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► **To cite this version:**

Gulce Dinc, Jean-Paul Callot, Jean-Claude Ringenbach. Shale mobility: From salt-like shale flow to fluid mobilization in gravity-driven deformation, the late Albian–Turonian White Pointer Delta (Ceduna Subbasin, Great Bight, Australia). *Geology*, 2023, 51 (2), pp.174-178. 10.1130/G50611.1 . hal-03979159

HAL Id: hal-03979159

<https://hal.science/hal-03979159>

Submitted on 8 Feb 2023

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Shale mobility: From salt-like shale flow to fluid mobilization in a gravity-driven deformation, the Late Albian-Turonian White Pointer Delta (Ceduna Basin, Great Bight, Australia)

Tracking no: G50611R

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Abstract:

Large offshore depocenters above a weak detachment level (either salt or shale) can undergo gravity spreading and/or gliding. The gravitational systems (e.g. gliding deltas) are classically composed of an up-dip domain affected by extensional listric normal faults and a down-dip domain affected by toe thrusts. While the role of salt in such systems is a classic of tectonic lesson, the role and mechanical behavior of mobile shale levels in shale-prone gravity driven systems are increasingly questioned. A 3D seismic dataset in the Ceduna sub-basin displays the Late Albian-Turonian White Pointer Delta (WPD) as having an unusual diversity of shale-cored structures. The early flow of shale results in depocenters showing wedges, internal unconformities, and shale diapirs and ridges, while fluidization of shales underneath a significant burial results in mud volcanism, secondary radial fault sets and collapse features beneath the Campanian-Maastrichtian Hammerhead delta (HHD) which lies above the WPD. Massive shale mobilization together with downdip shortening and a distal margin uplift localizes a major thrust in the core of the basin ending the downward propagating failure of the WPD. Mobilization of thick shale intervals, either as salt-like flow or mud volcanism, appears as a key process of deformation to be considered at large scale for worldwide gravity-driven deformation systems.

1 Shale mobility: From salt-like shale flow to fluid mobilization in
2 a gravity-driven deformation, the Late Albian-Turonian White
3 Pointer Delta (Ceduna Basin, Great Bight, Australia)

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7 **ABSTRACT**

8 Large offshore depocenters above a weak detachment level (either salt or shale) can
9 undergo gravity spreading and/or gliding. The gravitational systems (e.g. gliding deltas) are
10 classically composed of an up-dip domain affected by extensional listric normal faults and a
11 down-dip domain affected by toe thrusts. While the role of salt in such systems is a classic of
12 tectonic lesson, the role and mechanical behavior of mobile shale levels in shale-prone gravity
13 driven systems are increasingly questioned. A 3D seismic dataset in the Ceduna sub-basin
14 displays the Late Albian-Turonian White Pointer Delta (WPD) as having an unusual diversity of
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16 unconformities, and shale diapirs and ridges, while fluidization of shales underneath a significant
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19 mobilization together with downdip shortening and a distal margin uplift localizes a major thrust
20 in the core of the basin ending the downward propagating failure of the WPD. Mobilization of
21 thick shale intervals, either as salt-like flow or mud volcanism, appears as a key process of
22 deformation to be considered at large scale for worldwide gravity-driven deformation systems.

23 **INTRODUCTION**

24 Development of large sedimentary deltas on passive margins is often associated with
25 gravity-driven collapse (e.g. Rowan 2020; McClay et al., 2003), which is controlled either by
26 pure gliding/spreading, or a combination of both, above a ductile decollement level, usually
27 made up of evaporites or mobile shales (Peel 2014). Gravity collapse shows three main domains
28 connected by a basal detachment: (1) an up-dip extensional domain associated to listric normal
29 growth faults, (2) a translational domain showing symmetrical structures (e.g. rafts, turtle
30 structures, etc.) and (3) a down-dip compressional fold and thrust belt (Morley et al., 2011;
31 Rowan et al., 2000; 2004; Schultz-Ela, 2001; Hudec and Jackson, 2004). Evaporite properties
32 allow for an efficient decoupling in any condition, but shale levels are considered to be mobile
33 only when overpressured (e.g. Mourgues and Cobbold, 2006).

34 Overpressurization is commonly attributed to compaction disequilibrium, resulting either
35 from rapid sedimentation of low permeability materials, or fluid generation and expansion (e.g.
36 hydrocarbon maturation, clay diagenesis, Tingay et al., 2007; Morley et al., 2018; Blouin et al.,
37 2020). However, alternative explanations to this phenomenon have also been proposed (such as a
38 decrease of friction coefficient due to graphite, Rutter et al., 2013) as it partly fails to explain
39 mobilization of shales having already gone under significant burial, as well as fluidization of
40 clays (Soto et al., 2021). Gravity-driven collapse related to shale mobilization is observed in
41 many regions including the South Atlantic Margins (e.g. Niger Delta, Amazon Fan), the South
42 Australia Margin (Ceduna Sub-Basin), the Southeastern Asia and Indian Ocean margins (e.g.
43 Baram and Rovuma Deltas, Krishna Godavari domain), as well as in back-arc basins and
44 compressional prisms (e.g. Alboran Sea, Venezuela and Makran prisms) (Ahmed et al., 2022;
45 Hudec and Jackson, 2004; Choudhuri et al., 2010; Reis et al., 2010; Ruh et al., 2018; Soto et al.,

46 2021b; Corredor et al., 2005; Cruciani and Barci, 2016; Deville et al., 2006; Duerto and McClay,
47 2011).

48 Involvement of salt-like deformation in shale tectonics (e.g. diapirs, minibasins, welds,
49 etc.) has long been debated, following developments of deep offshore seismic acquisition on the
50 one side, improvement of seismic imaging and processing techniques on the other (Morley and
51 Guérin, 1996; Soto and Hudec 2021; Soto et al., 2021a, b, among others). Understanding of shale
52 mechanics helped to set the ground for understanding the ability of already compacted and
53 cemented shales to behave in a viscous manner (Brown, 1990; Soto et al., 2021a) and salt-like
54 shale tectonics was put at the forefront in various settings recently (e.g. Hudec and Soto 2021;
55 Dinc, 2020; Back and Morley 2016; Ruh et al., 2018).

56 Our study gives insights into the involvement of massive shale mobilization, over more
57 than 10^5 km², during the development of the Ceduna Sub Basin which consists of two
58 structurally independent and yet laterally stacked deltas, namely the Albian to Cenomanian
59 White Pointer Delta and the Campanian to Maastrichtian Hammerhead Delta (WPD & HHD)
60 above thick shale detachments (figure 1, Espurt et al., 2009; Totterdell et al., 2000; Ahmed et al.,
61 2022). Here we focus on the WPD, which has been subjected to shale mobilization all along its
62 development, evolving from salt-like shale flow to fluidization.

63 **GEOLOGICAL SETTING**

64 The Great Bight Basin (GBB) is part of the south Australia passive margins. The offshore
65 portion of it is composed of five sub-basins, among which the Ceduna Sub-Basin stands as a Late
66 Jurassic-Early Cretaceous rifted basin, covered by a maximum of 15km of Late Jurassic to Late
67 Cretaceous sediments, which propagated the break up during Early Cretaceous between Australia
68 and Antarctica (figure 1). The post-rift succession starts with the continental, Berriasian-Lower

69 Valanginian Southern Right and Valanginian to Mid Albian Bronze Whaler megasequences
70 (Totterdell et al. 2000).

71 The Ceduna Sub-basin gravity-driven and collapsing deltaic supersequences initiated
72 during the Late Albian-Santonian marine WPD, which involved massively the Albian Blue
73 Whale shale detachment (BW, figure 1B1, Espurt et al., 2009). This megasequence is formed of
74 two collapsing, gravity-controlled, systems (figure 1B2, see Ahmed et al., 2022 for a review).
75 First, a Late Albian-Early Cenomanian gliding system (Ahmed et al., 2022), located in the core
76 of the basin composed of a set of extensional up-dip listric faults, connected to the early downdip
77 thrust faults. This collapse system is followed by a Late Cenomanian set of extensional listric
78 faults initiating in the core of the delta and associated to down-dip thrust faults, offsetting the
79 earlier thrusts, which form a buttress for the main collapse system and localizes the decollement
80 of the secondary collapse system (Ahmed et al., 2022).

81 The deep margin uplift (Hill et al., 2019) results in the cessation of gravity gliding and a
82 slight inversion phase for the WPD. The deposition of the Turonian-Santonian Tiger
83 megasequence is coeval with the final separation of Australia and Antarctica (Totterdell et al.,
84 2000), and the Late Santonian-Maastrichtian Hammerhead megasequence (HHD), starts to
85 develop above the WPD.

86 **DATA AND METHODS**

87 The main dataset used in this study is the Ceduna PSDM 3D cube acquired by PGS in
88 2011. The survey covers an area of 12,413 km² with an inline and cross-line spacing of 12.5m
89 and 15m respectively (see figure 1A for cube and lines orientation). On top of this Ceduna
90 dataset, additional 2D seismic composite lines are used to connect the 3D survey up-dip to the
91 nearest exploration wells to have seismic marker ties, and down-dip to the distal margin. The 2D

92 lines (used in particular to tie the cube to the existing well but not displayed in the figure) were
93 extracted from the 2001 PSTM Flinders survey (lines w00fdw003, 0014 and 0023), 1997 AGSO
94 2D PSTM survey (line GA199-05B), and 1986 2D PSTM BMR 1986 survey (lines 065-07P1,
95 02P2, and 09P1) (Espurt et al. 2009; Totterdell and Bradshaw, 2004).

96 Three offshore wells have been used to tie the seismic picking to stratigraphic horizons,
97 Potoroo-1, Jerboa-1 and Gnarlyknots-1A, which are located outside the 3D survey, yet crossed
98 by the 2D regional lines (Totterdell et al., 2000; Dinc, 2020). Four key horizons are used in this
99 study (figure 1D): the top Blue Whale (BW, Late Albian), the top White Pointer (Cenomanian to
100 Early Turonian), the top Tiger (Late Turonian to Santonian), and the top upper Hammerhead
101 (Maastrichtian). Based on the recent recognition of the early collapse system (BW to lower
102 WPD, Ahmed et al., 2022), we also tracked three additional horizons: two within the WPD (the
103 Top Lower-Mid WP and Top Mid WP), and one within the Tiger Formation (Mid Tiger), where
104 they get available as they do not continuously extend and/or are poorly tied outboard the core of
105 the Ceduna Sub-Basin.

106 **RESULTS AND DISCUSSION**

107 A representative inline (n°2150), together with a connecting xline (n°11000) (figure 1A)
108 are displayed in figure 2, associated with two time slices from the 3D dataset, localized at 8km
109 and 5km depth, i.e. cutting through the BW and the Upper WPD megasequences respectively
110 (figure 3). In that perspective, the 8km depth time slice focuses on the first collapse system (Mid
111 Albian to Early Cenomanian) whereas the 5km depth time slice investigates the late stage of
112 evolution of the second collapse system (Early Cenomanian to Early Turonian).

113 **Evidence of shale mobility**

114 Evidence for salt-like shale mobility is mostly confined to the core of the Ceduna Sub-
115 Basin, where the phenomena is stratigraphically constrained to the early collapsed system
116 (Lower WPD). It mainly consists of low angle wedging observed at the edges of flat, low-
117 dipping depocenters, which abut chaotic ridges which are composed of mobilized shales (figure
118 2 A1-2, B1-2). These depocenters form pod-like minibasins with internal unconformities related
119 to their successive stages of growth. They present onlaps on the slopes of the ridges (Figure 2A1-
120 2, B2), similar to the shale-controlled minibasins observed onshore in the Makran (Ruh et al.,
121 2018). These minibasins are controlled by the ductile flow of the underlying BW shales, and
122 show an elongation parallel to the overall gliding direction (figure 3B1).

123 To the north, the proximal domain of the delta lacks good examples of minibasins.
124 However, when expressed, the top part of the depocenters localize the decollement horizon
125 responsible for the secondary collapse system development (figure 2A-A2-4). On the contrary,
126 within the distal domain of the WPD (figure 2B), these depocenters appear to be well expressed
127 and duplicated by a major thrust plane localized onto the BW detachment level (figure 2A, A1-2,
128 B2, figure 3A2, figure 4d-e). This part of the sub-basin shows extensive patterns of shale
129 mobilization controlling a large portion of Early WPD deposits downlapping onto the BW
130 shales. Above the duplexes, the transported depocenters show a more mature pattern, with
131 numerous welds and remnant of mobile shale masses separating the depocenters (figures 2B3-4).
132 Localization of the compressional deformation on these duplexes is associated with the decrease
133 of decollement depth and correlatively of the translated listric fault spacing (figure 2B1).

134 Shale mobility is quickly abandoned and buried beneath the growing WPD as early as the
135 first stage of gravity collapse (Late Albian-Early Cenomanian), displayed by the abandonment of
136 the early minibasins, passively transported and buried (figures 2A-B). During their burial, these

137 early minibasins are crosscut and deformed in the distal part by the development of fold and
138 thrusts related to the propagation of gravity collapse basinward. After the end of the WPD
139 deposition, transported minibasins are progressively welded, squeezing the shale plugs (figure
140 2B). During the Upper Tiger deposition, domal uplifts (figure 2A5) show the development of
141 sets of both radial and concentric normal faults (figure 3B1), which are stratigraphically
142 bracketed during the deposition of the lower HH Formation, and rooted in the top WPD deposits.
143 Polygonal faults system in the core of these radial normal faults sets, confined in this
144 stratigraphic interval, suggest high overpressures and two types of shale mobilization, here
145 involving fluidization (figure 3B1).

146 **Imbrication of gravity collapse: an updated scenario**

147 Both salt-like shale mobilization and shale fluidization together with the duplication of
148 the early minibasins along thrust faults are key features, improving the delta kinematic scenario
149 (figure 4). Following the deposition of the BW shales, early clastics of the lowermost WPD
150 megasequence trigger shale mobilization in the distal part (e.g. Morley et al., 2018), resulting in
151 the building of small, down-dip elongated, withdrawal minibasins similar to what is observed in
152 the western Gulf of Mexico (McDonnell et al., 2010; figure 4a, b), while the early collapse
153 system develops up-dip (figure 4b-c). During Early Cenomanian, the WPD early collapse system
154 forms in the inner domain and progressively migrates downdip, reactivating early developed
155 down-dip toe thrust (figure 4d). Buttressing against the early thrusts and deep margin uplift helps
156 to localize the major thrust duplex within the thickest part of the basin during the deposition of
157 the upper WPD sequence, duplicating the early minibasins (figure 4d-e). Although the ramp
158 developed at the toe of the delta slows down the WPD collapse, it favors the focus of shortening
159 above the major thrust and subsequent squeezing of the transported shale diapirs. This leads to

160 the final fluidization of the shales after Tiger deposition (figure 4e-g, Turonian). The entire WPD
161 system eventually gets frozen beneath the HHD megasequence (figure 4h).

162 **Controlling factors of shale mobility**

163 Even though bowl-shaped, subsiding depocenters (i.e. minibasins bordered by rising
164 chaotic mobile masses) are common features in salt tectonics, withdrawal depocenters related to
165 mobile shales are less common, yet repeatedly proposed and generally attributed to overpressures
166 and undercompaction during rapid sedimentation (e.g. Morley et al., 2018). In the case of early
167 WPD deposits, we suggest that the early shale mobilization is not related to the overpressure
168 with increasing burial depth due to clay dewatering, they are rather large mobile masses of
169 poorly compacted, water-rich unconsolidated sediments, with low viscosity and density,
170 mobilized early following their deposition, similarly to the olistrostromes of the Makran Prism
171 (Ruh et al., 2018). Early mobility is responsible for mechanical weakening of the shale masses
172 by penetrative deformation, up to a critical state, while repeated input of sediments increases
173 loading and pressurization and maintains the mobile shales at a critical state for plastic
174 deformation (Soto et al., 2021; Hudec and Soto, 2021).

175 The late stage of shale mobilization, i.e. fluidization at the crest of squeezed shale plugs,
176 occurs during the Turonian-Santonian time. This is coeval with generation of oil in the Blue
177 Whale formation and gas within the synrift Bronze Whaler megasequence of the Jerboa-1 well
178 (Ruble et al., 2001), which is considerably less buried than the core of the basin. Basin modelling
179 of the Potoroo and Gnarlyknots wells suggest that the Turonian source rocks generated liquid
180 products as early as Campanian (Totterdell et al., 2008). Oil and gas generation and migration
181 most probably occurred much earlier within the deeper, gas prone synrift sequence, thus leaving
182 time for gas to migrate and reach the shale plugs and withdrawal minibasins undergoing

183 shortening above the main thrust fault. Gas generation has a strong impact on the mechanics of
184 shale, promoting the complete loss of cohesive resistance (Tingay et al., 2018; Blouin et al.,
185 2020), a mechanism which may help shales to achieve critical state and enhance mobility (Soto
186 et al., 2021a), eventually leading to fluidization and through fracturing processes, to loss of
187 material.

188 **CONCLUSION**

189 The Great Bight Ceduna Sub-Basin displays a multi stage gravity collapse solely based
190 on shale mobility, over an area of more than 10^5 km², making the WPD one of the largest known
191 example of its kind at present. Our study shows that early shale mobilization led to the formation
192 of shale withdrawal minibasins at the distal part of the system, which eventually gets duplicated
193 in response to the propagation of the WPD collapse. A second stage of mobilization allows for
194 the fluidization of transported shale plugs due to hydrocarbon generation. More generally, our
195 results emphasize the need to consider salt-like mobilization of shale as a mechanism involved in
196 gravity-controlled tectonic systems and their evolution. Thus, even though salt and shales
197 tectonics bear thus strong analogies, contrarily to salt tectonics (i.e. halokinesis), argilokinesis
198 may involve a secondary deformation mechanism based on fluidization.

199 **ACKNOWLEDGEMENTS**

200 We thank TotalEnergies and the UPPA Chair of Structural Geology for funding this
201 project. We also thank J.I. Soto, C. Morley, the anonymous referee and editor G. Dickens for
202 their insightful reviews of a first version of the article.

203 **FIGURE CAPTIONS**

204 Figure 1. A) Geographic setting of the Ceduna Sub-Basin, location of the 3D data set (with
205 displayed inlines and crosslines) and the utilized composite 2D regional seismic lines; B) Two

206 previously published interpretative cross-sections; C) Simplified lithostratigraphic chart and
207 main targeted horizons.

208 Figure 2. A) Two interpreted 3D seismic lines located at the distal part of the delta (inline 2150),
209 and B) cross view of the delta (xline 11000). A1 and A3) Examples of wedging patterns in the
210 lower White Pointer. A4 and A5) Examples of intra minibasin unconformities; A2 and B1)
211 Example of concentric normal faults above a shale plug. B1) The main zone of minibasin
212 duplexation; B2) Example of wedging patterns in the lower White Pointer; B3) example of of
213 translated WPD rollers and depocenters.

214 Figure 3. Top: 5km depth slice cutting across the Top WP/Tiger megasequence. A1 Concentric
215 rounded closures of translated minibasins. B1 Close up on the radial and concentric fault sets
216 associated to polygonal faults in the core ontop a shale dome. Bottom: 8km depth slice showing
217 the shale withdrawal minibasins base (lower WP). B2. Close up on the elongated withdrawal
218 minibasins' base.

219 Figure 4. Kinematic evolution scenario of Ceduna Sub-Basin, White Pointer Delta (for the sake
220 of simplicity the double collapse system of the WPD is not fully sketched).

221

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Response to the main comments and remarks by reviewers and Editor

Prof. J. Soto

Structures related to shale fluidification: Polygonal or radial faults around the culmination of shale diapirs are, by itself, non-diagnostic of fluidification. I recommend to revise the text in lines 143 to 145, for example, to better constrain the structures observed by the authors to document this process (e.g., fluid pipes, feeders and conduits for mud volcanoes, etc.).

We agree that polygonal cracks as well as radial faults may derive from other processes and that only fluid conduits and/or mud volcanoes would surely demonstrate the importance of the fluid role. Nevertheless, these features are quite common in fluid-controlled domains and rather scarce (apart from volcanics systems) elsewhere. However, mainly due to seismic resolution, those features have not been demonstratively been observed. On places such as the inline of figure 2, it may be suspected if zoomed accordingly (e.g. considering vertical succession of enhanced portion of the reflectors, ...), but we rather think that the observed association of stratigraphically bracketed polygonal fault system surrounded by radial and concentric faults is sufficiently well established and comparable to other fluidized shale systems (e.g. Nigeria, offshore Azerbaijan, ...) to propose that the same phenomenon has occurred too in the Ceduna Sub-basin as well.

Include some information about timing of the sequences in figures 1 and 2. Nowadays, it is rather difficult to correlate many of the statements in the text regarding timing with those illustrations, because these figures do not contain any information regarding the age of the sequences and/or the key reflectors.

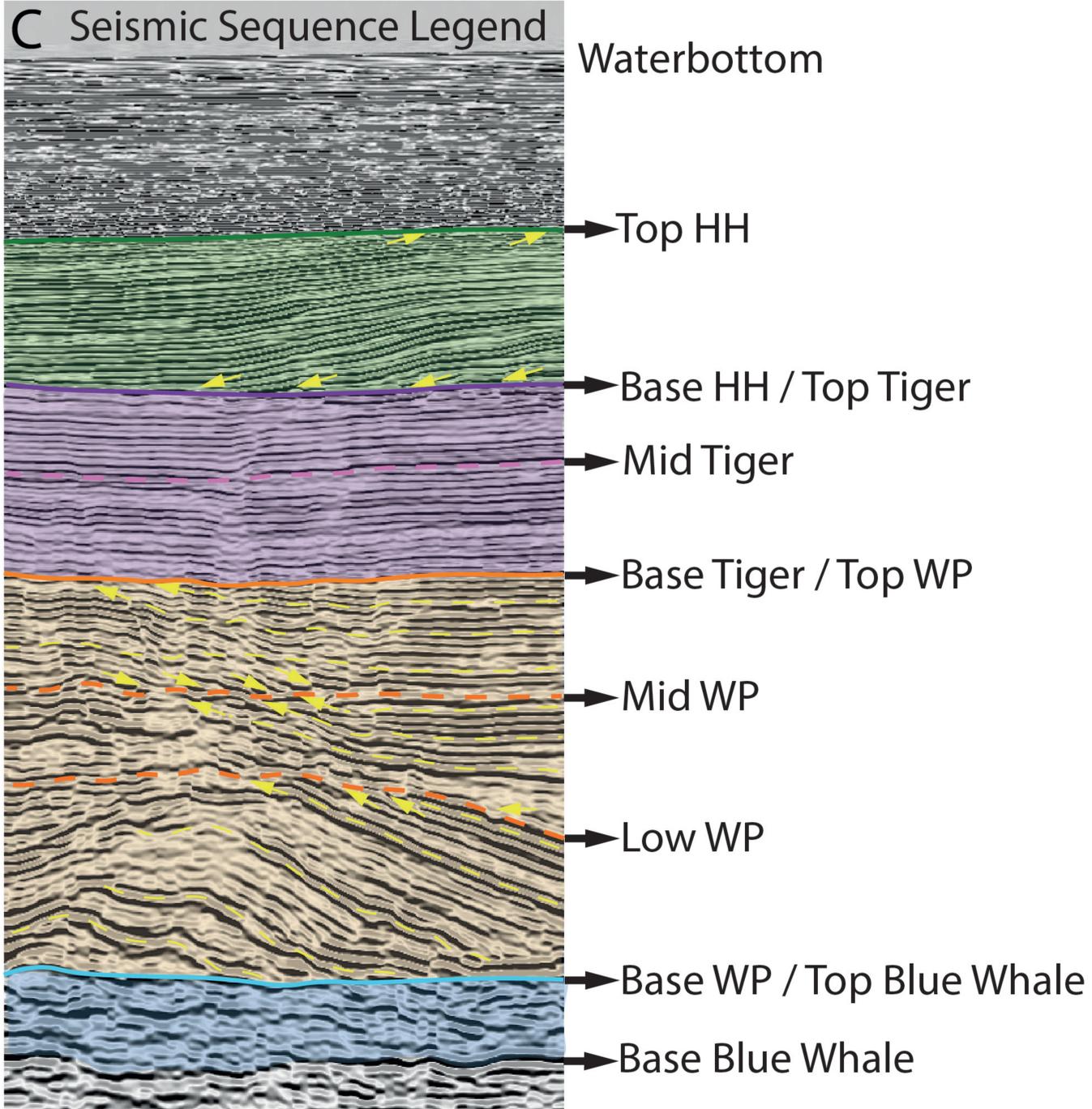
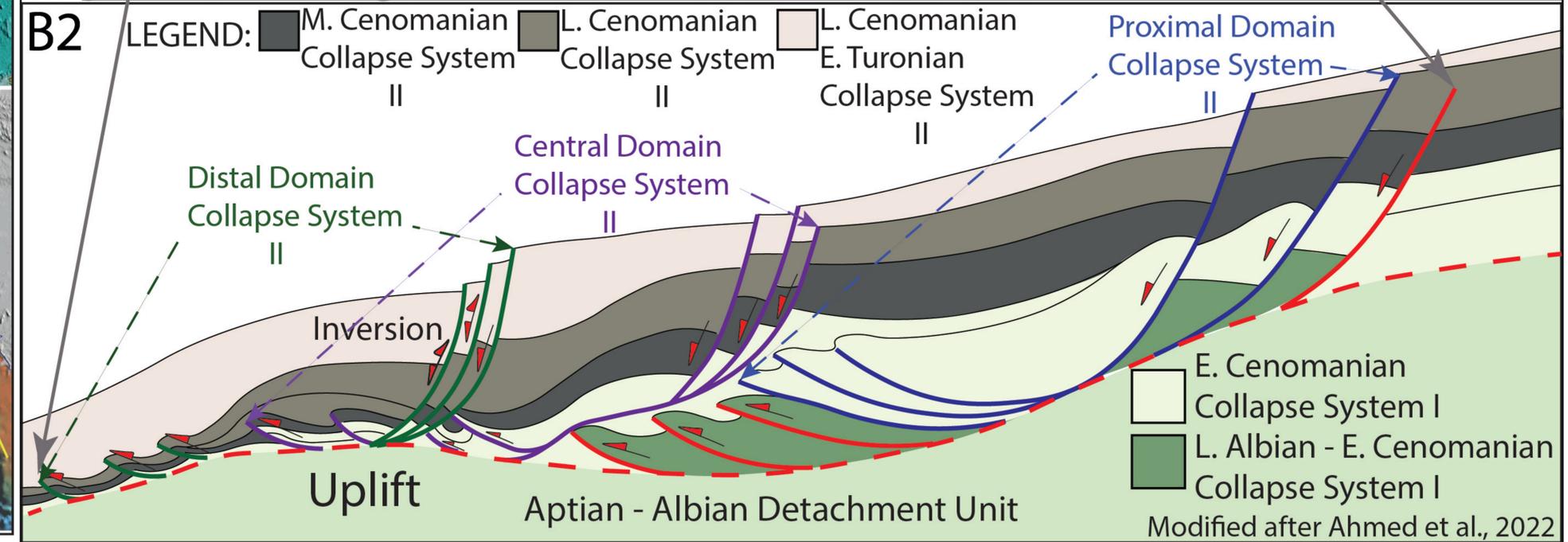
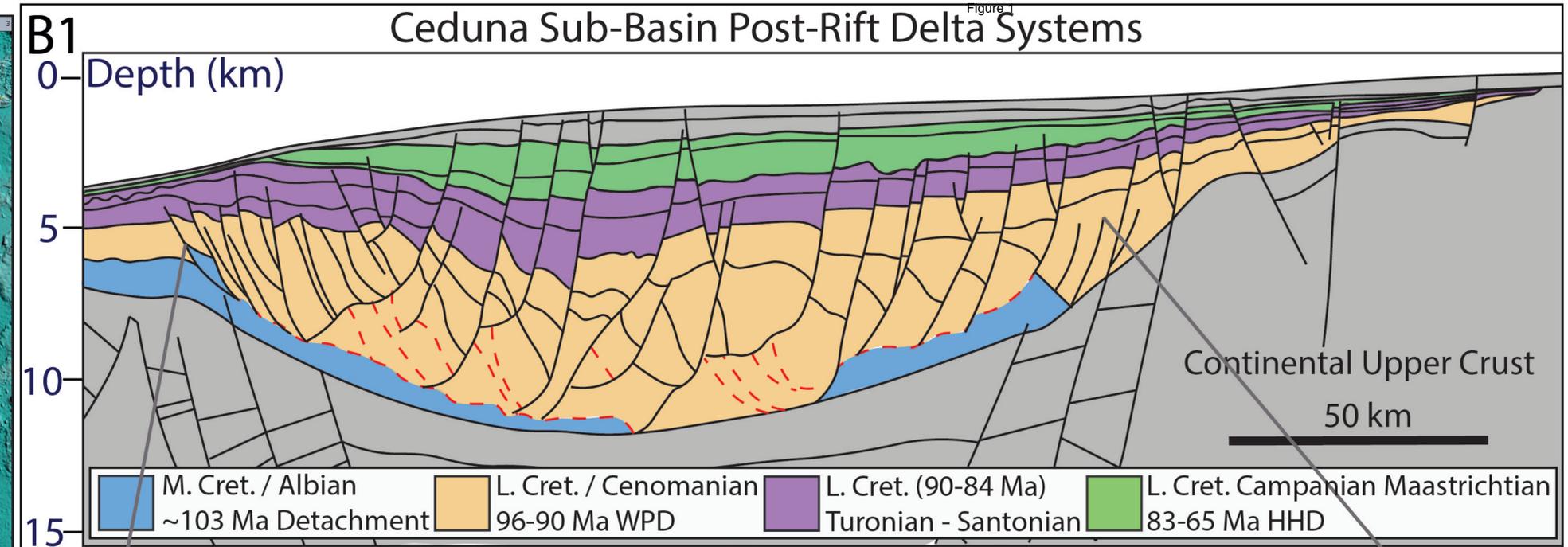
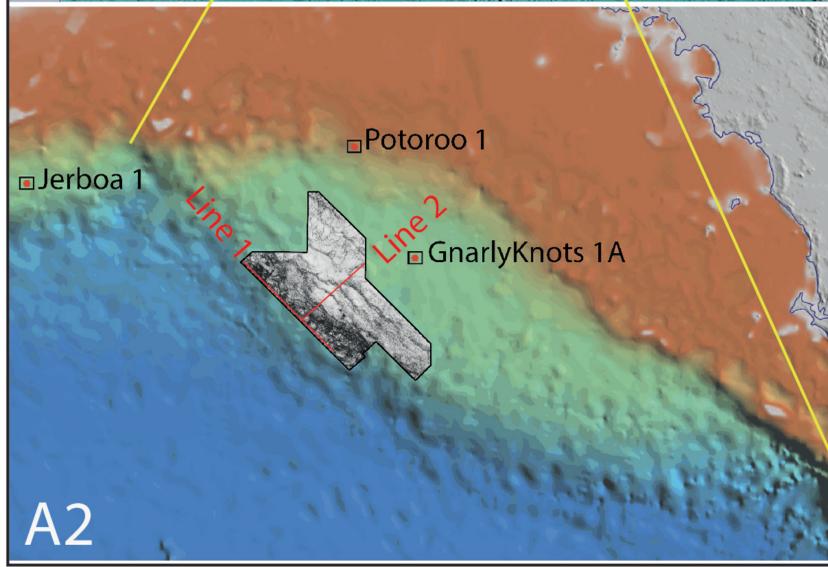
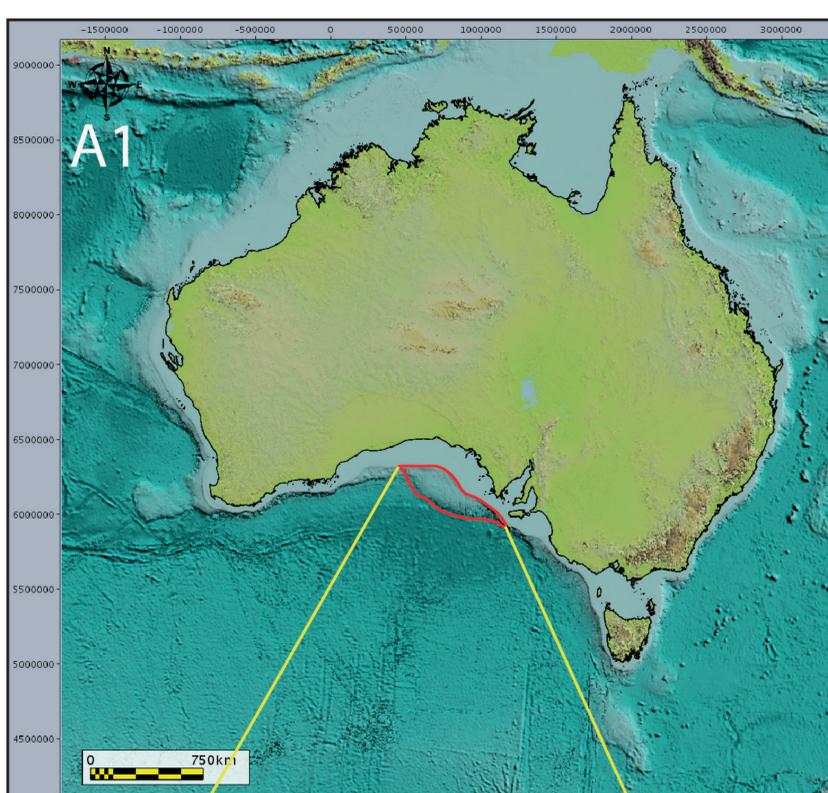
This is right and the figures have been modified accordingly and the labelling referred too better in the body of the manuscript.

All remarks made on the associated pdf file have been taken into account.

Pau, September the 20th 2022,

On behalf of G. Dinc and co-author, JP Callot





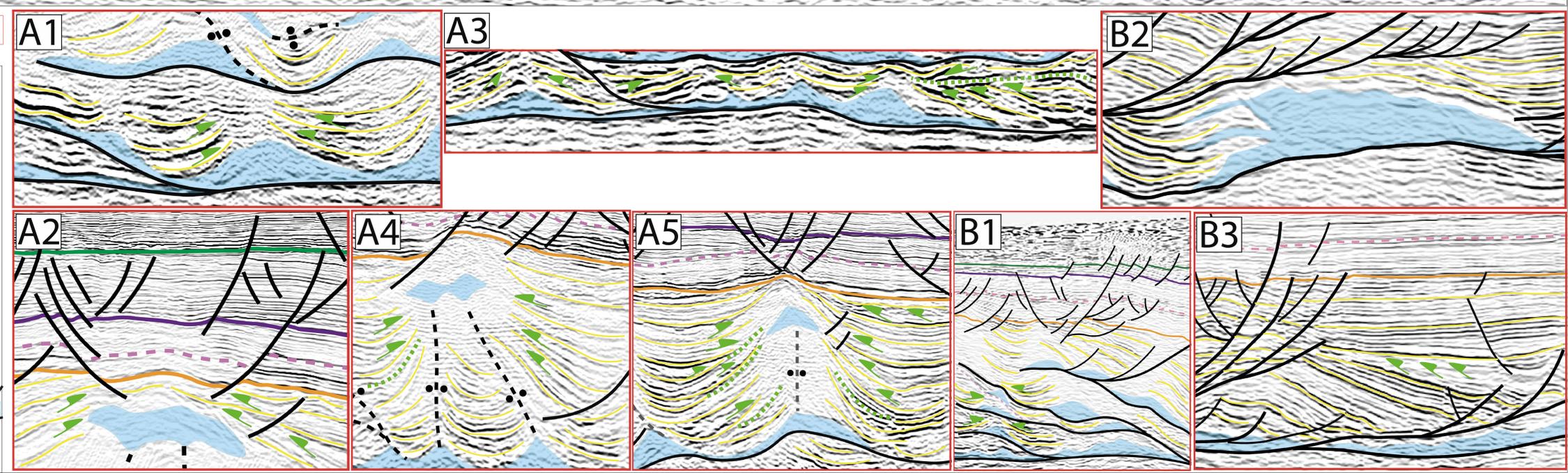
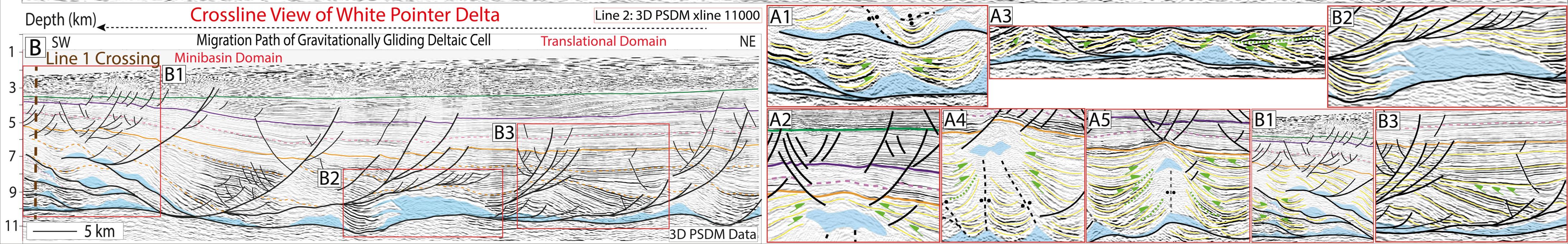
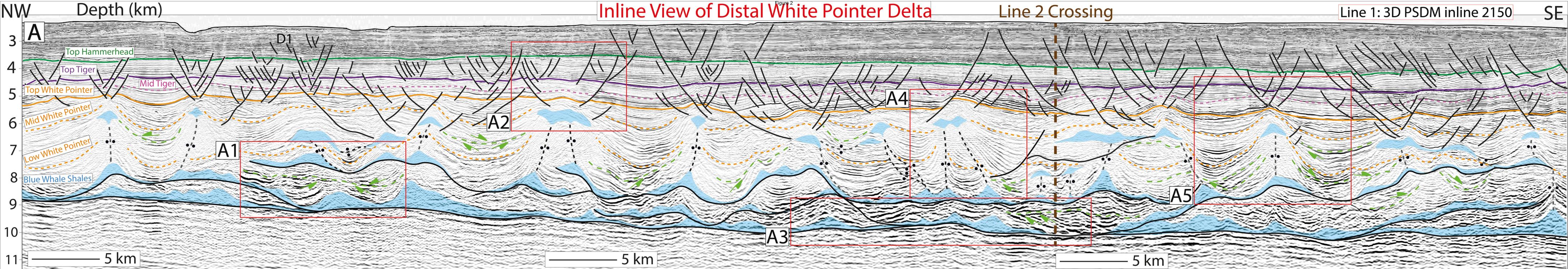
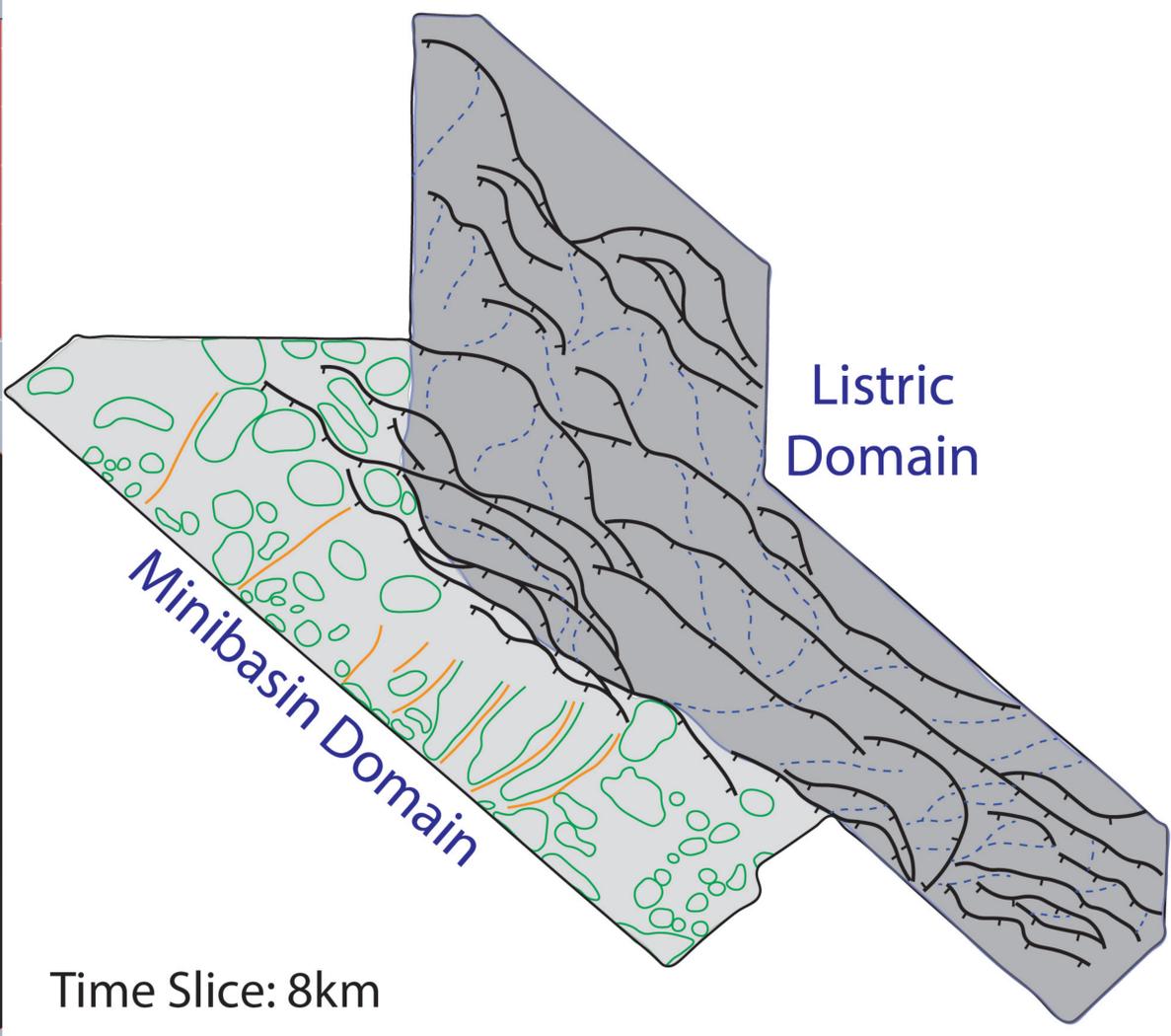
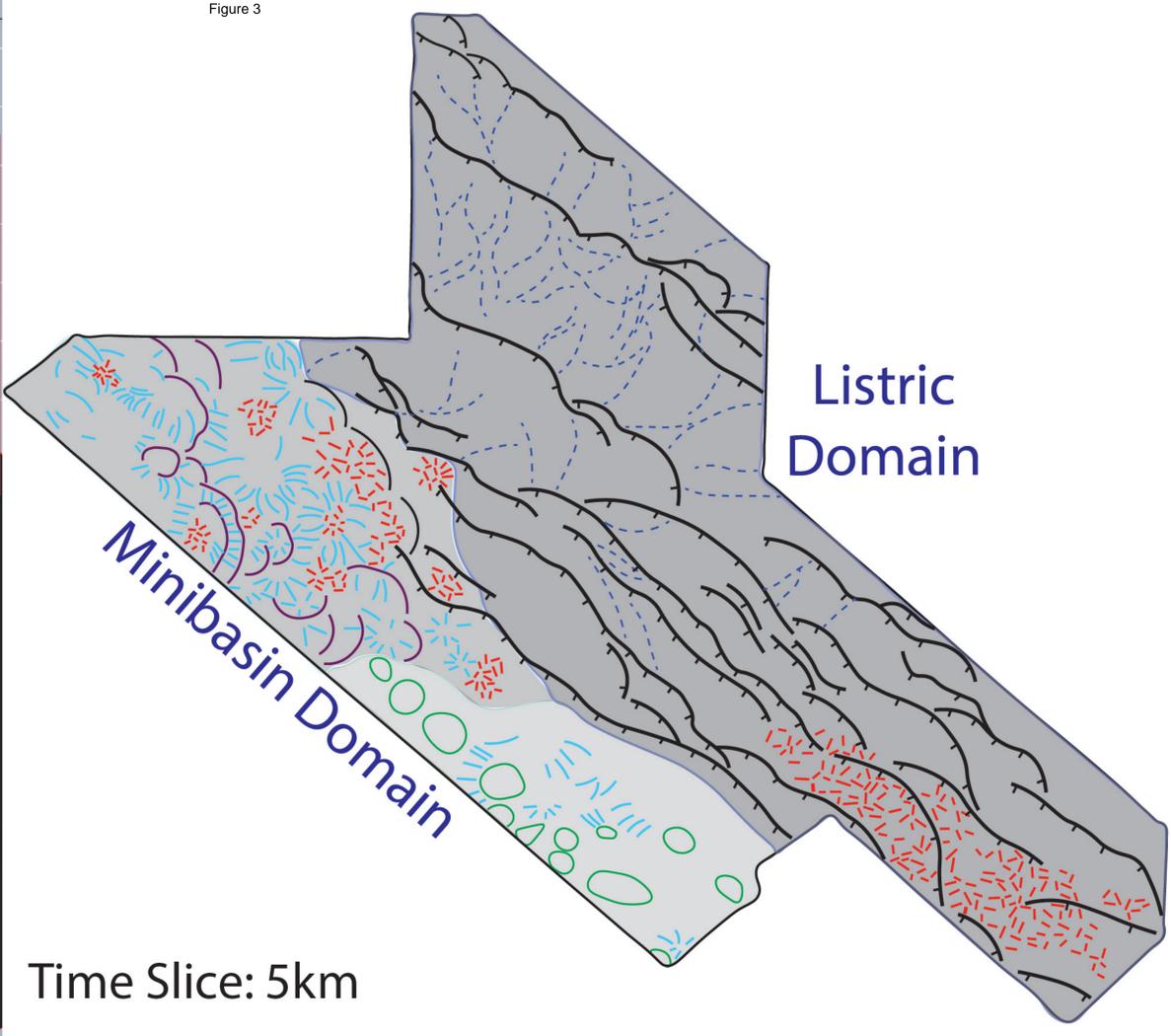
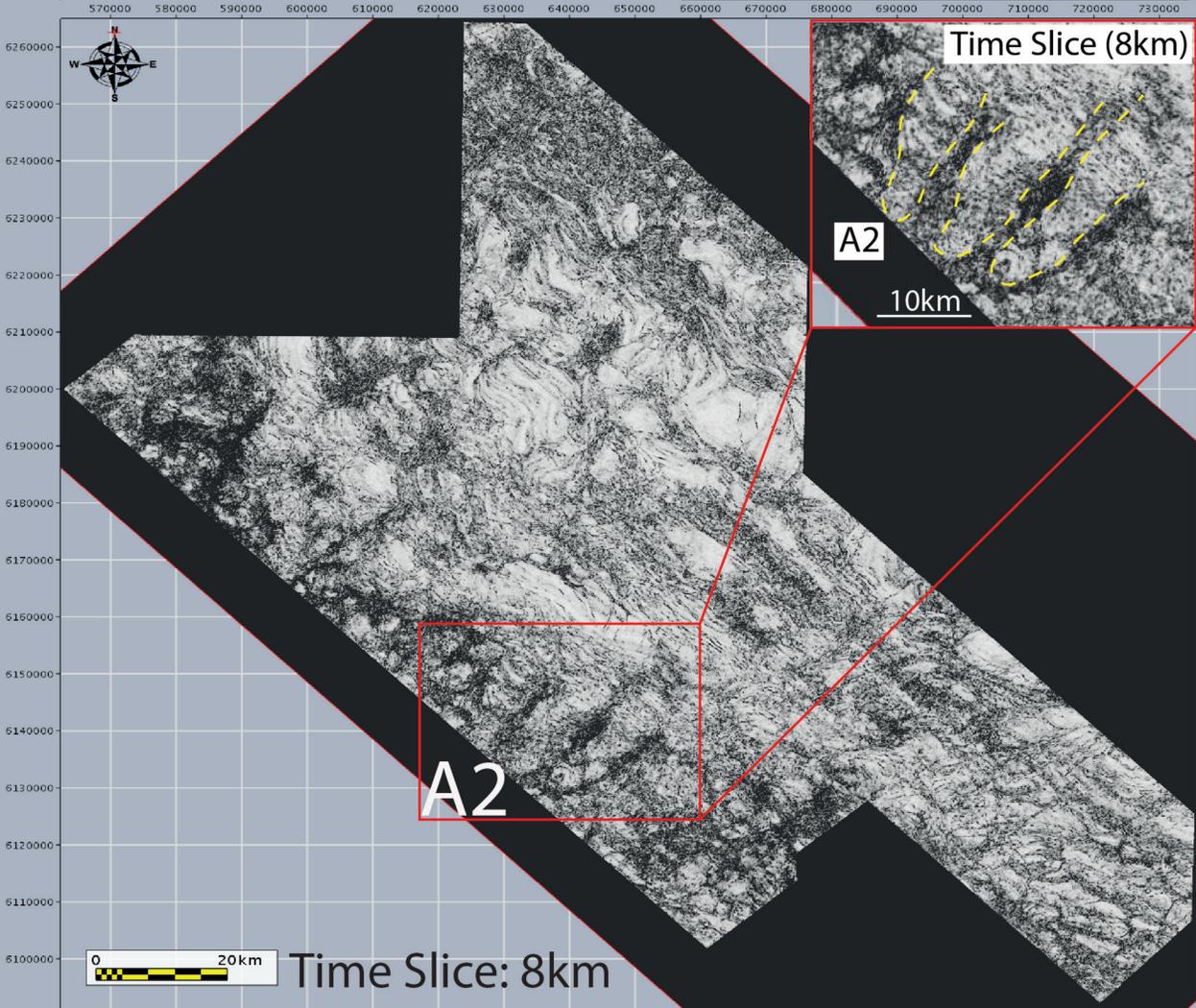
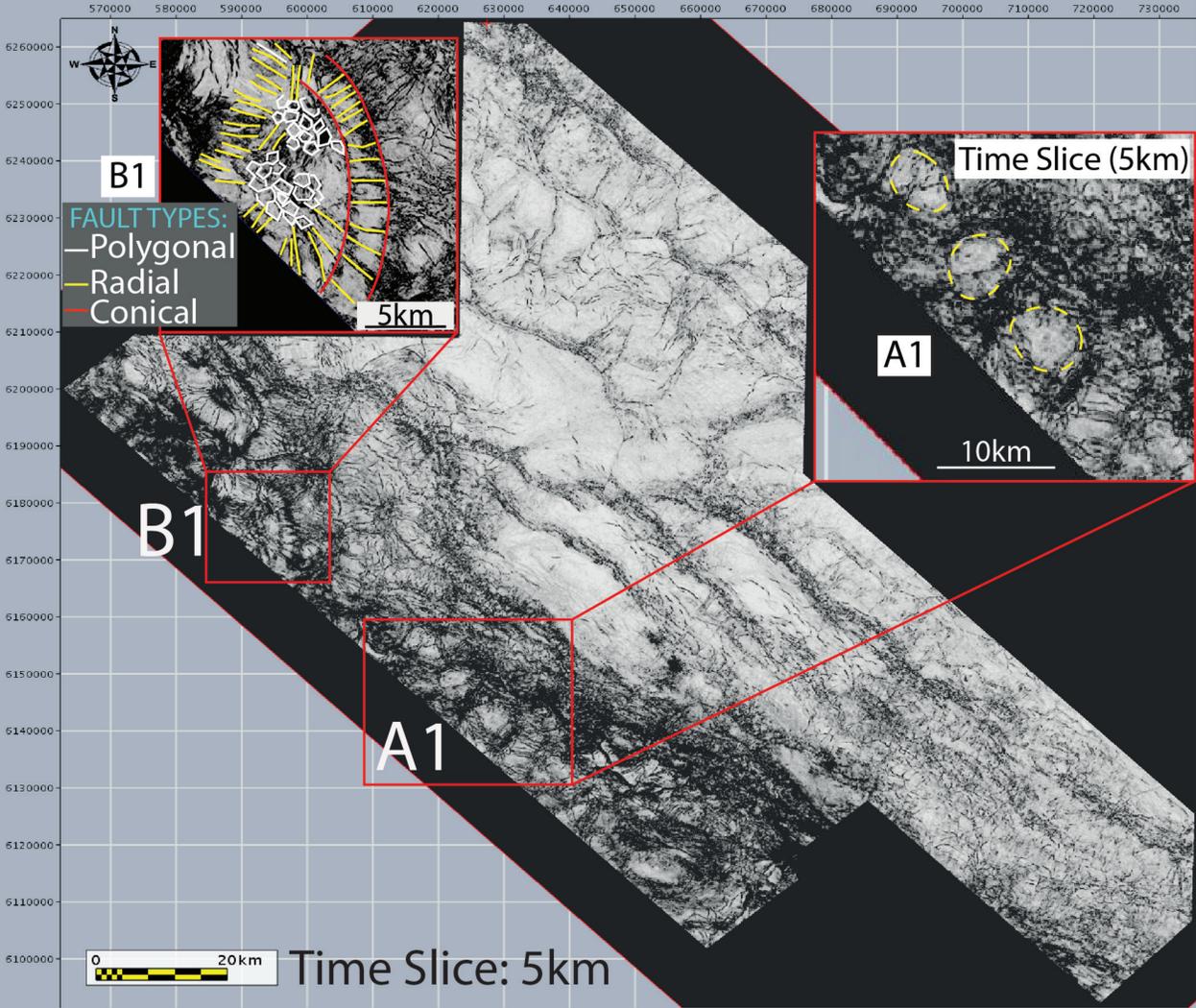


Figure 3



LEGEND:	
Listric Faults	
Strike Slip Faults	
Conical Faults	
Radial Faults	
Polygonal Faults	
Minibasin Closures	
Shale Ridges	
Listric Fault Domain	
Radial Faults Surrounding Diapiric Depressions	
Minibasin Features: Circular vs Elongated	

