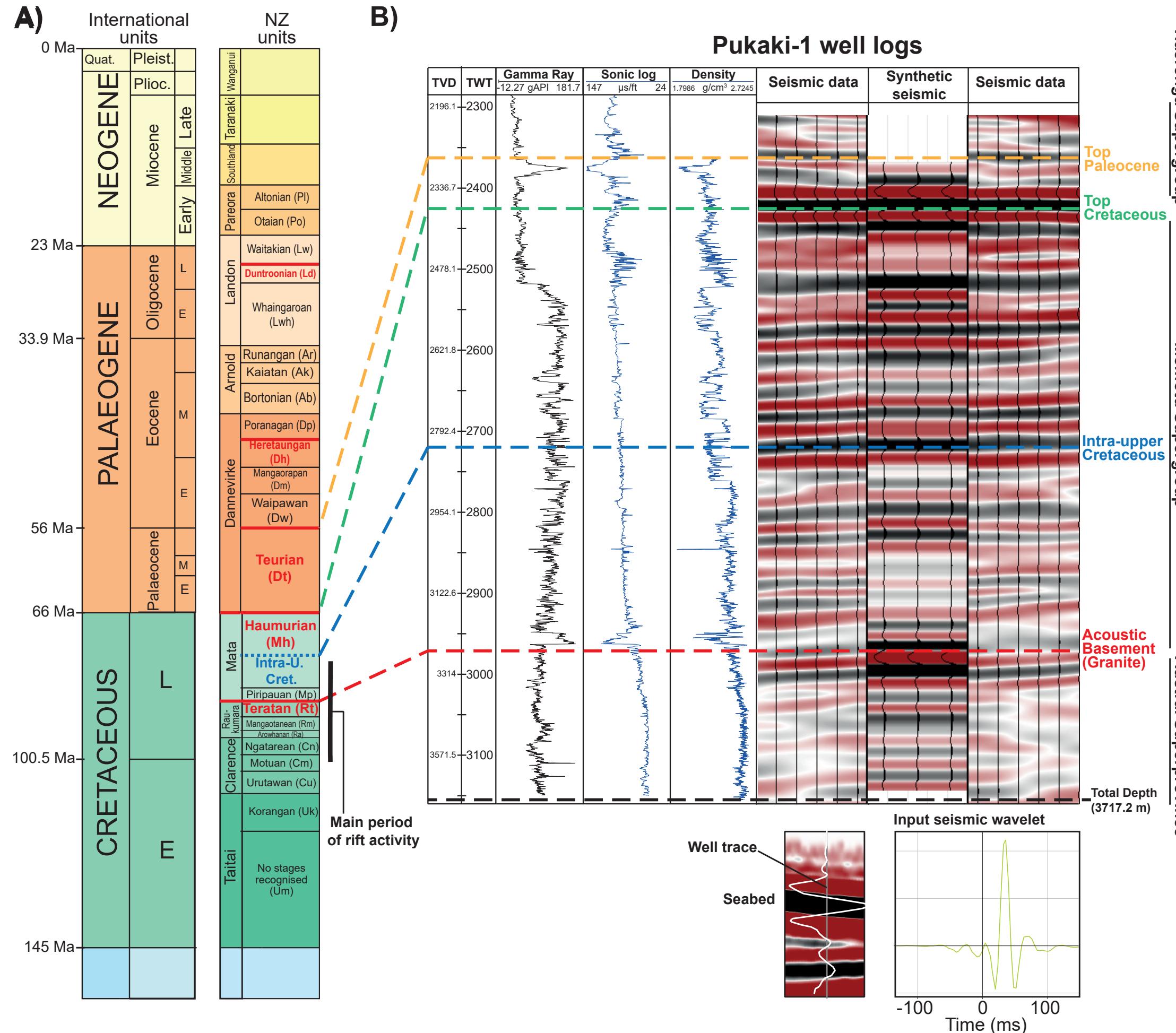
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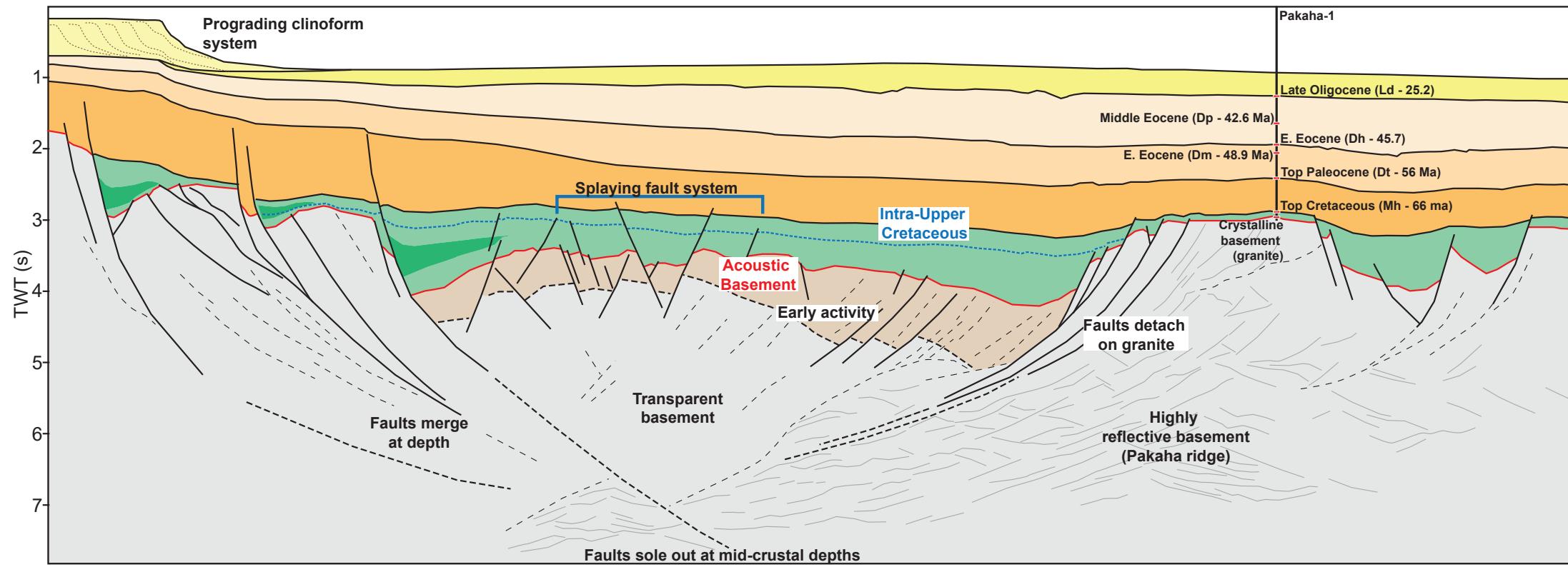
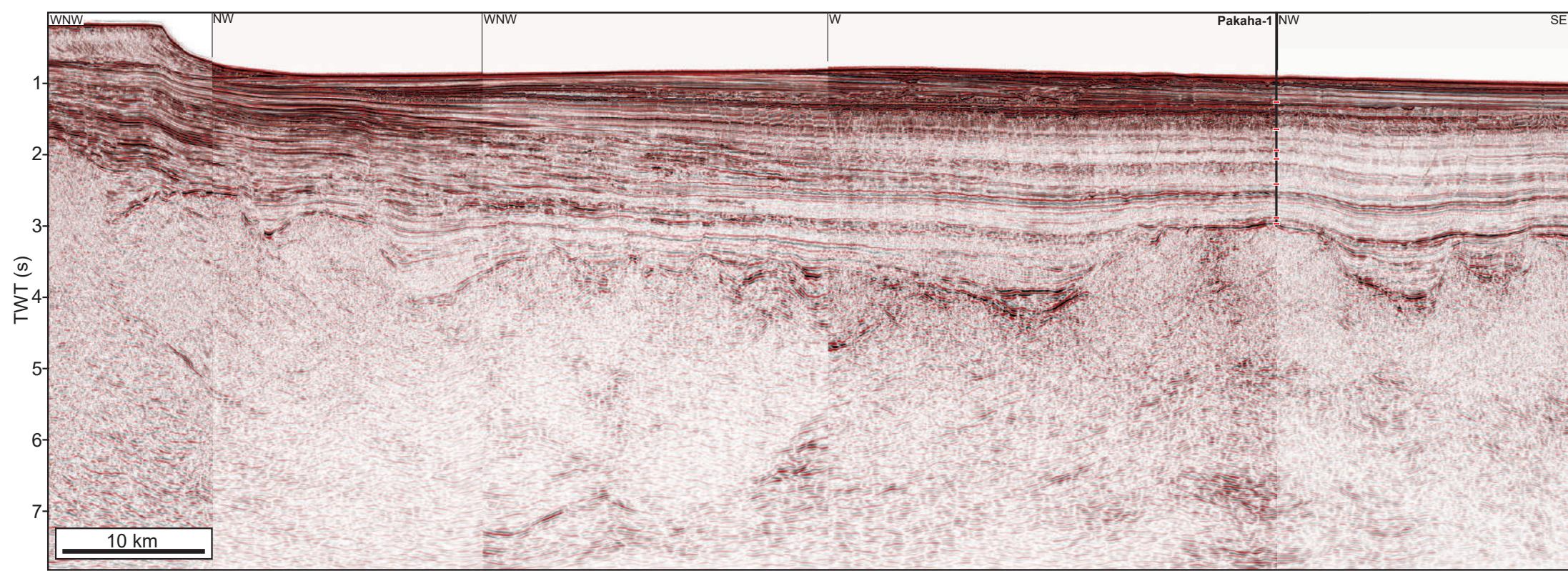
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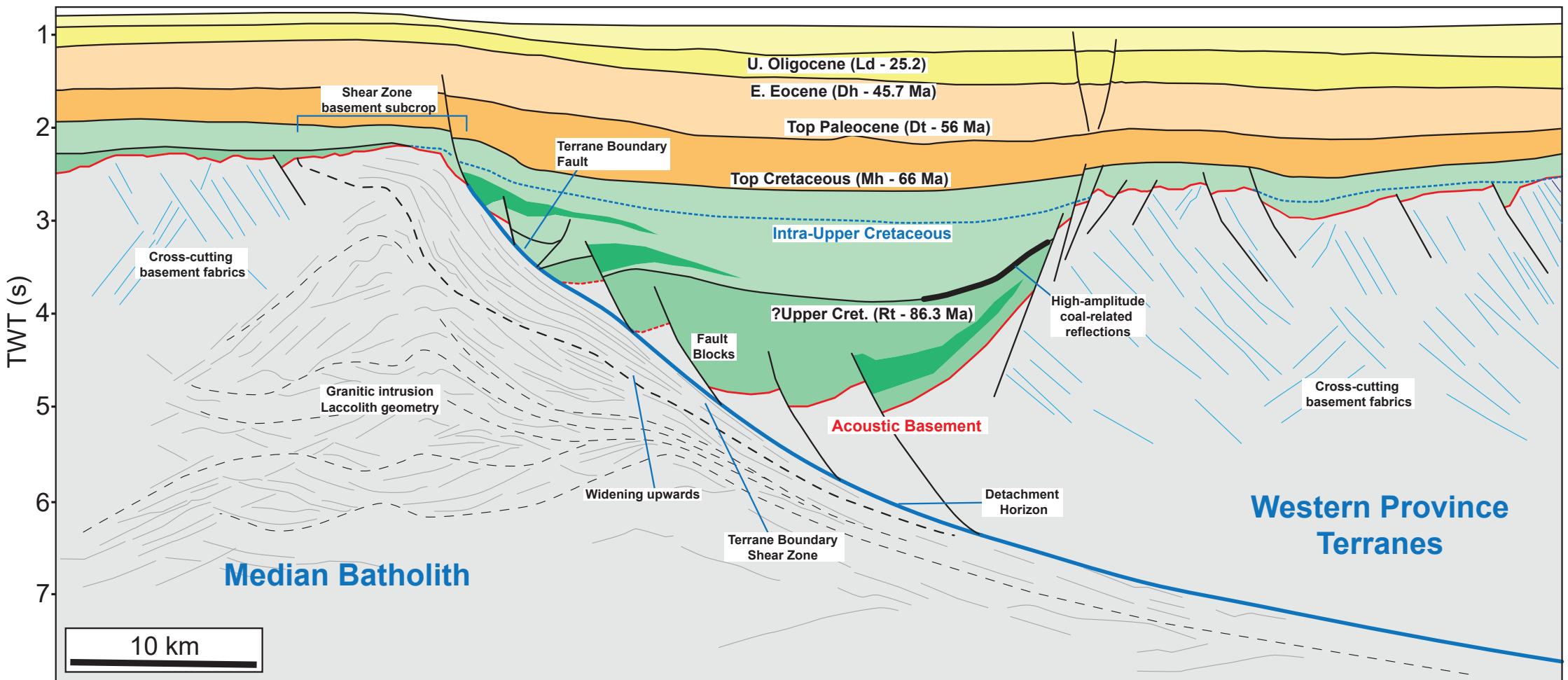
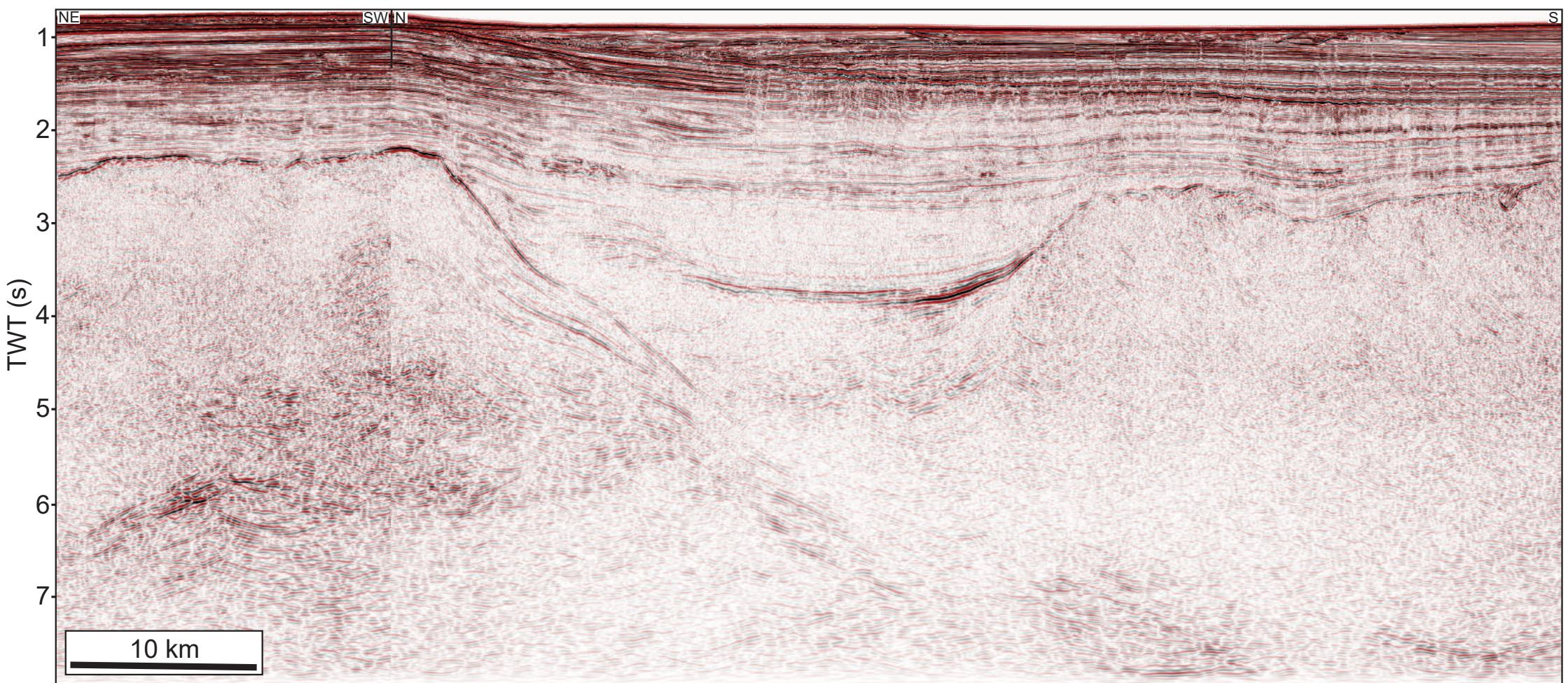
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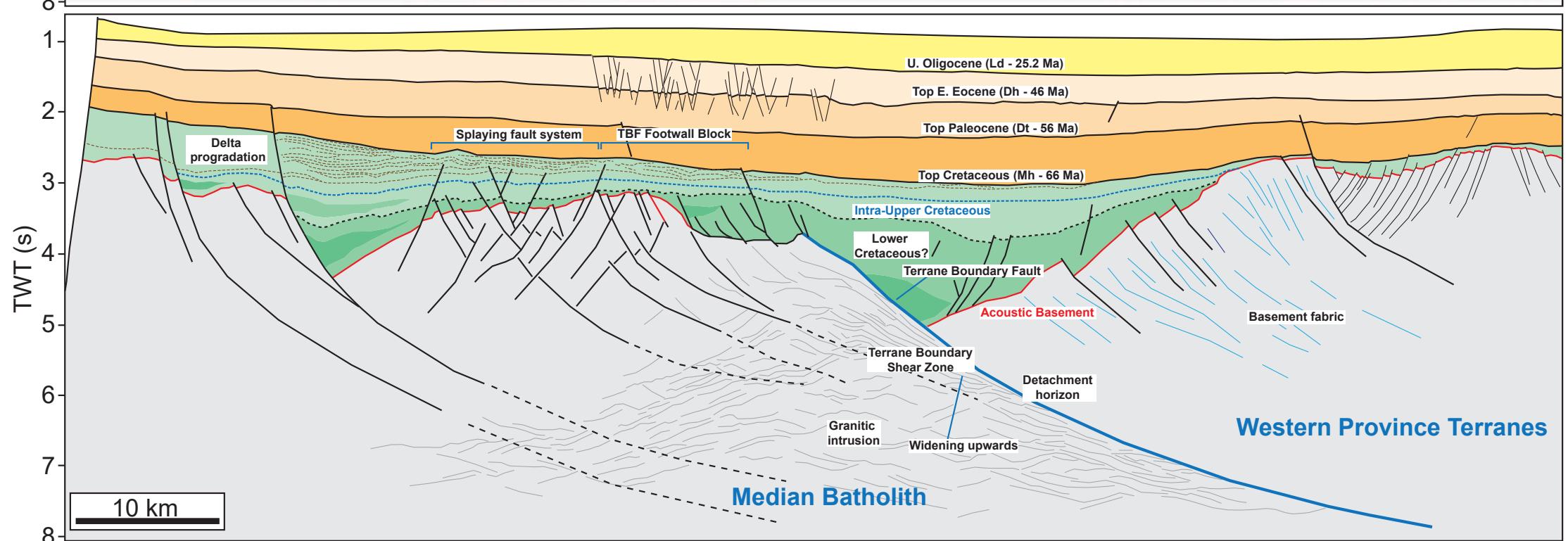
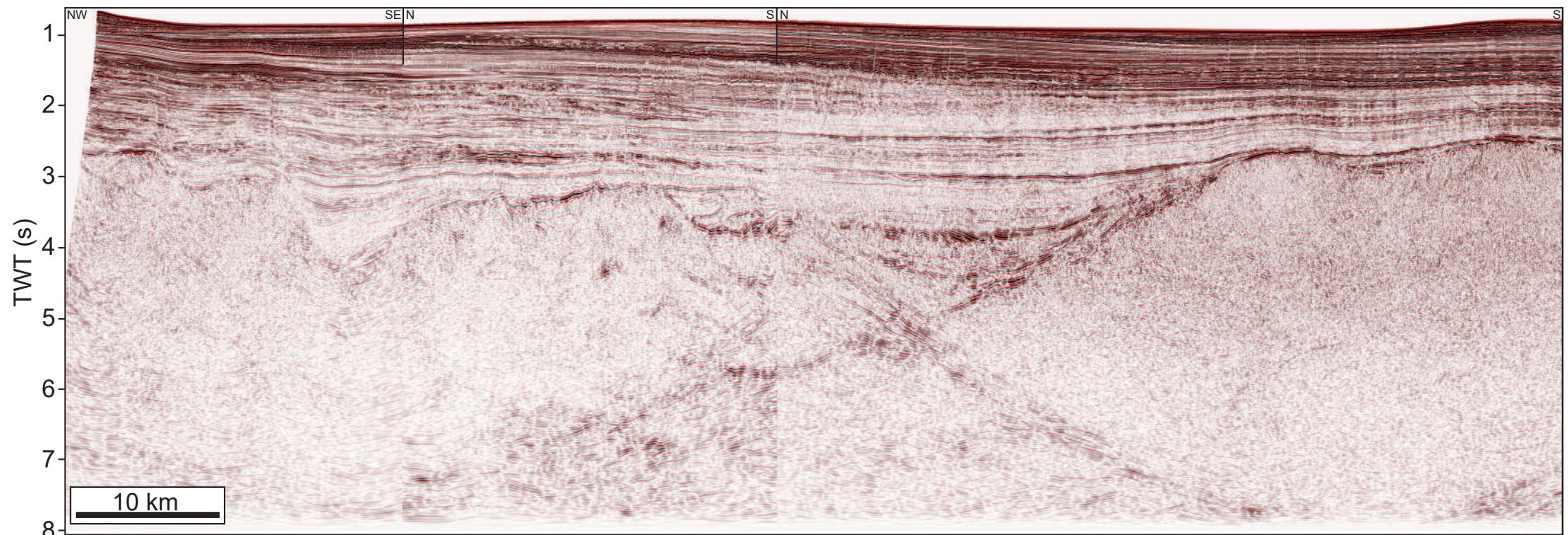
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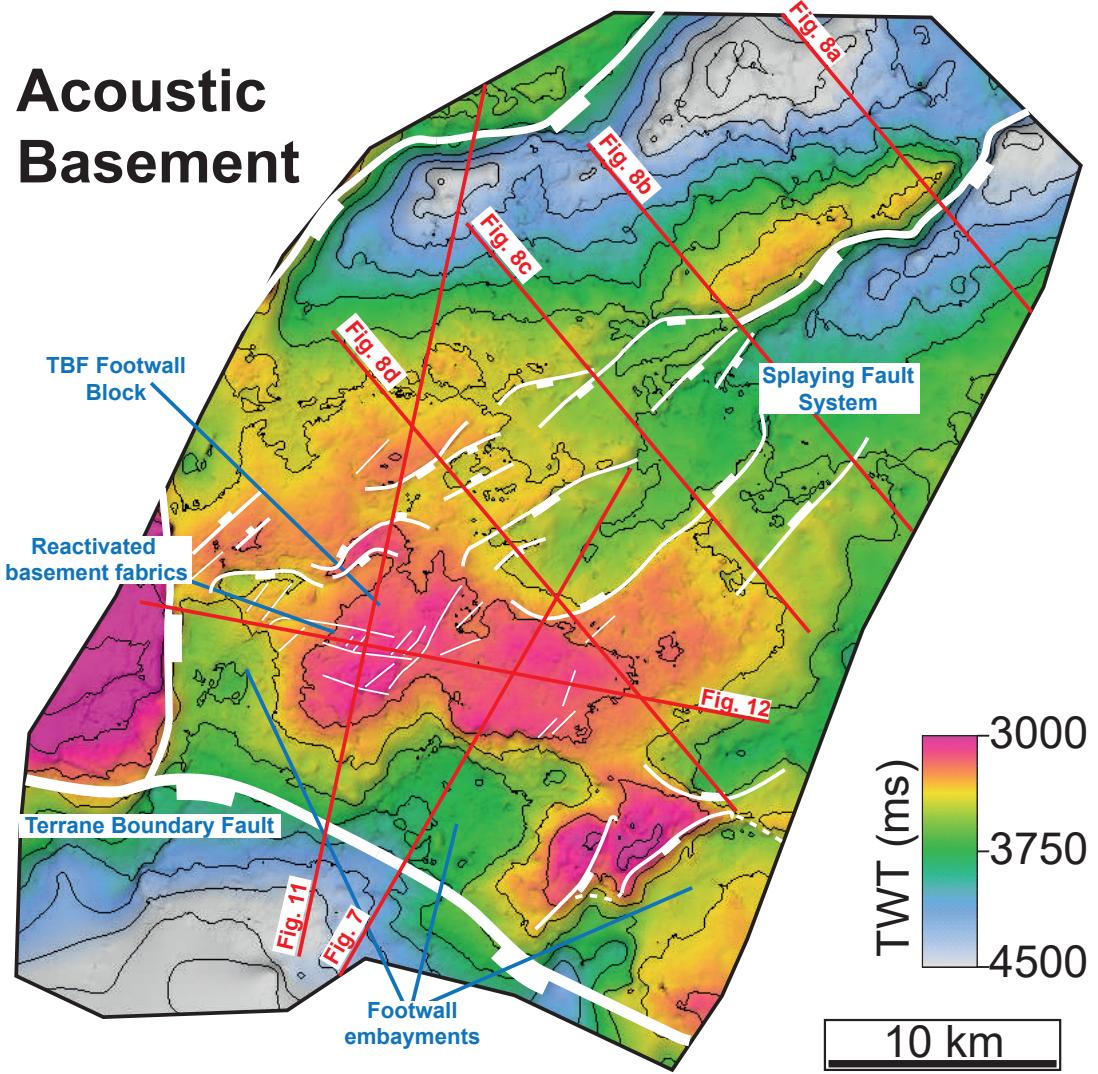




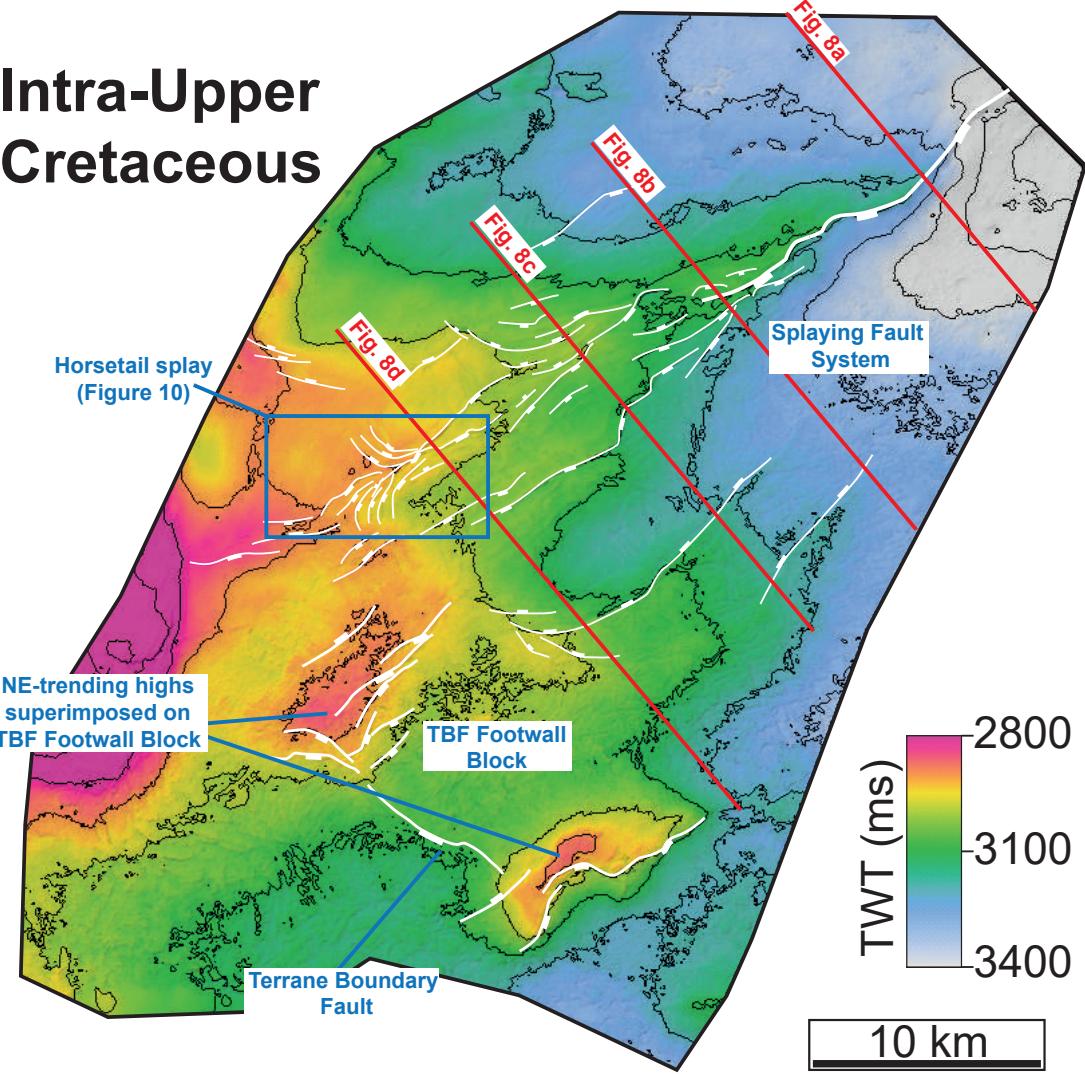


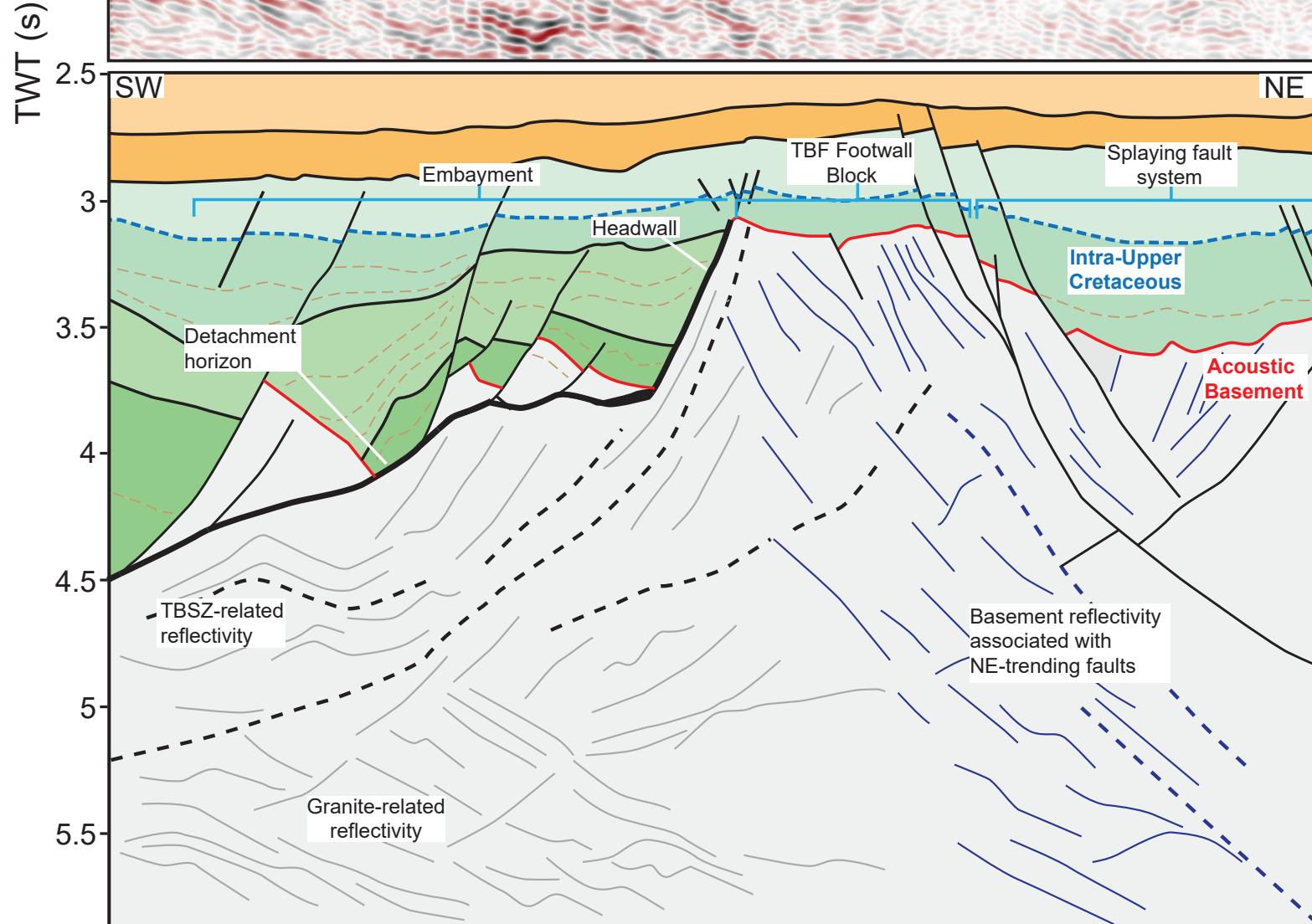
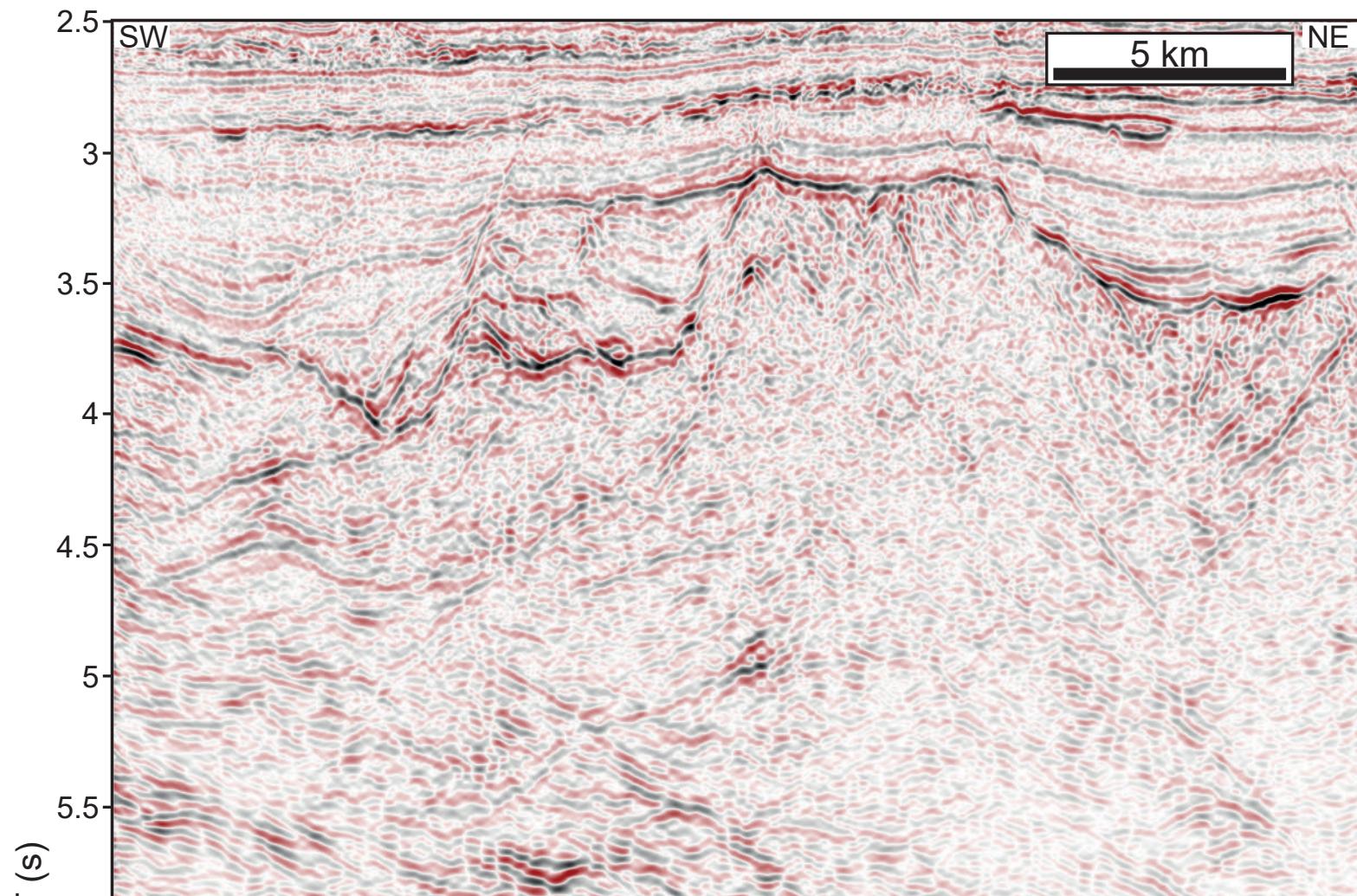


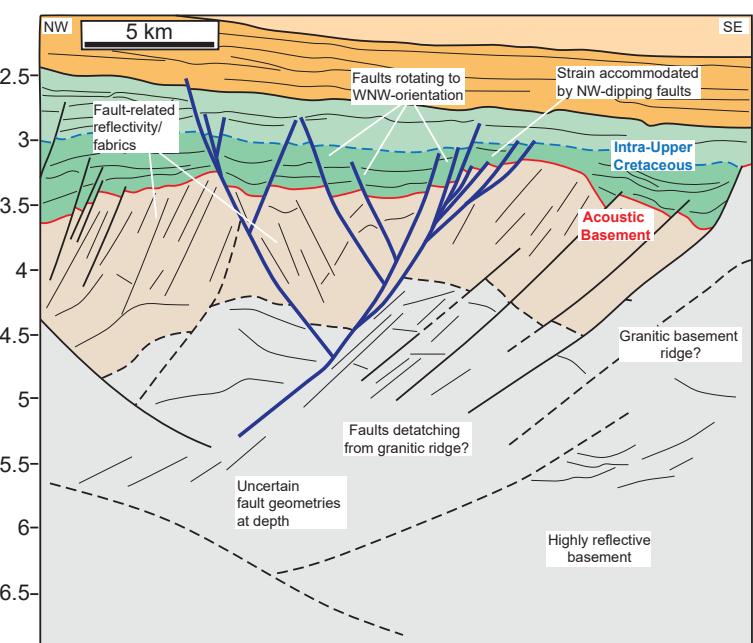
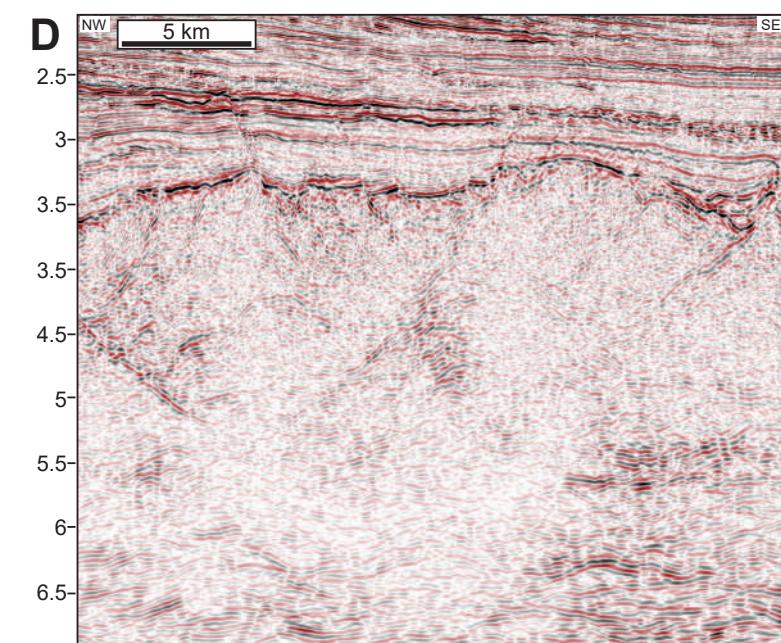
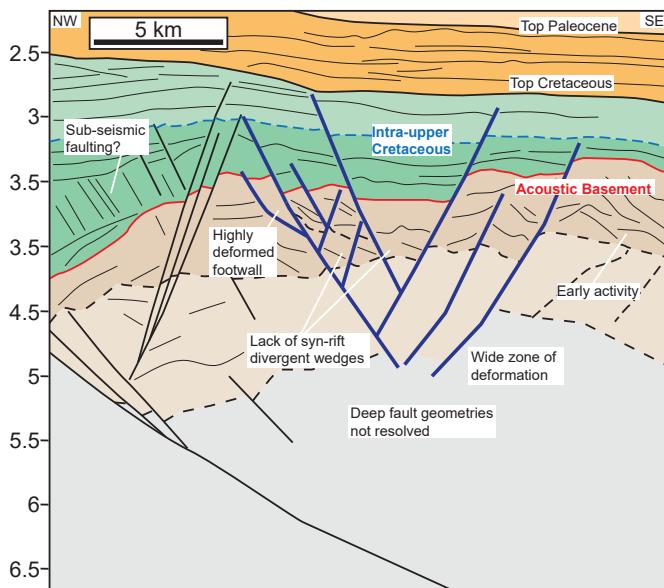
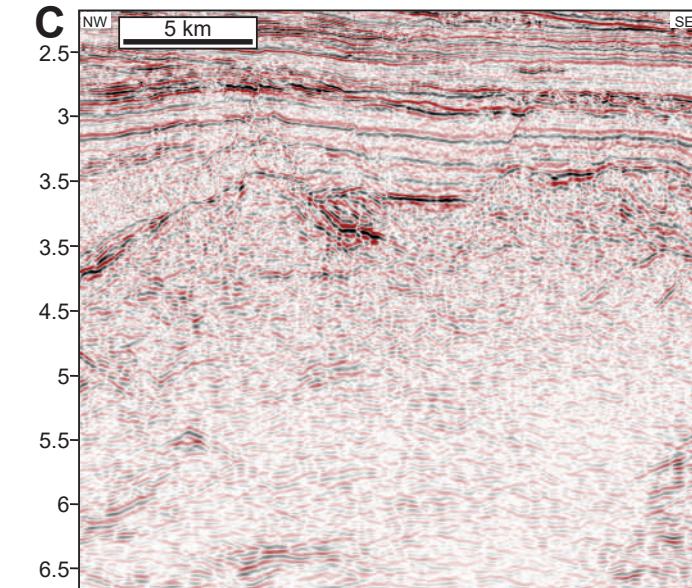
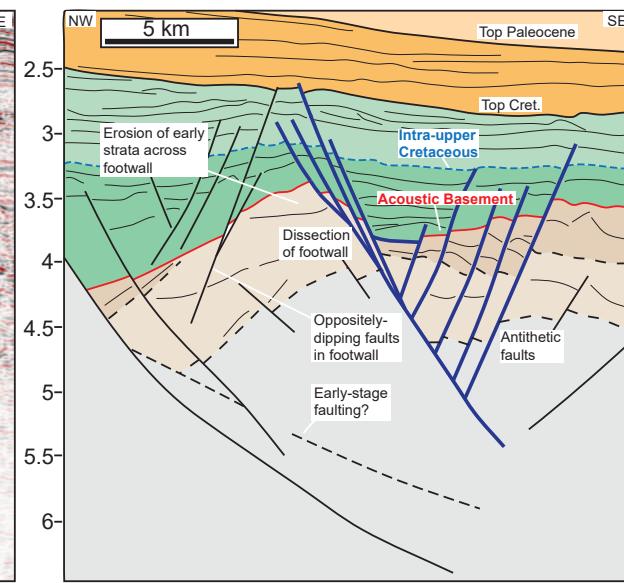
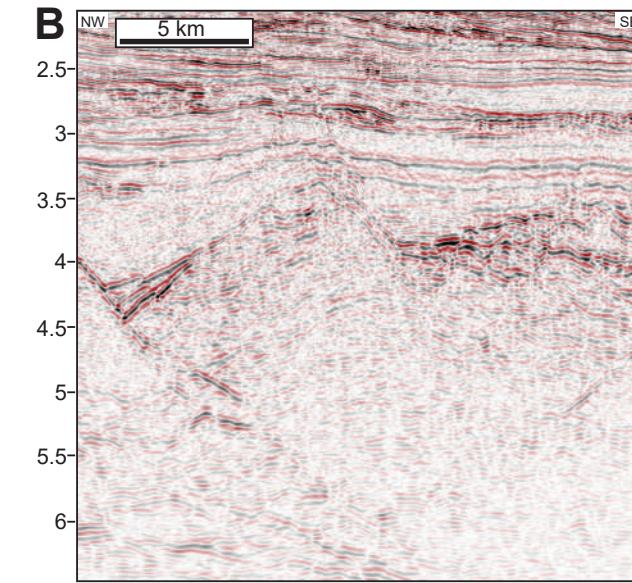
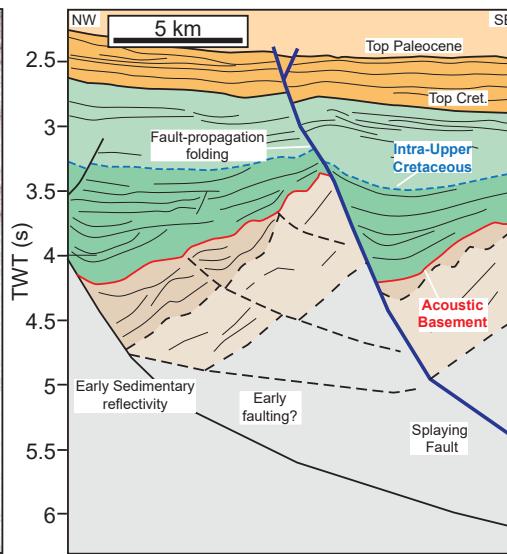
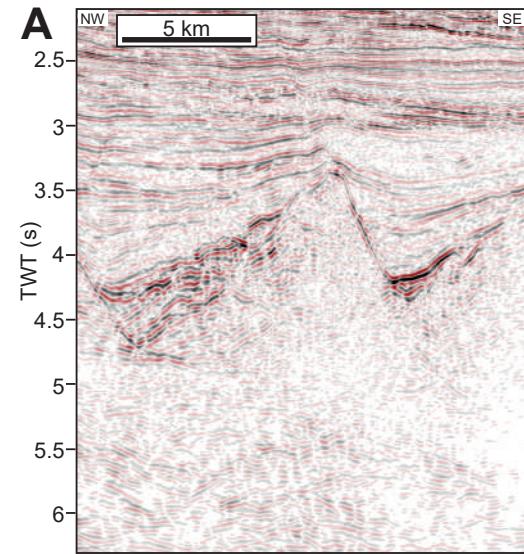
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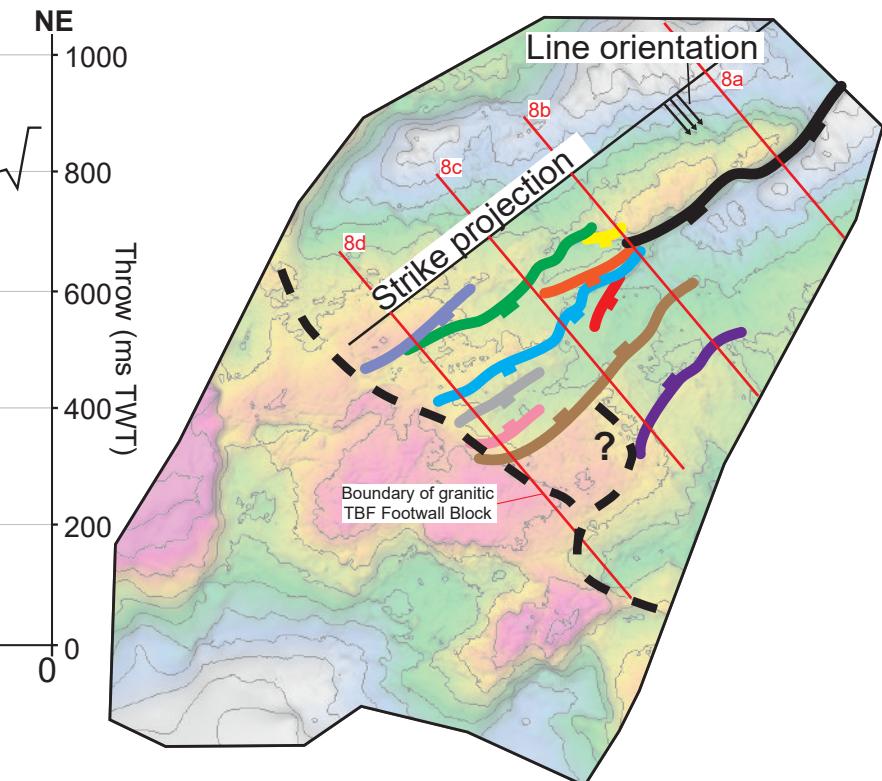
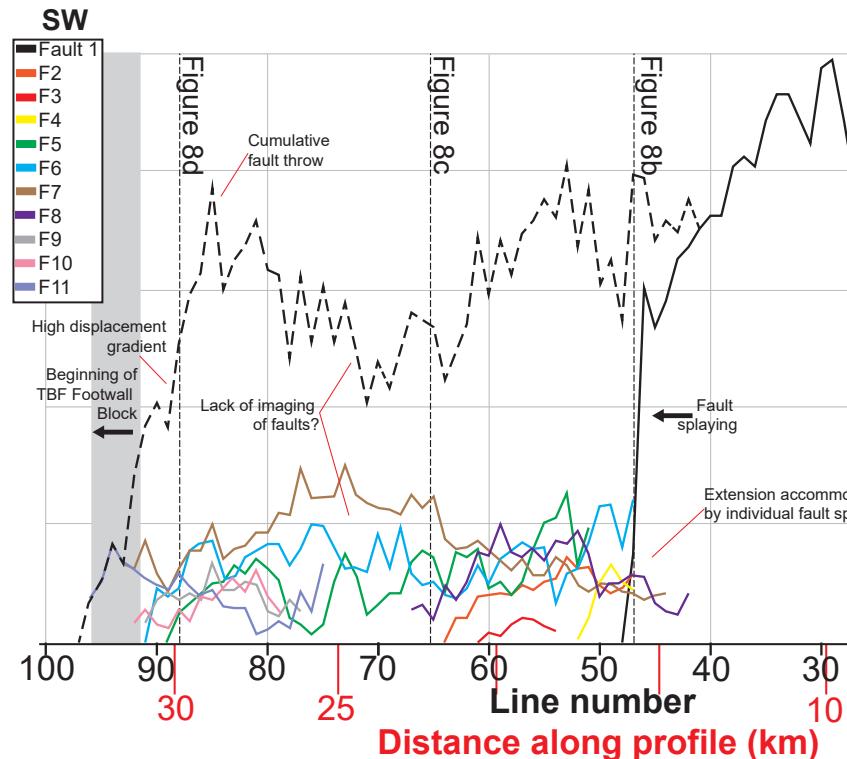


Intra-Upper Cretaceous







A**B**