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Shelf-derived mass-transport deposits: origin and significance in the stratigraphic development of trench-slope basins

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23 1. ABSTRACT

24 Continental shelves generally supply large-scale mass-wasting events. Yet, the origin and significance
25 of shelf-derived mass-transport deposits (MTDs) for the tectonostratigraphic evolution of subduction
26 complexes and their trench-slope basins have not been extensively studied. Here, we present high-
27 resolution, outcrop-scale insights on both the nature of the reworked sediments, and their mechanisms
28 of development and emplacement along tectonically active margins, by examining the Middle Miocene
29 shelf-derived MTDs outcropping in the exhumed southern portion of the Hikurangi subduction margin.
30 Results show that periods of repeated tectonic activity (thrust propagation, uplift) in such compressional
31 settings not only affect and control the development of shelfal environments but also drive the recurrent
32 generation and destruction of oversteepened slopes, which in turn, favour the destabilisation and
33 collapses of the shelves and their substratum. Here, these events produced both large-scale, shelf-
34 derived sediment mass-failures and local debris flows, which eventually broke down into a series of
35 coalescing, erosive, genetically-linked surging flows downslope. The associated MTDs have a regional
36 footprint, being deposited across several trench-slope basins. Recognition of tectonic activity as another
37 causal mechanism for large-scale shelf failure (in addition to sea-level changes, high-sedimentation
38 fluxes) has implications for both stratigraphic predictions and understanding the tectonostratigraphic
39 evolution of deep-marine fold-and-thrust belts.

40 **Keywords:** active margin, shelf failure, intra-slope basins, mass-wasting deposits, outcrop study,
41 tectonics

42 2. INTRODUCTION

43 Along active margins, tectonics predominate and exert a crucial control on the stratigraphic development
44 of the related sedimentary basins (e.g., trench-slope basins) and their basin-bounding structures (Moore
45 and Karig 1976; Karig et al. 1980; Underwood and Bachman 1982; Chanier and Ferrière 1991;
46 Underwood and Moore 1995; Bailleul et al. 2013; McArthur et al. 2019). Recurrent mass-wasting occurs
47 and thus, associated mass-wasting products, known as mass-transport deposits (MTDs) form throughout
48 the margin's history, flanking the sedimentary basins, such as trench-slope basins (Moore and Karig
49 1976; Underwood and Bachman 1982; Bailleul et al. 2007; Vinnels et al. 2010; Festa et al. 2015; Ortiz-
50 Karpf et al. 2018; McArthur et al. 2019).

51 A diverse range of MTDs has been described along tectonically active margins (Moscardelli and Wood
52 2015; Festa et al. 2016 and references therein) and numerous studies have investigated the potential
53 causal mechanisms for the related mass-wasting events (e.g., Pickering & Corregidor 2005; Moscardelli
54 et al. 2006; Lamarche et al. 2008; Romero-Otero et al. 2010; Vinnels et al. 2010; Gamberi et al. 2011;
55 Nelson et al. 2011; Strasser et al. 2011; Urgeles & Camerlenghi 2013; Ogata et al. 2014; Alves 2015;
56 Lehu et al. 2015; Festa et al. 2016; Ortiz-Karpf et al. 2018; Festa et al. 2019; Moore et al. 2019; Ogata
57 et al. 2019; Raymond 2019; Carey et al. 2019).

58 Based on the relationships that exist between their source region, sizes, and potential causal
59 mechanisms, Moscardelli and Wood (2008) and Moscardelli and Wood (2015) proposed to refine the
60 classification of mass-wasting products by grouping them into *attached* and *detached* systems,
61 respectively (1) sourced from regional (e.g., shelf) or local slopes; (2) regionally extensive (potentially
62 reaching hundreds to thousands of square kilometres in area, tens of kilometres in width and length, and
63 hundreds of metres in thickness) or smaller, local (occupying less than tens of square kilometres in area
64 and a few kilometres in width and length); and (3) essentially controlled by extrabasinal regional
65 processes (e.g., climate) or localised gravitational instabilities (Figure 1).

66 Continental shelves unequivocally supply some of the greatest mass-wasting events and deposits
67 recorded worldwide (i.e., *attached* systems) (Posamentier and Walker 2006). Yet, the origin and
68 significance of shelf-derived mass-wasting products for the tectonostratigraphic evolution of subduction
69 complexes and their related trench-slope basins have not been extensively scrutinised.

70 In this study, we propose to address this knowledge gap by presenting new occurrences of mass-wasting
71 systems, sourced from the shelf, cropping out in the emerged southern portion of the Hikurangi

72 subduction wedge (Coastal Ranges, North Island of New Zealand) (Figure 2). The related products are
73 Middle Miocene in age and include several episodes of mass-wasting that reworked shelf-derived
74 material (macrofaunas and sediments), can reach over 100 metres (minimum thickness, not
75 decompacted) at outcrop and were deposited across several trench-slope basins along a 70 kilometre-
76 long transect (Whareama, Te Wharau and Akitio trench-slope basins) (Figure 3).

77 Most studies on the shelf-derived mass-wasting events and deposits are based on seismic-reflection
78 data. Therefore, this work aims at bringing new high-resolution, outcrop-scale insights on both the nature
79 of the reworked sediments, and the mechanisms of development and emplacement of these MTDs along
80 tectonically active margins. Sea-level changes and high sedimentation rates are commonly inferred to be
81 the main causal mechanisms triggering the large-scale destabilisation, downslope mass-transport and
82 resulting deposition of shelf-derived sediments into deep-water (Posamentier and Kolla 2003; Moscardelli
83 and Wood 2008; Moscardelli and Wood 2015; Bull et al. 2020). Yet, the role of tectonics is undoubtedly
84 important, particularly along active margins (e.g., Lewis et al. 2004; Lamarche et al. 2008; Watson et al.
85 2020; Couvin et al. 2020).

86 Here, we specifically explore how continued period of tectonic activity (shortening, uplift and related
87 seismicity) can lead to the recurrent generation and destruction of oversteepened slopes at the shelf-
88 margins and in turn favour the repeated destabilisation and collapses of the shelf(ves).

89 Specific objectives are to:

- 90 • Describe the nature, geometries and internal characteristics of the reworked sediments (e.g.,
91 lithofacies) and assess the implication for subsurface assessment of similar, seismic-scale
92 MTDs,
- 93 • Gain a better understanding on the mechanism of development and emplacement of shelf-
94 derived MTDs in subduction complexes,
- 95 • Use the lithofacies and their associations to reconstruct the depositional environments and
96 palaeogeography of the Coastal Ranges of the Hikurangi Margin during the Middle Miocene,
- 97 • Highlight the role of shelf-derived MTDs as markers of the tectonic activity in mature trench-
98 slope basins.

100 **3.1. Geological history**

101 The Hikurangi subduction wedge started to form about 25 Ma ago as a result of the westward subduction
102 of the oceanic Pacific Plate beneath the Australian Plate along the eastern margin of the North Island of
103 New Zealand (Figure 2) (Ballance 1976; Spörli 1980; Pettinga 1982; Chanier and Ferrière 1991; Field et
104 al. 1997; Nicol et al. 2007).

105 Bounded by the Hikurangi Trench to the south-east and the Forearc Basin *sensu stricto* to the west, the
106 Hikurangi subduction wedge is made of a series of elongate, trench-parallel intra-slope basins (*i.e.*,
107 trench-slope basins (*sensu* Underwood and Moore 1995)) separated and confined by tectonically active,
108 sublinear bathymetric highs that are controlled by underlying landward-dipping thrust faults and
109 asymmetrical seaward-verging folds (Lewis and Pettinga 1993; Barnes et al. 2010; Bailleul et al. 2013;
110 Bland et al. 2015; McArthur et al. 2019).

111 Since the onset of subduction, the Hikurangi subduction wedge has undergone a complex and
112 polyphased tectonic history (Figure 4).

113 As the Pacific Plate began to subduct beneath the Australian Plate, the related compressional stresses
114 resulted in the seaward emplacement of ESE thrust nappes (25 – 18 Ma), on the back of which thrust-
115 bounded depocenters provided the necessary space for the development of trench-slope basins (17.5 –
116 15 Ma) (Pettinga 1982; Chanier and Ferrière 1989; Chanier and Ferrière 1991; Rait et al. 1991; Nicol et
117 al. 2007; Bailleul et al. 2013; Malie et al. 2017).

118 Then, from Middle to Late Miocene times (15 – 6.5 Ma), the entire margin experienced a period of mixed
119 N-S to NE-SW extension and compression, leading to general subsidence, gravitational collapses and
120 normal faulting in the inner portion of the wedge, as well as continued outward migration of the
121 deformation front in the middle and outer portions (Chanier 1991; Chanier et al. 1999; Barnes et al. 2002;
122 Bailleul et al. 2013).

123 Finally, from the Late Miocene to present-day (6.5 – 0 Ma), renewed E-W to NW-SE compressional
124 deformation and tectonic inversion dominated the margin and resulted in regional folding and reverse
125 faulting. Shortening has accelerated within the last million year and has led to the uplift and emergence
126 of part of the inner portion of the subduction wedge (*i.e.*, trench-slope break), which now forms the Coastal
127 Ranges of the eastern North Island of New Zealand (Figure 2) (Lamb and Vella 1987; Cape et al. 1990;

128 Chanier 1991; Chanier et al. 1999; Nicol et al. 2002; Nicol et al. 2007; Bailleul et al. 2013) and outboard
129 frontal accretion (Barnes et al. 2018).

130 The close interplay between the evolution of the margin and the development of the associated
131 sedimentary basins resulted in intricate trench-slope basin fills that are disrupted by a series of
132 discontinuities (Neef 1992; Neef 1999; Bailleul et al. 2007; Bailleul et al. 2013; Burgreen and Graham
133 2014; McArthur et al. 2019).

134 Their fills mostly comprise Miocene to Recent deep-marine gravity-driven deposits, extensive marine
135 hemipelagic mudstones and carbonate deposits (Figure 4) (Field et al. 1997; Lee and Begg 2002; Bailleul
136 et al. 2007; Bland et al. 2015; McArthur et al. 2019). They conformably or unconformably overlie the
137 Cretaceous to Paleogene pre-subduction basement, which can be divided into two main assemblages:
138 (1) the Lower Cretaceous Torlesse greywackes, witness of an older accretionary prism developed along
139 the south-eastern margin of Gondwana at the time (Spörli 1980; Bradshaw 1989; Mortimer 2004); and
140 (2) the Upper Cretaceous to Oligocene series evolving from detrital to pelagic sediments eastward (Figure
141 4) (Chanier and Ferrière 1991) and indicating a sustained period of tectonic quiescence (Chanier 1991;
142 Chanier and Ferrière 1991; Bailleul et al. 2013).

143 **3.2. Whareama and Te Wharau Basins**

144 The study area is located in the southern Coastal Ranges, and more particularly in the exhumed
145 Whareama and Te Wharau Basins (Figure 3; Figure 5).

146 The Whareama Basin is an elongate, NE-SW trench-parallel slope basin (Figure 3), ~50 kilometres long
147 and two to six kilometres wide, bounded by basement ridges composed of pre-Miocene strata (Chanier
148 1991). It started to form contemporaneously with the onset of subduction on the backlimb of the Glenburn
149 Nappe, a seaward-verging thrust nappe (Chanier 1991; Chanier and Ferrière 1991) that is composed of
150 Lower Cretaceous Torlesse greywackes and Upper Cretaceous to Eocene pelagic to detrital series
151 (Figure 4; Figure 5). Its sedimentary fill unconformably to conformably overlies the Glenburn Nappe and
152 is bounded to the west by the Adams-Tinui Fault complex and Pukeroro Fault (*i.e.*, landward basin
153 margins, Figure 3; Figure 5) and to the east by the Flat Point-Whakataki Fault complex (*i.e.*, seaward
154 basin margin, Figure 3; Figure 5).

155 The Te Wharau Basin is another elongate, thrust-bounded slope basin located in the emerged, inner-
156 portion of the subduction wedge (Figure 3). To the west of the Whareama Basin, the Te Wharau Basin is
157 smaller (~10 kilometres long), narrower (one to five kilometres wide) and oriented North-South (Figure 3;

158 Figure 5) (Chanier 1991; Bailleul et al. 2013). Its fill unconformably overlies the Lower Cretaceous
159 Torlesse greywackes (to the north) as well as the Upper Cretaceous to Eocene detrital series (to the
160 south) (Chanier 1991) (Figure 4; Figure 5). The Adams-Tinui Fault complex represents its seaward basin
161 margin (Figure 3), except in the central portion of the system, where it comprises two synclines and is
162 bounded by both the Adams-Tinui Fault complex and the Pukeroro Fault (Figure 5). Unlike the Whareama
163 Basin, the Te Wharau Basin only records deposits from the Middle to Upper Miocene (Chanier 1991).

164 3.3. Depositional systems

165 Gravity-driven deposits dominate the stratigraphic infill of trench-slope basins (Underwood and Bachman
166 1982; Underwood and Moore 1995; Underwood et al. 2003; Vinnels et al. 2010). Although submarine
167 canyons and channels play an undeniable role in the distribution of sediments, slope destabilisation can
168 act as another, agent of sediment delivery and reorganisation, triggering significant submarine mass-
169 failure and reworking (Underwood and Bachman 1982; Chanier and Ferrière 1991; Bailleul et al. 2007;
170 McArthur et al. 2019; McArthur and McCaffrey 2019).

171 In this study, we specifically focus on the Middle Miocene, Lillburnian (Late Langhian to Serravallian, 15.1
172 – 13.05 Ma) mass-wasting events that reworked shelf-derived material. The related mass-wasting
173 products crop out in the preserved portions of the Whareama and Te Wharau Basins, as well as in the
174 Akitio Basin farther north (Figure 3, sections b, c, n, r, s, tw).

175 Even though deep marine sedimentation dominated at the time, several contemporaneously developing
176 and older (Figure 4) shallow-marine, mixed siliciclastic-carbonate shelves were also reported in the area
177 (Figure 3, sections f, i, m, ms, o, p, t, w) (Crundwell 1987; Chanier 1991; Bailleul et al. 2007; Bailleul et
178 al. 2013; Caron et al. 2019; Bailleul et al. Submitted; Caron et al. 2021). Bailleul et al. (2013) and Bailleul
179 et al. (Submitted) demonstrated that whether attached to the continent or not, these shelfal systems
180 preferentially formed above trench-slope basin-bounding structures that were affected by active-margin
181 tectonic activity, such as uplift events. The abrupt shallowing provided the suitable depositional settings
182 (e.g., neritic conditions) for carbonates and biogenic sediments.

183 4. DATA AND METHODS

184 We undertook fieldwork in order to characterise the Middle Miocene strata outcropping in the southern
185 emerged portion of the Hikurangi subduction wedge. Over one kilometre of sea cliff outcrop along the
186 Whareama Basin coastline was mapped and studied through acquisition of photogrammetric data

187 (acquired from a drone), traditional fieldwork data (e.g., detailed sedimentary sections) and taphonomic
188 data (Figure 5, Sefton Hills outcrops, sections s-1 and s-2). In parallel, several hinterland localities were
189 also characterised through a series of outcrop observations in the Te Wharau Basin (Figure 5, sections
190 c, n, r, tw-1, tw-2). In the Akitio Basin, the contemporaneous MTD occurrences (Figure 3, section b) were
191 previously described by Bailleul et al. (2007) and Bailleul et al. (2013).

192 **4.1. Drone acquisition and photogrammetry**

193 Ground Control Point (GCP) coordinates and drone pictures of the one-kilometre-long coastal outcrop at
194 Sefton Hills were acquired so that a 3D georeferenced model could be built to observe and describe the
195 lateral and vertical variations of the sediment distribution. Over 500 high-resolution aerial images were
196 captured with a DJI Phantom 4 Pro UAV, and a total of nine GCP coordinates were recorded using a
197 Trimble GeoExplorer 2008 differential global positioning system tool (DGPS) as well as a Trimble
198 Tempest antenna positioned at two metres above the measured point. Standard *Structure from Motion*
199 workflows (Westoby et al, 2012) were then followed for data quality control, processing and rendering. A
200 3D outcrop model was created in the form of a high-resolution triangulated mesh textured with the
201 photographs using the Metashape Professional Edition software by Agisoft (Figure 6).

202 **4.2. Geological mapping and outcrop sedimentology**

203 Field mapping data were recorded with a Trimble ® TDC100 and integrated using ArcGIS software tools.
204 The stratigraphic expressions of the Middle Miocene, Lillburnian aged gravity-driven deposits were
205 examined along the coast at Sefton Hills and captured in three detailed sedimentary sections (total of
206 165 metres at bed scale, Figure 7). Detailed structural measurements (e.g., ductile deformation analysis),
207 as well as bedding and palaeocurrents were also collected. These measurements were corrected using
208 the geomagnetic models from GNS Science New Zealand. A dedicated diagnostic feature template was
209 used to thoroughly describe each MTD occurrence in a standardised manner, both along the coastline
210 and in the hinterland. The age of the sedimentary units and the palaeobathymetries were defined using
211 micro- and macropalaeontological analysis conducted by GNS Science New Zealand. Four samples were
212 collected in the study area to supplement the information already captured in the Fossil Record Electronic
213 Database (<https://fred.org.nz/>) (Appendix 1. Appendix 2).

214

4.3. Taphonomy

215 Due to the significant quantity of macrofossils contained in the MTDs, occurring both as whole skeletons
216 and moderately fragmented remains, a taphonomic analysis was performed in three sectors of the Sefton
217 Hills depositional system on approximately one square metre area of outcrop. It was restricted to the
218 coarsest fraction of death assemblages contained in the MTDs, *i.e.*, on fossil remains larger than five
219 millimetres allowing assignment to a taxonomic group (from, at best, Species to Class level). In this study,
220 three categories of skeleton damage, namely fragmentation, abrasion and bioerosion, were described
221 visually using the graded classification scale presented in Appendix 3, complemented by those proposed
222 by Caron (2011) and Caron et al. (2019). Encrustation of skeletons was also evaluated but was found to
223 be virtually absent. This approach aims at (1) extending the sedimentological knowledge on transport
224 and depositional processes in gravity-driven systems, (2) helping better characterise the source areas
225 and (3) defining diagnostic characteristics to help distinguish between MTDs.

226

4.4. Lithofacies, facies associations and depositional environments

227 The integration of the detailed fieldwork with the digital outcrop model (Figure 6; Figure 7) enabled us to
228 document the lateral and vertical facies variations, recognise the stratigraphic architectures and thus
229 propose facies assemblages and associated depositional environments (Table 1; Figure 8; Figure 9;
230 Figure 10; Figure 11). The facies associations and interpretations follow and complement the initial
231 nomenclature for trench-slope basins that was defined by Bailleul et al. (2007) and Bailleul et al. (2013),
232 whereby **Fa1** refers to turbidite systems and **Fa3** to mass-wasting systems.

233 Because our study focuses on shelf-derived MTDs, we do not provide an extensive description of the
234 turbidite lithofacies, already described in details along the margin (*e.g.*, Bailleul et al. 2007; Bailleul et al.
235 2013; Burgreen and Graham 2014; McArthur and McCaffrey 2019; McArthur et al. 2021), and we used
236 the facies associations **Fa1g** and **Fa1s** defined by Bailleul et al. (2007) and Bailleul et al. (2013) as
237 reference.

238 Alternatively, we scrutinised the different sedimentary expressions of the shelf-derived MTDs (**Fa3p**)
239 recorded on outcrops and recognised four distinct lithofacies (**DF**, **MF-1**, **MF-2**, **SL**) (Table 1). The
240 lithofacies comprise a variety of cohesive gravity flows (**DF**, **MF-1** and **MF-2**) extensively observed and
241 described in the Whareama and Te Wharau Basins (Figure 8, Figure 9, Figure 10; Figure 11) as well as
242 chaotic and contorted facies (**SL**) only witnessed in the Akitio Basin (Bailleul et al. 2007; Bailleul et al.

243 2013). Altogether, the shelf-derived cohesive gravity flows form the facies assemblage **Fa3p-d** whereas
244 the chaotic and contorted expressions form **Fa3p-s** (Table 1).

245 5. MIDDLE MIOCENE SHELF-DERIVED GRAVITY-DRIVEN SYSTEMS

246 5.1. Whareama Basin

247 In this study, we focus on a coastal transect from the eastern part of the Whareama Basin, at the Sefton
248 Hills locality, which is situated four kilometres south of Uruti Point and can be divided into two sections,
249 namely section s-1 and section s-2 (Figure 5). Section s-1 represents the main exposure that extends
250 over one kilometre along the coast. Section s-2 is located 500 metres south of section s-1, on the beach
251 (Figure 5). Both expose Middle Miocene, mid Lillburnian (Langhian, ca., 14 Ma) strata (Appendix 1).

252 Based upon the 3D outcrop model and detailed stratigraphic logging (Figure 6; Figure 7), two main
253 gravity-driven systems and related deposits were identified. The contact between these two systems is
254 stratigraphic, erosive yet can locally appear faulted on part of the outcrop.

255 5.1.1. Turbidite deposits

256 The lower part of the Sefton Hills outcrop (Figure 6) is characterised by a well-developed, several hundred
257 metres thick turbidite system made of laterally continuous, mostly medium-bedded (average 17
258 centimetres thick), fine-grained sandstones. Shell fragments (either diffuse to abundant) and plant debris
259 (either disseminated or organized) are frequent in the structured intervals, typically starting with coarse-
260 grained sands. The overall net-to-gross is of ~65%; mud caps are thus common and on average 10
261 centimetres thick. They often present bioturbations such as *Phycosiphon* sp., *Chondrites* sp., *Zoophycos*
262 sp. and *Thalassinoides* sp. Details on the lithology, stratification and internal bedding characteristics of
263 the different sandstone intervals (**Fa1g** and **Fa1s** as defined by Bailleul et al. (2007) and Bailleul et al.
264 (2013)) are given in Table 1.

265 Observations

266 **Fa1g** mostly comprises normally graded, amalgamated, slightly erosive, medium- to thick-bedded
267 sandstones (Figure 6; Figure 8a, b, g, h). The thicker beds are made of (very) coarse- to fine-grained
268 sands and their base, concave up, truncates the underlying strata with a low angle (centi- to decimetric
269 scale incision). Channel-based drapes (*sensu* Barton et al. 2010) are not uncommon below the erosional

270 cut (Figure 8g, h). These turbidites sometimes evolve into several very fine- to medium-grained
271 sandstone beds overlain by draping muddy layers, before alternating with either (1) fining and thinning
272 upward interbedded sandstones and mudstones (**Fa1g-a**) (Figure 8a, b, g, h), or (2) finer and thinner
273 interbedded mudstones and sandstones displaying local low-displacement features (**Fa1g-f**) (Figure 8b,
274 c, d, e, f). The turbidites tend to be thicker (~20 centimetres), more massive and amalgamated at the top
275 of the turbidite system (Figure 8d; Figure 9f), where they also include a couple episodes of concentrated
276 bioclastic grits (10 to 20 centimetres thick) (Figure 7).

277 Most of the **Fa1g-f** occurrences are recorded in the lower part of the turbidite system, where they are
278 often found interbedded with a series of tabular (sheet-like), continuous thin- to thick-bedded turbidites
279 (**Fa1s**) (Figure 6; Figure 8e, f).

280 Palaeocurrent measurements were collected in the upper part of the system, along the sedimentary
281 section SS-01 (Figure 7); they display a general SW-to-NE direction with a dispersion from the NW to the
282 SE (Figure 6).

283 Interpretations

284 The facies association **Fa1s** was previously described by Bailleul et al. (2007) and Bailleul et al. (2013)
285 and interpreted as sheet-like turbidites. These tabular, highly continuous turbidites commonly result from
286 unconfined, waning turbidity currents (Lowe 1982; Kneller 1995) and either characterise the most distal
287 region of a lobe setting before it evolves into basin plain environment (Galloway 1998) or the basin floor
288 setting. These facies are generally associated with mixed to muddy systems which can disperse sand far
289 into the basin (Galloway 1998). **Fa1s** is generally found interbedded with **Fa1g-f**, inferred to represent
290 the lobe fringe facies from the medial to distal regions (Prélat et al. 2009; Burgreen and Graham 2014;
291 McArthur et al. 2021). This interplay supports the presence of a particularly distal and unconfined setting
292 at the start of the Sefton Hills system (**Fa1s**) that sometimes recorded the distalmost incursions (**Fa1g-f**)
293 of a depositional lobe system.

294 The series then slowly evolve into more confined and proximal settings, recording the emplacement of a
295 depositional lobe system, as was previously described and interpreted as **Fa1g** by Bailleul et al. (2007)
296 and Bailleul et al. (2013) in the Akitio Basin. At Sefton Hills, **Fa1g** can be divided into **Fa1g-c**, **Fa1g-f** and
297 **Fa1g-a** that have contrasting facies and internal architecture outlining the different parts of the lobe
298 system.

299 **Fa1g-c** illustrates the network of small, low-relief distributary channel fills or scours (Galloway, 1998) that
300 likely contributed to the development of the lobe system. **Fa1g-c** differs from lobe axis deposits usually

301 characterised by thick, amalgamated sandstone units and better compares to lobe off-axis deposits
302 (Prélat et al. 2009; Burgreen and Graham 2014; McArthur et al. 2021). Although amalgamation is
303 frequently observed, the strata is mostly medium-bedded and display a lower net-to-gross to the
304 traditional lobe axis deposits (65% instead of 80%) (Prélat et al. 2009).

305 The small channel fills commonly show fining- and thinning- upward sequences (**Fa1g-a**) reflecting both
306 the progressive abandonment of the distributary channel segment and filling of the unfilled relief
307 (Galloway 1998; McHargue et al. 2011). The lobe fringe deposits (**Fa1g-f**) are less frequent towards the
308 top of the sequence.

309 The nature (e.g., shell fragments, plant remains) and abundance of debris in the deposit also highlight
310 that the flow most likely initiated in a shallow marine environment that was continually connected to a
311 hinterland sourcing the land-derived material (Kuenen 1964). Palaeocurrents recorded in the upper
312 turbidite intervals indicate a sourcing from the WSW. Their variations (Figure 6) however outline that the
313 flow of sediments occurred in fairly confined settings. Interactions between gravity currents and
314 topography commonly result in spatial flow variations related to flow deflection (Kneller and McCaffrey
315 1999). We can thus infer the presence of a sublinear topography to the NE of the Sefton Hills locality,
316 responsible for the deflection of the incoming turbidity currents. Yet, the presence of unconfined deposits
317 (**Fa1s**) cropping out at the base of the Sefton Hills turbidite system suggest that such topography did not
318 initially exist. It therefore developed coevally with the overriding **Fa1g** turbidite system.

319 **5.1.2. Locally-derived mass-transport deposits**

320 In the lower part of the Sefton Hills outcrop, the sandstone intervals are interspersed with recurrent, small-
321 scale (one to five metres thick) chaotic, contorted (**Fa3l-s**) to matrix-supported (**Fa3l-d**) deposits (Figure
322 6).

323 Observations

324 **Fa3l-s** is the most commonly occurring and is made of several metre-thick intervals between undeformed
325 turbidites (Figure 6). These intervals mostly comprise contorted turbidite beds (e.g., recumbent folding)
326 and sometimes include dislocated, pebble- to boulder-graded clasts of turbidites, within a silty mudstone
327 background facies (Figure 6; Figure 8a, d, e, f, g, h). Towards the top of the turbidite system, most of the
328 contorted strata indicate a SW apparent direction of movement. Overall, **Fa3l-s** is characterised by a
329 good lateral continuity and thus its occurrences are easily followed across the outcrop. It often seems
330 adjacent to **Fa1g-f** (Figure 6; Figure 8a, b).

331 **Fa3I-d** was only observed once (Figure 8h, lower MTD) and is characterised by a matrix-supported
332 deposit containing at least 50% of intraformational clasts. They are mostly made of pebbles to outsized
333 clasts (deci- to decametric) of turbidites. A couple of skeletons belonging to Molluscan species (*e.g.*,
334 gastropods) were also locally observed, floating in the matrix.

335 Interpretations

336 **Fa3I-s** is interpreted to represent small-scale MTDs resulting from sliding and or slumping of initially
337 coherent turbidite beds under the action of gravity (Nardin et al. 1979; Nemeč 1990). The recurrence of
338 these deposits suggests a generally unstable slope whereas their size, extent and nature imply a rather
339 local source of input. The directions of mass-movements are fairly consistent and would indicate a slope
340 that dipped to the SW (Woodcock 1979; Alsop et al. 2019), thus reinforcing the hypothesis of a ridge that
341 was contemporaneously developing to the NE of Sefton Hills. The high sedimentation rates observed in
342 the turbidite deposits (Table 1) can increase the prospect of depositing water-rich and mechanically weak
343 sediments, more prone to fail along an unstable, rising slope (Lee 2009). We therefore interpret **Fa3I-s**
344 as the result from local failures of the recently deposited turbidites (**Fa1g**) while the topography rose to
345 the NE. **Fa3I-s** sometimes seems to laterally evolve from the lobe fringe deposits, thereby suggesting
346 potential preferential destabilisation of these deposits. Finally, we interpret **Fa3I-d** to represent small-
347 scale MTDs resulting from the transformation of **Fa3I-s** into a cohesive flow as it moved downslope (*e.g.*,
348 Strachan 2008).

349 **5.1.3. Shelf-derived mass-transport deposits**

350 The upper part of the Sefton Hills outcrop is characterised by six distinct matrix-supported deposits,
351 coalescing to over 100 metres of total vertical thickness and 50 to 80 metres of lateral continuity (Figure
352 6). They can be separated into two stacked sets of the same three main lithofacies (Figure 10) deposited
353 in the same order (Figure 6). Despite erosional and sharp bases, one set essentially evolves between
354 matrix-supported deposits containing a high-density (lithofacies **DF**) to a more diluted, dispersed amount
355 of gravel-grade sediments (lithofacies **MF-1** and **MF-2**), thus displaying a general fining upward trend.
356 The matrix of these deposits is made of light grey, silty mudstone and mostly contains extraformational
357 clasts of pre- and syn-subduction material, in varying quantities, sizes and shapes.

358 **Lithofacies Debris Flow (DF)**

359 Observations

360 **DF** is a disorganised, poorly-sorted polymict conglomerate comprising ~50% of matrix. Its basal surface
361 is sharp and slightly (<30 centimetres) to highly erosive into the underlying gravity-driven deposits (Figure
362 6).

363 In **DF**, pre-subduction material largely dominates. It is mostly made of sub-rounded to rounded dark
364 granules to pebbles of Lower Cretaceous Torlesse greywackes. The remaining pre-subduction material
365 (less than 1%) includes sub-rounded pebbles and cobbles of Upper Cretaceous (e.g., calcareous
366 mudstones), Paleocene (e.g., Waipawa black siltstones) and Eocene to Oligocene strata, as well as sub-
367 angular pebbles of Cretaceous to Paleocene strata (Figure 10a, f). Some rare sub-angular cobbles of
368 Lower Cretaceous Torlesse greywackes can also be found.

369 Clasts of syn-subduction material can be divided into lithoclasts and bioclasts.

370 Lithoclasts are characterised by pebbles to boulders (sometimes oversized: deci- to decametric) of
371 coherent to dislocated turbidites of similar nature to the ones from the underlying turbidite system,
372 boulders to oversized mud clasts, sub-angular indurated shell bed clasts and black pieces of organic
373 matter (e.g., wood) (Figure 9b, c, e; Figure 10b, c, d, e). SE-verging recumbent folds were measured
374 throughout the contorted expression of some of the turbidites (Figure 6; Figure 9c; Figure 10c).

375 Bioclasts are abundant and composed of macrofossils mostly belonging to Molluscan species (e.g.,
376 bivalves and gastropods) and rarely to Corals (details in Appendix 2). This bioclastic material can either
377 be found: (1) as shell fragments, finely milled and dispersed in the matrix (Figure 10a); or (2) as skeletons,
378 partly to mostly well-preserved (being one to eight centimetres long) and floating in the matrix (Figure
379 10a, g). *Struthiolaria (Callusaria) callosa*, *Polinices* sp. as well as *Turritella* sp. were identified as the most
380 recurrent macrofossil species of gastropods. Most of the bivalve shells appear to be only partially well-
381 preserved, thereby making it complicated to classify some of the species; *Glycymeris* sp., *Cardium* sp.
382 and *Ostrea* sp. were recognised.

383 Despite their common characteristics, differences exist between the two occurrences of the lithofacies
384 **DF** at the Sefton Hills locality. The diversity encountered in the pre-subduction clasts decreases
385 drastically in **DFb**. Lower Cretaceous Torlesse greywackes still dominate and are also locally particularly
386 abundant (Figure 10a) whereas only a few Cretaceous to Paleocene clasts (e.g., calcareous mudstones)
387 are present. In terms of syn-subduction material, the mud clast content largely increases towards the top
388 of **DFa** (Figure 10d) while this crude sorting does not exist in **DFb**, which records decametric, randomly
389 scattered mud clasts (Figure 9b, e). The transported turbidites evolve from oversized, sometimes
390 overturned rafts (Figure 9f; Figure 10b) to contorted and then dislocated cobbles and or boulders towards

391 the top of **DFa** (Figure 10c), whereas **DFb** is mostly made of dislocated, randomly scattered cobbles to
392 boulders. Both contain several types of shell bed clasts that are typically sub-angular, range from five to
393 20 centimetres in length and constitute a major part of the overall syn-subduction clasts at the base of
394 **DFa**.

395 Finally, the taphonomic analysis of the macrofossil content (Figure 12) shows that bioerosion contrasts
396 markedly between facies **DFa** and **DFb**, being overall low to moderate (combined frequencies of 78.2%
397 to 100%) for both the coarser and the finer skeletal fraction. Fragmentation, for grains larger than three
398 centimetres that include whole skeletons and partly broken ones, is similar within both facies, being
399 predominantly low to moderate (cumulated frequencies of 76.2% and 87%, respectively). Unsurprisingly,
400 fragmentation is high to very high for the finer skeletal fraction dominated by clastic material. The coarser
401 skeletal fractions in facies **DFa** and **DFb** exhibit similar degrees of abrasion (cumulated frequencies for
402 low to moderate abrasion is 71.4% in **DFa** and 60.9% in **DFb**, and for high to very high degrees of
403 abrasion, 28.6% in **DFa** and 39.1% in **DFb**). Interestingly, abrasion for the finer skeletal fraction is higher
404 in **DFa** than in **DFb** (high to very high degrees of abrasion of 33.8% and 16.6% respectively; Figure 12).
405 Macrofaunal assemblages and bioclastic remains are remarkably similar in facies **DFa** and **DFb**. At
406 outcrop scale, concentration of well-preserved skeletons in **DFa** may appear higher than in **DFb**. The
407 square metres of outcrop investigated for the taphonomic analysis show no difference in the
408 concentrations of well-preserved skeletons between both facies. However, the overall bioclastic content
409 is more abundant in **DFa** than in **DFb** (Figure 12).

410 Interpretations

411 **DF** is interpreted to represent a MTD produced by cohesive debris flows (*sensu* Mulder and Cochonat
412 1996; Mulder and Alexander 2001). The disorganised and chaotic arrangement is characteristic and the
413 predominance of matrix in the deposits indicates that matrix strength was the dominant grain-support
414 mechanism for the failed material (Nardin et al. 1979; Lowe 1982). Grain interactions may also be locally
415 important due to the abundance of coarse lithoclastic material.

416 The erosive nature of the deposits and presence of allochthonous, rafted blocks of contemporaneous
417 Miocene turbidites, sometimes completely overturned, at the base (cf. **DFa**) suggest basal interaction
418 between the overriding mass-flow and the substrate. Erosional ploughing and scouring is a common
419 feature of MTDs (Posamentier and Martinsen 2011; Festa et al. 2019) especially when hydroplaning
420 (*sensu* Mohrig et al., 1998) is not seen as the main mechanism responsible for the mobility of the flow.

421 The sedimentary rocks of the substrate are thus incorporated into the overflowing MTD by basal erosion
422 (Posamentier and Martinsen 2011; Sobiesiak et al. 2018). The crude grading observed in their shape and
423 size (outsized clasts to pebbles; raft to contorted or dislocated turbidites) throughout **DF** suggests layer-
424 parallel shearing within the flow. As the flow moved downslope and further substratum material was
425 added, it first remained coherent before partly disaggregating and starting to shear and deform in the
426 direction of the flow (Fonnesu et al. 2016). Alternatively, deformation could result from shearing and
427 compaction after the freezing of the flow (Mulder and Alexander 2001). The SE-verging measurements
428 collected in the contorted turbidites indicate a mass-flow travelling southward, likely parallel to the NW-
429 SE sublinear topography that developed to the NE of Sefton Hills (see 5.1.1 and 5.1.2).

430 Although **DFb** is also characterised by an erosional base, only a small amount of turbidites (of pebble- to
431 cobble-grades) are present. Large-scale mud clasts dominate throughout, thereby suggesting a change
432 in the nature of the underlying substratum being ploughed. **DFa** is the first episode of debris flow recorded
433 at Sefton Hills right above a well-developed turbidite system (Figure 6) whereas **DFb** is the second
434 episode. At least another two MTDs were recorded in between the two debris flows (Figure 6, cf. **MF-1a**
435 and **MF-2a**), thus providing an entirely different substrate (*i.e.*, mud-rich) to be eroded and incorporated
436 into the flow for **DFb**. Mud clasts are also present in the first debris flow although smaller and concentrated
437 towards its top (Figure 9b, e). These could be the result of hydraulic jumps at the time the debris flow
438 reached the base of slope (Henstra et al. 2016) or as it travelled above the uneven basin-floor topography.

439 The variety of lithoclasts and bioclasts encountered in **DF** illustrates the level of internal heterogeneity
440 usually associated with debris flows (*e.g.*, Mulder and Alexander 2001) and also provides insights about
441 the nature of the failed source area (Posamentier and Martinsen 2011). The quantity and diversity of pre-
442 subduction clasts suggest that the event of mass wasting did not only destabilise the sediments that were
443 being deposited in the source area (*i.e.*, Lillburnian sediments), but that the substratum onto which they
444 were depositing was remobilised as well. The nature of the clasts implies that this substratum mostly
445 comprised the pre-subduction series (*e.g.*, Cretaceous up to Oligocene) (Chanier 1991; Chanier and
446 Ferrière 1991). Yet, the few occurrences of Miocene shell bed clasts indicate that it also comprised some
447 syn-subduction sedimentary rocks previously deposited in shallow-marine, mixed siliciclastic-carbonate
448 environments (Chanier 1991; Bailleul et al. 2007; Bailleul et al. 2013; Caron et al. 2019; Bailleul et al.
449 Submitted; Caron et al. 2021).

450 The macropalaeontological analysis conducted onto the sampled fauna indicates a neritic shelfal
451 environment whereas the micropalaeontological data reveal that the deposition of the debris flow

452 occurred at lower bathyal depths (>1000 metres), with a planktic abundance varying from >80 to >95%,
453 thus indicating deposition in a sub-oceanic to fully oceanic setting.

454 The taphonomic analysis suggests that the first event of mass wasting (**DFa**) remobilised macrofaunal
455 assemblages that were either alive or only recently deceased on the shelf floor, whereas the second
456 event (**DFb**) transported organisms that were, for most part, already dead and bio-eroded. Since the
457 nature of the macrofossils transported in **DFa** and **DFb** remains the same, a repeated destabilisation of
458 the same sourcing region can be inferred, with not enough time between the two events for the molluscan
459 communities to replenish the neritic zone, *i.e.*, shelfal environment.

460 Mass-wasting is therefore interpreted to have initiated in shallow waters, from potential failure of a shelf
461 that developed above a substratum composed of both pre- and syn-subduction material. The coevally
462 developing shallow-marine, mixed siliciclastic-carbonate shelves to the north of Sefton Hills are great
463 candidates for being the source, having formed on a pre- (*e.g.*, Upper Cretaceous to Paleogene series)
464 and syn-subduction (*e.g.*, Miocene sediments) substratum (Figure 3, section f, i, m, p) (Bailleul *et al.*
465 2007; Bailleul *et al.* 2013), and presenting markedly similar faunal assemblages, which include
466 *Struthiolaria* sp., *Polinices* sp., Turritellids, *Glycymeris* sp., Oysters or some Corals (Bailleul *et al.*
467 Submitted). The destabilised material was then transported downslope and resulted in deposition of **DF**
468 at deeper waters, into the Whareama Basin.

469 Finally, the high percentage (>30%) of sub-rounded to rounded, granules and pebbles of Lower
470 Cretaceous Torlesse greywackes unlikely results from the underwater substratum. Instead, it might either
471 come from (1) direct erosion of the hinterland that mostly comprises exhumed Torlesse rocks and or (2)
472 reworking of Upper Cretaceous conglomerates, known to already contain sub-rounded granules and
473 pebbles of Lower Cretaceous Torlesse greywackes, previously reworked through fluvial processes
474 (Chanier 1991; Chanier and Ferrière 1991). Indeed, several shelfal deposits were described as containing
475 sub-rounded pebbles to boulders of Torlesse greywackes (*e.g.*, in the Middle Miocene shelfal series of
476 Oumukura (Chanier 1991) and in the Pliocene limestones of Hawke's Bay (Caron *et al.* 2004)), thereby
477 indicating that Torlesse material, either already reworked or recently eroded, can likely be transported
478 from the hinterland onto a shallow shelf, where it is then exposed to littoral processes. The presence of
479 wood fragments in the deposits also indicates a connection (continuous or not) with an emerged land
480 (Kuenen 1964), which could have also been used to bring and store the reworked sub-rounded Torlesse
481 clasts into the source area.

482 **Lithofacies Mudflow 1 (MF-1)**

483 Observations

484 **MF-1** is another type of disorganised, poorly-sorted polymict conglomerate. It is primarily distinguished
485 by its high matrix content (~95%) and its resemblance to a diluted version of the lithofacies **DF**. It has a
486 sharp, undulating basal surface, that laterally evolves into becoming highly erosive (decametric) towards
487 the south (Figure 6, cf. **MF-1a** and **MF-1b**, Figure 9a, b, c, d, e, h; Figure 10h).

488 Pre-subduction material is largely dominant in **MF-1**, with a very high proportion of sub-rounded to
489 rounded Lower Cretaceous Torlesse greywackes of very coarse sand to granule grades (Figure 10h).
490 Cobbles and boulders of Cretaceous to Paleocene clasts are rarely found scattered in the matrix (Figure
491 10l).

492 The variety of syn-subduction lithoclasts is comparable to that of the **DF** lithofacies, and includes Miocene
493 turbidites, shell bed clasts, organic matter (*e.g.* wood) and some mud clasts. It also punctually includes
494 clasts of the underlying **DF** material. In general, the shell bed clasts and wood fragments (>1% of the
495 total contribution) do not exceed pebble grades and are mostly sub-angular, and rarely sub-rounded
496 (Figure 10k).

497 The bioclastic content remains important, however this material is now mostly found as shell fragments
498 dispersed in the matrix (Figure 10h). A few (well- and partly-) preserved molluscan skeletons were
499 identified (Figure 10m); gastropods tend to be the best preserved (details in Appendix 2).

500 We performed a taphonomic analysis on the finer skeletal fraction of **MF-1a** related deposits, the coarser
501 fraction (*i.e.*, >3 centimetres) being virtually absent (Figure 12). Degrees of fragmentation range from
502 high to very high. Overall, abrasion is low to moderate (45.6% and 50%, respectively; cumulated
503 frequencies of 95.6%). Bioerosion is predominantly low (84.8% of no- or poorly-infested bioclasts) to
504 moderate (10.9%).

505 The two occurrences of the lithofacies **MF-1** display quasi-similar characteristics at the Sefton Hills
506 locality. The main difference affects the incorporated syn-subduction turbidites. In both cases, they are
507 essentially characterised by pebbles to boulders of contorted to dislocated turbidites which can
508 occasionally present bioclastic grits or laminations (Figure 9d, h; Figure 10i). A decametric mass of
509 coherent thin-bedded turbidites (*i.e.*, raft) is however present at the top of **MF-1b** (Figure 9a; Figure 10i).
510 It displays a high number of angles and truncations, and is wrapped by the matrix.

511 Interpretations

512 **MF** is interpreted as a MTD resulting from cohesive mudflow (*sensu* Mulder and Cochonat 1996; Mulder
513 and Alexander 2001). The dominance of matrix suggests that cohesive strength (*i.e.*, matrix strength)
514 was the dominant grain-support mechanism for the incorporated material in this lithofacies (Nardin et al.
515 1979; Lowe 1982). The presence of unusually large clasts (*e.g.*, turbidite decametric raft) floating on top
516 of the flow is not uncommon in MTDs (Posamentier and Martinsen 2011). This occurrence indicates the
517 presence of additional support mechanisms in **MF-1b** such as high local pore pressures, buoyancy and
518 or clast-to-clast interaction (Pierson 1981; Johnson 1984; Nemeč and Steel 1984; Postma et al. 1988;
519 Mulder and Alexander 2001).

520 The nature of the reworked material (lithoclasts and bioclasts) is equivalent to that of **DF**, thereby
521 suggesting destabilisation and remobilisation of a similar, if not identical, sourcing region. The
522 macrofaunal species remain the same as the ones recorded in **DF** and thus indicate that the failure
523 responsible for the deposition of **MF-1** destabilised a neritic shelfal environment as well.

524 The geometry and distribution of the basal incisions recorded in **MF-1** can be used to infer the gross
525 general transport direction. Their characteristics suggest that the flow was moving almost perpendicular
526 to the outcrop orientation along a NW-SE direction, with a migration of incision towards the south (Figure
527 6, cf. **MF-1a** and **MF-1b**). These incisions could either result from basal erosion (Posamentier and
528 Martinsen 2011; Sobiesiak et al. 2018) or could be associated with the build-up of lateral margins (Bull et
529 al. 2009; Posamentier and Martinsen 2011). In both cases, such features provide a primary constraint on
530 the flow direction of the MTD and also indicate the potential position of the lithofacies within the MTD
531 body and across the seafloor. Lateral margins and flow-ploughing commonly develop in the translational
532 domain of the MTD body, which is located between the up and downslope extremes (*i.e.*, the headwall
533 and toe domains) (Bull et al. 2009), outboard of the base of slope. In this domain, the MTD is
534 characterised by intense deformation, dislocation, basal erosion as well as incorporating translated, rafted
535 blocks (Frey-Martínez et al. 2005; Bull et al. 2009; Posamentier and Martinsen 2011), all being features
536 of the **MF-1** lithofacies.

537 Lithofacies Mudflow (MF-2)

538 Observations

539 **MF-2** is mostly made of light grey, silty mudstone (Figure 10n). The matrix represents 99% of the overall
540 flow deposits and the remainder is divided between that with a high bioclast content and that with rare

541 scattered lithoclasts. The basal surface is sharp yet sometimes can appear as slightly gradational from
542 **MF-1**.

543 **MF-2** shows good lateral continuity (Figure 9a, g, h). For example, its second occurrence (**MF-2b**) can
544 be traced over one kilometre from the southern part of the Sefton Hills section 1 locality to the Sefton
545 Hills section 2 (Figure 9g).

546 In **MF-2**, the lithoclasts are rare and do not display much variety. In order of frequency, they are (1) a few
547 syn-subduction decametric mud clasts, (2) rare syn-subduction pebbles to boulders of contorted and
548 dislocated turbidites (Figure 10o) and (3) rare pre-subduction elements of sand sizes, likely of Lower
549 Cretaceous Torlesse greywackes. Where dominated by mud clasts, **MF-2** can easily be mistaken for
550 hemipelagic mudstones; but is differentiated based upon the matrix that surrounds the mud clasts
551 laterally. The bioclasts are essentially shell fragments; only a couple of molluscan skeletons were found
552 floating in the matrix, partly preserved yet highly disarticulated (details in Appendix 2).

553 Interpretations

554 **MF-2** is also interpreted as a MTD resulting from cohesive mudflow (*sensu* Mulder and Cochonat 1996;
555 Mulder and Alexander 2001). Its texture closely resembles that of lithofacies **DF** and **MF-1**, albeit in a
556 very low-density version. Mass-transport processes can either be intergradational or not (*i.e.*, one process
557 can evolve into another with time or remain the same) (Stow 1986; Nemeč 1990). Sediment dilution
558 through water entrainment, particularly at the head (Middleton and Hampton 1973) or at the upper
559 boundary of a flow (Mulder and Alexander 2001) is known as a major mechanism contributing to the
560 transformation of one cohesive flow into another (Lowe 1982; Mulder and Alexander 2001). Therefore,
561 **MF-2** could represent the diluted expression of an initial debris flow (**DF**) or mudflow (**MF-1**). The low
562 density of clasts may also indicate that either the source area was fairly depleted at the time of
563 destabilisation or that the flow did not directly initiated from this location, but further downslope, from a
564 muddier, deeper environment (*e.g.*, the upper- or mid-slope environment (Posamentier and Martinsen
565 2011)).

566 Once again, the clast content suggests the failure of a shelfal environment with a stock of reworked
567 Torlesse clasts whereas the micropalaeontological study (Appendix 1, sample T27/f0643 taken in **MF-**
568 **2b**) reveals that deposition remained at lower bathyal depths (>1000 metres). The mud clast content
569 would have again resulted from the seafloor ploughing effects (Posamentier and Martinsen 2011;
570 Sobiesiak et al. 2018) and thus points towards an erosive character of the flow.

571

5.1.4. Stratigraphic architecture of the Sefton Hills gravity-driven systems

572 Overall, the Sefton Hills outcrop is characterised by deposition of two main syn-subduction gravity-driven
573 systems during the Middle Miocene, mid Lillburnian. The underlying turbidite system evolved from an
574 unconfined, distal sheet-lobe setting (**Fa1s**) to a more confined and proximal depositional lobe setting
575 (**Fa1g**) as a NW-SE sublinear topographic high developed to the north-east and isolated this part of the
576 Whareama Basin from the unconfined basin floor to the east. Most likely controlled by the underlying
577 seaward-verging Flat Point-Whakataki Fault complex, the rise of this topographic high not only resulted
578 in the development of a SW-dipping slope (*i.e.*, backlimb setting) that deflected the incoming turbidity
579 currents but also favoured repeated destabilisation of the syn-kinematic turbidites, thereby generating
580 local gravitational instabilities leading to deposition of small-scale (one to five metres thick) MTDs (**Fa3l**).

581 This turbidite system was then abruptly interrupted by the emplacement of six amalgamated MTDs (**DFa**,
582 **MF-1a**, **MF-2a**, **DFb**, **MF-1b**, **MF-2b**) that reworked a vast quantity of shelf-derived material. Together,
583 they form a large-scale mass-transport complex (MTC) (**Fa3p-d**) of over a hundred metres in thickness,
584 with up to a kilometre of lateral continuity. The nature of these deposits suggests the repeated failures of
585 a shallow marine, shelfal environment developed above a substratum composed of both pre- and syn-
586 subduction material, which also caught and stored land-derived elements (*e.g.*, reworked pebbles of
587 Torlesse greywackes, wood and plant debris). Mass-failures likely initiated at shallow water depths north
588 of the study area. The failed material then travelled southward, parallel to the Whareama Basin seaward
589 margin, and downslope through erosive cohesive flows (*e.g.*, debris flow and mudflow). Deposition
590 eventually occurred onto the Whareama trench-slope basin floor, above the Sefton Hills turbidite system,
591 at greater water depths, *i.e.*, lower bathyal, and within southward migrating depocentres.

592 The two main gravity-driven systems of Sefton Hills are not genetically linked. Yet, they were fed by
593 similar sources of material (shell fragments, wood and plant debris). Shoreline river systems could have
594 directly supplied land- and beach-derived material to the shelfal domain (Posamentier and Walker 2006)
595 making it readily available to be transferred beyond the shelf edge and farther downslope, either caught
596 (1) in canyon heads, generally ending their course downslope into turbidite systems (Posamentier and
597 Allen 1999) or (2) in unconfined shelf edge failures, resulting in large-scale MTDs (Moscardelli and Wood
598 2008; Moscardelli and Wood 2015).

599 The palaeocurrent variations recorded in both systems (north-eastward migrating turbidite system and
600 southward MTDs) indicate that the shallow marine shelfal environment(s) located to the west of the
601 Whareama system at the time was(were) persistent, well-developed and geographically extensive.

602

5.2. Te Wharau Basin

603 In this study, we also examined outcrops located in the main portion of the Te Wharau Basin (Figure 5,
604 sections c and r) and in its easternmost secondary fold portion (Figure 5, sections tw-1, tw-2 and n).
605 These outcrops expose additional occurrences of contemporaneous shelf-derived MTDs from the Middle
606 Miocene, Lillburnian (Late Langhian to Serravallian, 15.1 – 13.05 Ma) (Appendix 1). Intermittent, these
607 inland outcrops did not allow the same detail of descriptions and measurements as the coastal outcrops.
608 Nevertheless, we were able to characterise each outcrop following the same approach and nomenclature
609 defined at the Sefton Hills locality (Table 1; Figure 11).

610 We identified several occurrences of matrix-supported deposits identified in the Te Wharau Basin (Figure
611 5). Their apparent dimensions are of three to 20 metres of vertical thickness and 15 to 30 metres of lateral
612 continuity. However, both the base and top surfaces could not be distinguished, thereby suggesting
613 possibly greater thickness of deposits (Figure 11). They essentially hold similar general characteristics to
614 those of Sefton Hills. Their matrix is made of light grey, silty mudstone and mostly contains gravel-grade
615 extraformational clasts of pre- and syn-subduction origins (Figure 11a). Despite poor outcrop conditions,
616 the deposits seem to hold between 30 to 40% of lithoclasts and bioclasts; which could imply that they are
617 best defined by the lithofacies **DF** (Table 1).

618 Lithofacies Debris Flow (DF)

619 Observations

620 In the Te Wharau Basin, pre-subduction material also largely dominates the disorganised, poorly-sorted,
621 polymict conglomerates of lithofacies **DF**. They mostly include Lower Cretaceous Torlesse greywackes,
622 either as sub-rounded to rounded pebbles or sub-angular cobbles, boulders or outsized clasts (Figure
623 11a, c, d, f). The remaining pre-subduction material comprise sub-angular pebbles to outsized clasts
624 (metric) of other Lower Cretaceous (*e.g.*, red cherts), undifferentiated Cretaceous (*e.g.*, calcareous
625 mudstones) and Paleocene strata. The syn-subduction lithoclasts are essentially characterised by sub-
626 angular pebbles to cobbles of shell beds (Figure 11b, c). Contorted turbidites are rarely found.

627 Bioclasts are abundant and composed of a large variety of Molluscan species (details in Appendix 2;
628 Figure 11b, d, e) either found: (1) as shell fragments, finely milled and dispersed within the matrix or (2)
629 as skeletons, partly to mostly well-preserved (generally two to three centimetres) and floating in the
630 matrix. The gastropods are the best preserved, whereas the bivalves are commonly partly broken and
631 chalky.

632 Despite some characteristics that are similar to those of Sefton Hills, the Te Wharau occurrences present
633 some differences. Overall, the clasts are dominantly sub-angular. The largest clasts (e.g., boulders) are
634 found in the Te Wharau road-2, Ngaumu and Rangiora sections (Figure 5). In particular, pre-subduction
635 material dominates at Ngaumu and Rangiora. It includes Lower Cretaceous Torlesse greywackes,
636 Cretaceous calcareous mudstones and Paleocene glauconitic sandstones. At Ngaumu, Lower
637 Cretaceous red cherts and lavas are also present. At Te Wharau road-1, the syn-subduction lithoclasts
638 are represented by different types of shell beds. At Te Wharau road-2, both shell bed clasts, skeletal and
639 bioclastic fine-grained sandstones (respectively the facies S1 described by Caron et al. (2004) and the
640 facies Fa6b described by Bailleul et al. (2007)) are found (Figure 11e). At Ngaumu, the syn-subduction
641 material comprises shell bed clasts along with rare scattered and contorted turbidites.

642 Interpretations

643 We interpret the different occurrences of DF observed in the Te Wharau Basin to be MTDs produced by
644 cohesive, likely debris flows (*sensu* Mulder and Cochonat 1996; Mulder and Alexander 2001). Despite
645 great internal heterogeneity, the extraformational clast content remains similar across the different
646 occurrences, displaying the same types of pre- and syn-subduction material and thus demonstrating
647 failures of comparable sources.

648 The nature of the lithoclasts, largely dominated by Lower Cretaceous material and Miocene shell bed
649 clasts, suggests slightly different substratum(s) to the one(s) sourcing the contemporaneous MTDs of
650 Sefton Hills. These substrata were made of Lower Cretaceous Torlesse greywackes and cherts, above
651 which Middle Miocene shelfal environments developed, highlighting a substantial sedimentary hiatus.

652 During the Middle Miocene, Clifdenian (Early Langhian, ca. 15.9 – 15.1 Ma) and Lillburnian (Late
653 Langhian to Serravallian, 15.1 – 13.05 Ma), a few episodes of mixed siliciclastic-carbonate shelves
654 unconformably overlying Lower Cretaceous Torlesse basement were documented in the sector of Te
655 Wharau, and more particularly at the Wainuioru and Mapapa stream localities (Figure 5, sections w, o,
656 ms) (Crundwell 1987; Chanier 1991). Their failure could have directly provided the material for the
657 macrofossil content, shell bed and Torlesse clasts recorded in the MTDs of the Te Wharau Basin (Figure
658 5). The rounded clasts of Torlesse greywackes probably resulted from fluvial and or littoral reworking of
659 the material, initially exposed in the hinterland (Chanier 1991; Chanier and Ferrière 1991) and later
660 transferred onto the shelfal environment.

661 Input from the pre-subduction Upper Cretaceous to Paleogene series are scarce and only clearly
662 observed in the MTDs from the Ngaumu and Rangiora sections. Around these areas, owing to the Adams-

663 Tinui Fault complex (Figure 5), the Lower Cretaceous Torlesse basement overrides the Glenburn Nappe
664 and thus locally provides a substratum that also includes the Upper Cretaceous to Paleogene series.

665 Finally, the micropalaeontological studies reveals that the deposition of the debris flows generally
666 occurred at bathyal depths. More particularly, the Te Wharau road occurrence (section tw-1) indicates
667 mid-bathyal water depths (700 metres), which are shallower than in the Whareama Basin, and the
668 planktic abundance of 25% also indicates that an outer neritic water-mass was overlying the site of
669 deposition at the time, thereby suggesting nearby shelfal source(s). Overall, the local source regions
670 (maximum of seven kilometres distance from the known Wainuioru and Mapapa shelves) (Figure 5)
671 support the prospect of the Te Wharau cohesive flow deposits being more proximal to their sources than
672 those at Whareama.

673 **6. DISCUSSION**

674 **6.1. Stratigraphic record of shelf-derived mass-wasting events at outcrop**

675 The shelf-derived mass-wasting products presented in this study are captured across several exhumed
676 trench-slope basins and exhibit a variety of lithofacies and geometries. They always incorporate reworked
677 well-preserved to fragmented shallow marine macrofauna as well as (pre- and syn-subduction)
678 extraformational clasts, suggesting the destabilisation and collapse of similar depositional environments.
679 However, the diversity observed in the shapes, sizes, percentages of reworked material and the
680 interactions with the underlying surface imply that different physical and sedimentary processes
681 interplayed as the failed material moved downslope. Such variety also suggests that the deposits may
682 have been recorded at different locations (*e.g.*, distance) relative to the source regions.

683 **6.1.1. Source regions**

684 The analysis of the macrofossil content (palaeontology and taphonomy) indicates that the staging areas
685 were located at shallow depths in neritic shelfal waters. The analysis of the extraformational content also
686 adds that the events remobilised the fauna and sediments that were depositing in the failed source area
687 (*i.e.*, Middle Miocene, syn-subduction) as well as partially destabilised the substratum upon which they
688 were settling (*i.e.*, syn- and or pre-subduction material). The contemporaneously developing shallow-
689 marine, mixed siliciclastic-carbonate shelves, markedly installed above pre- and or syn-subduction
690 substratum and presenting similar faunal assemblages are thus great candidates for the source regions

691 (Figure 3, sections f, i, m, ms, p, t, w) (Crundwell 1987; Chanier 1991; Bailleul et al. 2007; Bailleul et al.
692 2013; Bailleul et al. Submitted). The failed material was then transported downslope into deeper water
693 settings, being deposited either along the main slope, proximally to the source area (e.g., Te Wharau
694 road MTDs) or onto the trench-slope basin floor, further from the source and at lower bathyal water depths
695 (e.g., Sefton Hills MTDs). The land-derived material (e.g., wood fragments, reworked sub-rounded
696 pebbles) captured in these deposits probably results from the uplift and erosion of hinterland areas, which
697 typically transfer such material to the coastal and shelfal environments, making it readily available to be
698 incorporated into the failed deposits. Isolated islands developed above tectonically controlled topography
699 can also be considered for providing plant material (McArthur et al. 2016).

700 6.1.2. Taphonomic insights

701 A key question related to the taphonomic character of the shelfal skeletal sediments contained in the
702 studied MTDs and presented in Figure 12, is as to whether they were inherited or, at least partly, acquired
703 during transport and emplacement of the MTDs. Explanations for limited bioerosion of skeletal material
704 are multifarious, including unfavourable ecological conditions for bioeroders, substrates unsuitable to
705 drilling organisms, high fine-grained siliciclastic inputs, increasing water depths, predominance of
706 organisms buried alive and rapid burial preventing infestation (e.g., Kidwell 1989; Perry 1998; Martin
707 1999; Richet et al. 2011). Notwithstanding the possibility for fragmentation to be related to biotic factors
708 (e.g., Zuschin et al. 2003), the degrees of fragmentation and abrasion may help assess whether flows
709 were either laminar or turbulent, and whether sediments were deposited by traction or suspension (e.g.,
710 Lowe 1982). Due to the abundance of coarse lithoclastic material in the lithofacies **DF**, there is a potential
711 for fragmentation to have originated from *en masse* crushing during transport, and abrasion to reflect *en*
712 *masse* friction as possible mechanisms by which skeletons were altered. Fragmentation during transport
713 of previously broken and abraded material will lower its taphonomic evaluation because this secondary
714 mechanical event generates new angular edges. This process may explain why abrasion values compare
715 well in the various size fractions of lithofacies **DF**. In contrast, the abundance of silty mudstone matrix
716 and the low siliciclastic content in lithofacies **MF**, hence reducing *en masse* friction between grains and
717 making crushing unlikely (e.g., Li et al. 2019), may explain their limited abrasion and could indicate that
718 abrasion and fragmentation were inherited.

719 6.1.3. Distance to source and facies

720 In the Te Wharau Basin, we interpret the Te Wharau road cohesive flows to represent the fairly proximal
721 and immature expressions of the failure, captured close to the sourcing area(s), most probably on the

722 slope. The disorganised clast fabric may reflect short travel distance (Nemec and Steel 1984) whereas
723 the high density of angular, boulder-grade clasts could also suggest a rather recent mobilisation (*sensu*
724 Iverson 1997).

725 Further north, in the Akitio Basin, a 175-metre thick series of large-scale slides and slumps (cf. **Fa3p-s**
726 in Table 1) interbedded with a few cohesive flows, similar in nature to the ones of the Te Wharau Basin,
727 were also observed (Branscombe MTDs of Bailleul et al. (2007)). These MTDs deposited in proximal
728 position to the contemporaneously developing mixed siliciclastic-carbonate outer shelf of Pongaroa
729 (Figure 3, sections b and p) (Bailleul et al. 2007; Bailleul et al. 2013) and thus indicate that both sediment
730 mass-failure (e.g., Akitio) and mobilisation (*sensu* Iverson 1997) (e.g., Te Wharau) can occur close to the
731 source areas.

732 In the Whareama Basin however, the cohesive flows captured at Sefton Hills deposited farther from the
733 sourcing shelf area(s), at lower bathyal water depths onto the trench-slope basin floor. More importantly,
734 the Sefton Hills deposits are characterised by amalgamated cohesive flows that can result from several
735 failures that coalesced downslope. In particular, we observed repeated sequences of coalescing, erosive
736 flows that display a rough fining upward trend (**DF**: debris flow, to **MF-1** and **MF-2**: mudflows in Figure 8
737 and Figure 10). Debris flows do not always move downslope as one single flow and commonly break into
738 a series of surges (e.g., Iverson 1997; Mulder and Alexander 2001; Felix et al. 2009; Allen et al. 2020).
739 One flow event can therefore be characterised by a multitude of surges, either arising naturally (e.g.,
740 induced by surface wave coalescence (Iverson 1997)) or initiated by external triggers such as sporadic
741 slope failures. Here, each failure would have triggered the development of a cohesive flow, breaking up
742 downslope into at least three separated surges. During multiple-surge events, the first surge is usually
743 the coarsest one, then tailed by surge(s) of medium and finer particles behaving as muddy flow(s)
744 (Zanuttigh and Lamberti 2007). Consistent replications of grading and structure divisions can be expected
745 in such deposits, and we therefore infer that the Sefton Hills deposits recorded two main events of shelf
746 destabilisation (event a and b), each divided into three genetically-linked surging flow deposits (lithofacies
747 **DF**, **MF-1** and **MF-2**).

748 As such, the shelf-derived deposits presented in this study indicate that shelf failures triggered both
749 sediment mass-movement (**Fa3p-s**) and development of debris flows (**Fa3p-d**) close to the source
750 region(s) (e.g., Akitio and Te Wharau MTDs), which may eventually break down into a series of erosive,
751 upward fining surges downslope (e.g., Whareama MTDs) (e.g., Figure 13).

752

6.1.1. Deposit dimension and scale

753 The source regions, regional footprint and internal characteristics of these MTDs all suggest that they
754 belong to *attached* systems sourced from the shelf (Moscardelli and Wood 2008; Moscardelli and Wood
755 2015). In order to better comprehend the full three-dimensionality and extent of these shelf-derived mass-
756 wasting deposits at outcrop scale, we used the set of morphometric relationship equations calculated by
757 Moscardelli and Wood (2015) as a basis for reconstructing their potential dimensions.

758 We used the best outcropping occurrences of Sefton Hills (Whareama Basin) and Branscombe (Akitio
759 Basin) as references, having access to representative thickness estimations from fieldwork
760 measurements. We considered whether or not these MTDs were part of the same event or had a coeval
761 trigger (e.g. a megathrust earthquake); yet, we rapidly discarded this hypothesis since the
762 micropalaeontological analysis showed that they were not contemporaneous; the Branscombe MTDs
763 being slightly older (lower Lillburnian) (Bailleul et al. 2007; Bailleul et al. 2013).

764 The resulting morphometric calculations, whether using the general or specific set of equations, provided
765 volume, area and length values that are generally above the generic thresholds for *attached* systems
766 (Moscardelli and Wood 2015) (i.e., $V > 1$ cubic kilometres; $A > 100$ square kilometres and $L > 11$ kilometres
767 (Figure 14; Appendix 4), thereby reinforcing such an interpretation of these MTDs.

768 In addition, we considered the average deposit length parameter (*sensu* Moscardelli and Wood 2015) to
769 account for the lateral thickness variations that are typical of MTDs and gain additional insights onto the
770 possible source areas, especially those of the Sefton Hills MTDs. Notwithstanding the presence of
771 potentially closer source regions, yet to be discovered in the studied area, we used the shortest distance
772 between the deposits and the already well-known shelfal areas as a proxy (Appendix 4). The results
773 favour a potential source region located 40 to 70 kilometres to the north, nearby the Tinui, Takiritini or
774 Waihoki-Mangatiti shelves (Figure 14; Appendix 4). However, these results should only be considered as
775 general insights since the Sefton Hills deposits have not been proven to be the termination of the MTDs,
776 the input deposit lengths do not account for possible tortuous pathways or closer source regions, the
777 deposit thickness does not take into account potential compaction effects, which can be substantial in
778 muddy sediments (Jones 1944), and the outcrop conditions hindered their full exposure (e.g., upper
779 bounding surface is not visible).

780 Interestingly, the MTDs from the Te Wharau Basin show contrasting results that suggest the coeval
781 presence of smaller (i.e., *detached*) systems (Figure 14; Appendix 4). The limited outcrop exposures may
782 explain such results, preventing the recognition of representative thickness values. Yet, the potential

783 presence of isolated shelves (e.g., Caron et al. 2021) and or the particular geotectonic settings and
784 triggering mechanisms evidenced for the shelf-derived MTDs we present in this study (i.e.,
785 oversteepened slope due to thrust activity), which contrast with the causal mechanisms traditionally
786 invoked for shelf failure (e.g., sea-level changes, high-sedimentation fluxes) (see 6.2), should also be
787 taken into account. Whilst oversteepened slopes at the thrust fronts (e.g., forelimb settings) appear to
788 generally source reduced MTDs volumes ($\sim V < 5$ cubic kilometres) (e.g., Watson et al. 2020), the complex
789 interactions that exist between sediment supply, slope profile and shelf width along convergent margins
790 can also alternatively promote the development of *attached* or *detached* systems from regional slope
791 settings (e.g., shelf) (e.g., Naranjo-Vesga et al. 2020). Therefore, although further work is required to
792 generalise such observations and interpretations to our study area, the different styles and sizes of shelf-
793 derived MTDs described in this study rather support the prospect of slightly more complicated
794 morphometric relationship and classification along tectonically active margin settings, whereby the shelfal
795 region may contemporaneously source both *attached* and *detached* systems.

796 Overall, the morphometric values suggest seismic-scale shelf-derived MTDs throughout the study area.
797 Traditionally, the seismofacies of mud-dominated cohesive flows is defined by low amplitude, semi-
798 transparent and chaotic reflections (Bull et al. 2009). Here however, we cannot expect for the internal
799 architecture of the Sefton Hills MTC, as described in this high-resolution study (i.e., several coalescing
800 shelf-derived MTDs), to be imaged by the seismic data because of resolution limitations. A mud-
801 dominated deposit containing clasts, whether milli-, deci- or decametric or having contrasting
802 concentrations, would hold similar acoustic impedance characteristics and thus look the same at seismic
803 scale. Therefore, the coalescing shelf-derived MTDs of Sefton Hills will be imaged as one unique MTD
804 (seismofacies) at seismic-scale, thereby missing the potential discrete, multiple-surge events responsible
805 for deposits holding distinct lithological and petrophysical properties at outcrop-scale.

806 **6.2. Causes and controls for continued destabilisation of source regions**

807 We previously demonstrated that the MTDs described in this study were sourced from the destabilisation
808 of the contemporaneously developing shelfal environments. Gravity-driven instabilities can however
809 result from a variety of processes, and fortunately, the MTDs characteristics (e.g., geomorphologic
810 features) provide direct evidence on the former failure processes and basin settings (Mulder and
811 Alexander 2001; Bull et al. 2009; Posamentier and Martinsen 2011; Talling et al. 2012). Accordingly,
812 shelf-derived MTDs are generally inferred to be controlled by extrabasinal, regional-scale processes;
813 notwithstanding gas-hydrate dissociation, storms, longshore currents or tectonic activity (e.g.,

814 earthquakes) as other important causal mechanisms, relative sea-level changes and high sedimentation
815 fluxes remain the most commonly invoked triggers (e.g., Posamentier and Kolla 2003; Moscardelli and
816 Wood 2008; Moscardelli and Wood 2015; Bull et al. 2020).

817 The nature and size of the remobilised material presented here indicates powerful events that
818 destabilised both the shelf substratum and fresh sediments. The resulting products, recorded across
819 several trench-slope basins (along a 70 kilometre-long transect), point towards a margin-wide episode of
820 destabilisation leading to a regional footprint of the associated deposits. The different ages captured in
821 the MTDs (e.g., T27/f632: mid Lillburnian; T27/f638: early Lillburnian) however argue for a period (rather
822 than a single, brief episode) of widespread failure that lasted ca. 1 to 2 Ma. The Sefton Hills MTDs also
823 add that within this period, a series of close, high-frequency collapse events (i.e., multi-surge events)
824 repeatedly occurred.

825 At global scale, the sea-level changes highlighted a couple of drops during the Middle Miocene,
826 Lillburnian (Haq et al. 1987; Miller et al. 2005) that may have punctually influenced the stability of the
827 shelf(ves). However, although shelf edges are commonly steep already (Schlager and Camber 1986)
828 and thus prone to both oversteepening and failure, no statistically significant link or pattern seem to exist
829 between the sea-level changes and occurrences of slope failure (Urlaub et al. 2013). Conversely, sea-
830 level variations will generally have a major impact on seafloor pressures (e.g., hydrostatic pressure) and
831 temperatures (e.g., warm currents) (Urlaub et al. 2013). An increase in temperature of as little as 1°C at
832 water depths <600 metres (e.g., shelf) can shift the gas hydrate stability zone downslope, engender
833 dissociation of the hydrate accumulation, release substantial quantities of free gas and thus promote
834 slope failure (Reagan and Moridis 2008). Widespread evidence of gas-hydrate deposits exists in the
835 Hikurangi Margin; however, it is unclear whether these deposits already existed during the Middle
836 Miocene. Moreover, Moscardelli and Wood (2008) and Moscardelli and Wood (2015) trust that gas-
837 hydrate dissociation preferentially leads to the catastrophic failure of a large sediment volume (rather
838 than a succession of failures), thereby discarding it as a potential cause for the MTDs described in this
839 study. Storm-induced waves and longshore currents are also known to potentially trigger slope failure in
840 shallow waters. In the Akitio Basin, the Middle Miocene Pongaroa shelf displays a shallowing-up trend
841 capped by storm-influenced deposits (Bailleul et al. 2007). However, the related sedimentary features
842 are of too small a magnitude (i.e., two to 10-centimetre-thick shell lineation in 30 to 50-centimetre-thick
843 shell beds) to suggest a powerful event responsible for large-scale destabilisation. The duration of such
844 event, although greater than that of an earthquake, also does not explain the recurrence and surges that
845 were observed in some of the deposits. Also, no indication of contour current deposits has ever been
846 reported on this margin during the Middle Miocene, thereby ruling out this other mechanism.

847 On the Hikurangi Margin, shelves commonly formed in association with margin uplift and are located
848 above tectonically induced stratigraphic surfaces (e.g., angular unconformities) resulting from rapid
849 motion of the basins' margins (Bailleul et al. 2013). For example, the Pongaroa and Waihoki-Mangatiti
850 shelves developed above silty deep-marine deposits (Bailleul et al. Submitted). Interestingly, the angular
851 unconformities not only appear to be coeval with the accumulation of the first shelfal sediments but can
852 also be correlated with the remobilisation and deposition of the associated MTDs along the slope and
853 into deep-water settings. The tectonic activity related to the development of basin-bounding structures
854 (e.g., thrusts) follows timescales of ca. 1 to 2 Ma (Nicol et al. 2002; Bailleul et al. 2013). Therefore, these
855 short tectonic periods have not only recorded discrete, high amplitude structural movements (e.g. uplift)
856 responsible for dramatic changes in depositional environments (e.g., neritic conditions) (Figure 15). They
857 also most likely controlled the continuous (with or without break) propagation of the associated thrust
858 fault(s) and thus favoured the development of abrupt, unstable areas near the shelf edges (e.g., forelimb
859 setting).

860 High sediment fluxes, known to fundamentally modify the dynamic equilibrium of an area and influence
861 the growth of (pre-existing) structures (Storti and McClay 1995; Malavieille 2010; Graveleau et al. 2012;
862 Barrier et al. 2013; Noda 2018) could have also contributed to some of the oversteepening. Hence, we
863 attribute the above-described shelf-derived MTDs to be primarily controlled by tectonic uplift and
864 oversteepening. These findings are in agreement with those of Watson et al. (2020) (although built from
865 the analysis of MTDs sitting on the seafloor), who proposed for these two mechanisms to be mainly
866 responsible for the mass-wasting processes occurring along the Hikurangi Margin thrust ridges. We here
867 bring new insights as to some of the depositional environments being destabilised by these mechanisms
868 in the older stratigraphic record.

869 Finally, vertical movements of the coastline can also result from earthquakes (Pilarczyk et al. 2014) and
870 the Hikurangi Margin has a history of both subduction and upper plate fault earthquakes (Clark et al.
871 2019). The accompanying co-seismic shaking can trigger large-scale subaqueous slope instabilities and
872 the subsequent generation of gravity-driven flows (e.g., MTDs) (Hampton et al. 1996). A series of
873 tsunamigenic waves (i.e., series of surges) can also be induced, resulting in the seaward downslope
874 transport (tsunami backwash) of a wide range of material from terrestrial (e.g., organic matter) to shelfal
875 (e.g., mollusc macrofossils) origins; and despite high-energy transport, the fossils can remain
876 taphonomically unaltered (i.e., pristine) (Einsele et al. 1996; Pilarczyk et al. 2014). However, no seaward
877 to landward current reversals nor violent fluid escape features, characteristics of tsunamites (Dawson
878 and Stewart 2007), were observed in our deposits.

879 [Watson et al. \(2020\)](#) argued against ground shaking as a primary control in thrust-related mass-wasting
880 processes. Although ground shaking is undoubtedly important, we also believe that for the MTDs
881 described in this study, this process may not be the primary (but a secondary) control. We interpret
882 periods of repeated tectonic activity (thrust propagation and uplift) to be the main causal mechanism for
883 shelf destabilisation and collapses (Figure 15). Continued (ca. 1 to 2 Ma) tectonic activity (possibly
884 combined with earthquake(s)) would lead to recurring generation and destruction of oversteepened
885 slopes. The shelf-edge escarpments would thus be repeatedly destabilised, allowing for the development
886 of multiple episodes of mass-wasting along the margin. Like other mechanisms, such as gas-hydrate
887 dissociation or storm-induced waves, sea-level changes and high sedimentation rates, commonly
888 inferred to be the dominant causal mechanisms, most likely contributed to some mass-wasting, punctually
889 influencing the stability of the shelf(ves), however they did not act as the main triggers for the shelf-
890 derived MTDs described here.

891 **6.3. Implications for the Coastal Ranges and active Hikurangi Margin**

892 A number of mixed siliciclastic-carbonate shelfal environments coexisted in the Coastal Ranges during
893 the Middle Miocene, Lillburnian ([Crundwell 1987](#); [Chanier 1991](#); [Bailleul et al. 2007](#); [Bailleul et al. 2013](#);
894 [Bailleul et al. Submitted](#)) and their linear distribution along a 120 kilometre-long, NE-SW transect (Figure
895 3; Figure 5) indicates that they most likely formed a regional continental shelfal domain in the south-
896 western portion of the Hikurangi Margin at the time. The high amount of land-derived material (e.g.,
897 organic matter, reworked sub-rounded pebbles), incorporated in both the shelfal and resulting MTDs, is
898 in favour of a narrow, continent-attached system receiving regular terrigenous input from the hinterland
899 areas. No lateral continuity has yet been established between the different locations, therefore
900 development of partially connected or isolated, continent-detached platform systems upon and about
901 actively fault-growing folds ([Caron et al. 2004](#); [Caron et al. 2021](#)) may have also locally occurred (e.g.,
902 [Bailleul et al. 2013](#)), Fingerpost shelf).

903 The diversity observed in the nature of the reworked material (e.g., clast content, size) and the regional
904 footprint of the MTDs suggests destabilisation of most, if not all, of these platforms (Figure 16). These
905 shelves developed above substantially different substratum inherited from local tectonics, thereby
906 allowing us through the thorough analyses of the reworked material to retrace the potential sourcing
907 region(s) of the different MTDs recorded in the trench-slope basins (see 5.1.3, 5.2, 6.1). The northern
908 shelves from the Akitio Basin (Figure 3, sections i, p, m, t) most likely sourced the Branscombe and
909 southward-moving Sefton Hills MTDs respectively captured in the Akitio and Whareama Basins (Figure

910 3; Figure 16; sections b, s), whereas the southern shelves of Wainuioru and Mapapa (Figure 3; Figure
911 16; sections ms, w) are great candidates for the MTDs recorded in the Te Wharau Basin (Figure 3; Figure
912 16; sections c, n, r, tw). Therefore, the Middle Miocene, Lillburnian, not only staged the development of
913 regional shelfal domain(s) across the south-western portion of the Hikurangi Margin (Crundwell 1987;
914 Chanier 1991; Bailleul et al. 2007; Bailleul et al. 2013; Bailleul et al. Submitted) but they also recorded
915 their coeval destabilisation and failure(s) (Figure 16).

916 The Akitio and Whareama Basins were connected during the Early Miocene (Bailleul et al. 2013), and
917 this connection most probably persisted, at least partially, during the Middle Miocene to allow for some
918 of the mass-wasting products sourced from the Akitio shelves to travel southwards into the Whareama
919 Basin (e.g., Sefton Hills MTDs) (Figure 16). We therefore propose that the seaward margin of the Akitio
920 Basin, partially emerged at the time (i.e., Cape Turnagain Structural High), formed together with the
921 seaward margin of the Whareama Basin a rather continuous topographic barrier (emerged or submerged)
922 to the east, most probably in the southward continuation of Cape Turnagain (Figure 16). Such ridge was
923 likely controlled by the underlying Whakataki-Turnagain Fault complex to the north, laterally evolving into
924 the Flat Point-Whakataki Fault complex to the south (Figure 3).

925 Finally, from ca. 15 Ma, the Hikurangi Margin is inferred to have undergone a major change in tectonic
926 regime, entering into a period of generalised subsidence, after 10 Ma of active folding and reverse faulting
927 (Chanier and Ferrière 1989; Chanier and Ferrière 1991; Rait et al. 1991; Chanier et al. 1999; Nicol et al.
928 2002; Bailleul et al. 2007; Nicol et al. 2007; Bailleul et al. 2013; Malie et al. 2017; McArthur et al. 2019).
929 However, we just demonstrated (see 6.2) that the southern portion of the Hikurangi Margin was still
930 dominated by shortening and uplift during the Middle Miocene, thereby delaying the age for the onset of
931 subsidence in this region. In the Akitio Basin, the work of Bailleul et al. (2013) supports this result, with a
932 previously established younger subsidence starting at 13.2 Ma. In the Whareama Basin, in the absence
933 of other stratigraphic markers, the age of the MTDs (mid Lillburnian, ca. 14 Ma) can be used as a guide
934 to propose that the subsidence did not start before, at least, 14 Ma. For the Te Wharau Basin, whilst the
935 first recordings of subsidence date from 15 Ma (Chanier et al. 1992; Chanier et al. 1999), periods of active
936 tectonics persisted until the end of the Middle Miocene, particularly affecting the structures to the east
937 (Crundwell 1987). The MTDs spanned the Middle Miocene, Lillburnian and thus cannot be used to
938 precisely refine the age of the generalised subsidence in the Te Wharau Basin. Chanier et al. (1999)
939 observed that this major change in tectonic regime gradually occurred along the margin. We here offer
940 an additional insight as to the subsidence timeframe in the Whareama Basin, shifting the starting age
941 from 15 Ma to 14 Ma at minima.

6.4. Implications for mass-transport deposit nomenclature

943 Mass-wasting *attached* systems can be divided into two types (Moscardelli and Wood 2008; Moscardelli
944 and Wood 2015). The *shelf-attached* systems are essentially sourced by shelf-edge deltas whose stability
945 is mainly controlled by sea-level changes and sedimentation rates whereas the *slope-attached* systems
946 result from isolated, catastrophic sediment collapse(s) typically related to gas-hydrate dissociation and
947 or tectonic activity (e.g., earthquakes) (Moscardelli and Wood 2008; Moscardelli and Wood 2015). The
948 latter will successfully destabilise huge volumes of sediments simultaneously whereas the former will
949 involve multiple, semi-uninterrupted episodes of mass-failure. As highlighted by Moscardelli and Wood
950 (2015), characterising if a system is *shelf-* or *slope-attached* is particularly critical since it does not only
951 inform on the potential sourcing areas but also helps to better predict the impending causal mechanisms
952 and modalities of development.

953 Whether or not the shelf-derived MTDs described in this study correspond to the *shelf-attached* or *slope-*
954 *attached* nomenclature is uncertain. The deposits result from the regional destabilisation of neritic shelfal
955 environments, however there is no evidence of a shelf-edge delta that could have fed such a system in
956 the Hikurangi Margin. In fact, the Hikurangi shelfal environments are often referred to as mixed
957 siliciclastic-carbonate systems formed in association with margin uplift and where the carbonates
958 accumulated on a narrow shelf(ves) receiving recurrent terrigenous input from the hinterland (Caron et
959 al. 2004; Bailleul et al. 2007; Bailleul et al. 2013). As previously discussed, the destabilisation and
960 collapse of these shelfal environments most likely resulted from the generation and destruction of
961 oversteepened slopes controlled by tectonic activity (shortening, uplift and seismicity) rather than
962 changes in eustatic level (see 6.2). The multiple, successive mass-wasting occurrences recorded at
963 outcrop do not point toward an isolated catastrophic event but a series of semi-continuous events with a
964 regional footprint. Similar divergences with such classification have been observed elsewhere in the world
965 in similar tectonically active convergent settings (e.g., in the Sinu fold belt, offshore Colombia (Romero-
966 Otero et al. 2010; Ortiz-Karpf et al. 2018)).

967 We therefore propose that notwithstanding sea-level changes and high sedimentation rates as causal
968 mechanisms (Posamentier and Walker 2006; Moscardelli and Wood 2008; Moscardelli and Wood 2015;
969 and references within), recurrent tectonic activity (shortening, uplift and related seismicity) along active
970 margins also has potential to trigger large-scale shelf(ves) destabilisation and collapses. Therefore,
971 although these systems, sourced from the shelf, seem to preferentially occur at mature stages of
972 convergent margin development (Underwood and Bachman 1982; Bailleul et al. 2007; Vinnels et al. 2010;

973 Ortiz-Karpf et al. 2018), they will not always post-date the main phases of active tectonics (*i.e.*, can be
974 syn-kinematic) as suggested by Ortiz-Karpf et al. (2018).

975

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977

978 (1) Sea-level changes and high sedimentation rates are commonly inferred to be the main causal
979 mechanisms for large-scale continental shelf(ves) collapses (*i.e.*, *shelf-attached* systems),
980 thereby underestimating the role of tectonics. This study demonstrates that periods of tectonic
981 activity (shortening, uplift and related seismicity) act as another causal mechanism to consider
982 for large-scale shelf failure. In fact, recurring tectonic motion in compressional settings (*e.g.*,
983 active margins) can not only affect the basin-bounding structures and control the development
984 of the shelfal environments but also drive the recurrent generation and destruction of
985 oversteepened slopes, which can, in turn, favour repeated destabilisation and collapses of the
986 shelves.

987

988 (2) Short-lived periods (ca. 1 to 2 Ma) of tectonic activity can result in the emplacement of recurrent
989 mass-wasting products thereby reinforcing the importance of mass-wasting systems in deep-
990 marine fold-and-thrust belt evolution.

991

992 (3) Shelf-derived mass-wasting products are preferentially recorded and captured during mature
993 stages of trench-slope basin and subduction margin development. Yet, they do not always post-
994 date the main phases of active tectonics. They can result from the destabilisation and collapses
995 of shelves, either directly attached to the continent or potentially locally isolated, developing upon
996 and about actively fault-growing folds.

997

998 (4) The associated shelf-derived products have a regional footprint.

999

1000 ○ Both sediment mass-movements (*e.g.*, slides, slumps) and mobilisation (*e.g.*, debris
1001 flows) can occur. Yet, cohesive gravity flows dominate, eventually breaking down into a
1002 series of erosive, upward fining surges downslope.

1003 ○ At outcrop scale, the MTDs always incorporate sediments and well-preserved to
1004 fragmented macrofossils from neritic shelfal environments and mostly comprise (pre-
1005 and syn-kinematic) extraformational clasts. Their sizes generally oscillate between a ten
1006 to a couple hundreds of metres (minimum thickness). Regionally extensive, they are

1007 deposited across several intra-slope basins, even though smaller, localized MTDs can
1008 also be punctually found.

1009 ○ At seismic scale, both sediment mass-movements and cohesive gravity flows are
1010 commonly observed. However, the seismic resolution does not allow identification of the
1011 multitude of downslope surges observed at outcrop-scale. The coalescing gravity flows
1012 will be commonly imaged as one single seismofacies, thereby missing the lateral and
1013 vertical facies variations. This will, in turn, have a significant impact for both the causal
1014 mechanism and stratigraphic predictions.

1015

1016 (5) Taphonomic analysis of the fossil content of MTDs is a powerful tool to gain additional knowledge
1017 on the transport and depositional processes of mass-wasting events. It also helps identifying and
1018 better characterising the source areas.

1019

1020 (6) Finally, MTDs can be used as a guide to help refining the tectonostratigraphic evolution of
1021 subduction complexes and their related trench-slope basins. Here, the analysis of the MTDs
1022 allowed us to:

1023 ○ Reconstruct the depositional systems and palaeogeography at a particular time: the
1024 Middle Miocene, Lillburnian not only staged the development of a regional mixed
1025 siliciclastic-carbonate shelfal domain across the south-western portion of the Hikurangi
1026 Margin but also recorded its coeval destabilisation, which resulted in the remobilisation
1027 and deposition of shelf-derived MTDs across several trench-slope basins (*i.e.*,
1028 Whareama, Te Wharau and Akitio Basins). The Whareama and Akitio Basins were likely
1029 connected at that time (one single trench-slope basin), sharing the same seaward border
1030 to the east, controlled by the underlying Whakataki-Turnagain Fault complex to the north,
1031 laterally evolving into the Flat Point-Whakataki Fault complex to the south.

1032 ○ Better characterise the Hikurangi Margin tectonic framework: previous studies have
1033 inferred that the margin underwent a major change in tectonic regime at ca. 15 Ma,
1034 entering into a period of generalised subsidence. However, this study demonstrates that
1035 the southern portion of the Hikurangi Margin was still dominated by shortening and uplift
1036 during the Middle Miocene, Lillburnian, and thus, that the subsidence did not start before,
1037 at least, ca. 14 Ma in the Whareama Basin.

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1051 No potential conflict of interest was reported by the author(s).

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1054 **11. DATA AVAILABILITY STATEMENT**

1055 The data that support the findings of this study are openly available in figshare at:

1056 [https://figshare.com/articles/journal_contribution/Claussmann_et_al_NZJGG_Supplementary_material/](https://figshare.com/articles/journal_contribution/Claussmann_et_al_NZJGG_Supplementary_material/13614101)
1057 [13614101](https://figshare.com/articles/journal_contribution/Claussmann_et_al_NZJGG_Supplementary_material/13614101).

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1439 13. FIGURES

1440 Figure 1: Generic model for trench-slope systems. Evolving structural style towards the trench influences the generation of
1441 accommodation space and sediment pathways. (g): Failure of the regional continental shelf and upper-slope regions will
1442 source attached mass-wasting systems (*sensu* Moscardelli and Wood 2008) and thus large-scale mass-transport deposits.
1443 (h): Collapse of the local thrust-related slopes will feed detached systems (*sensu* Moscardelli and Wood 2008), characterised
1444 by smaller, localized mass-transport deposits. Modified from McArthur et al. (2019).

1445 Figure 2: (A): Plate tectonic setting of New Zealand. (B): Major subduction-related morphostructural features of the Hikurangi
1446 Margin. Black arrows show present-day relative plate motion between the Pacific and Australian plates from Beavan et al.
1447 (2002). See (C) for the a – b general cross-section of the Hikurangi subduction complex. (C.R – Coastal Ranges). Modified
1448 after Chanier et al. (1999); Bailleul et al. (2007, 2013).

1449 Figure 3: Bathymetric map (Lewis et al. 1999) and onshore structural map (modified from Chanier et al. (1999), Lee and Begg
1450 (2002) and Bailleul et al. (2013)) of the southern Hikurangi subduction wedge. The offshore area includes the location of the
1451 well Titihaoa-1. Locations of the fault complexes = (I): Adams-Tinui Fault complex, (II): Pukeroro Fault, (III): Flat Point-
1452 Whakataki Fault complex to the south, evolving into the Whakataki-Turnagain Fault complex to the north, (IV): Turnagain
1453 Fault from Malie et al. (2017). Location of the onshore sedimentological vertical sections displaying Middle Miocene [NZ stage:
1454 Lillburnian] shelfal deposits = (f): Fingerpost section, (m): Waihoki-Mangatiti section, (p): Pongaroa section, (t): Takiritini
1455 section from Bailleul et al. (2013) and Caron et al. (2019); (ms) : Mapapa stream section from Chanier (1991); (i): Tinui section
1456 from Johansen (1999) and Bailleul et al. (2013); (w): Wainuioru sections from Crundwell (1987) and Chanier (1991) and late
1457 Middle Miocene [NZ stage: Waiauan] shelfal deposits = (o): Oumukura section from Chanier (1991). Location of the onshore
1458 sedimentological vertical sections displaying Middle Miocene [NZ stage: Lillburnian] MTDs = (b): Branscombe section from
1459 Bailleul et al. (2013); (tw): Te Wharau road sections; (n): Ngaumu section, (r): Rangiora section; (s): Sefton Hills sections; (c):
1460 Craigie Lea section.

1461 Figure 4: Chronostratigraphic chart for the southern emerged portion of the Hikurangi subduction wedge. Lithostratigraphy
1462 details adapted from Chanier (1991), Chanier and Ferrière (1991), Field et al. (1997), Lee and Begg (2002) and Bland et al.
1463 (2015); and detailing the pre- and syn-Hikurangi subduction series. Regional tectonism adapted from Chanier et al. (1999),
1464 Bailleul et al. (2013) and Malie et al. (2017). New Zealand stages after Raine et al. (2015) showing the equivalence with the
1465 international stages.

1466 Figure 5: Satellite map from World Imagery (ESRI), and onshore geological map from Chanier (1991) of the Te Wharau and
1467 Whareama Basin areas. Location of the drone acquisition and related 3D outcrop model = (s-1): Sefton Hills section. Location
1468 of the onshore sedimentological vertical sections displaying Middle Miocene [NZ stage: Lillburnian] shelfal deposits = (ms):
1469 Mapapa stream section from Chanier (1991), (w): Wainuioru sections from Crundwell (1987) and Chanier (1991) and late
1470 Middle Miocene [NZ stage stage: Waiauan] shelfal deposits = (o): Oumukura section from Chanier (1991). Location of the
1471 onshore sedimentological vertical sections displaying Middle Miocene [NZ stage stage: Lillburnian] MTDs = (c): Craigie Lea
1472 section, (n): Ngaumu section, (r): Rangiora section, (s-1, s-2): Sefton Hills sections, (tw-1, tw-2): Te Wharau road sections.

1473

1474 Figure 6: 3D outcrop model (top) and interpretation (bottom) of the Sefton Hills coastal outcrop (section-1). The letters refer
1475 to some of the architectural elements that supported the interpretations and which are detailed in Figure 8 and Figure 9.
1476 Stereoplots (Schmidt, lower hemisphere) highlight the palaeocurrents measured in the turbidites (Fa1g) as well as the fold
1477 axis and planes of the slump-related folds measured in the shelf-derived mass-transport deposits (Fa3p) after back-tilting of
1478 bedding planes to initial horizontal position (assuming cylindrical folding).

1479 Figure 7: Sedimentary section 01 (SS-01) recorded at the Sefton Hills outcrop locality (section s-1). Location is found on
1480 Figure 6. This section covers the upper part of the turbidite system and ends at the top of the first mass-wasting event which
1481 comprises three distinct lithofacies (DF, MF-1, MF-2, see Table 1). Details on the facies assemblages (FA) are provided in
1482 Table 1. All the palaeocurrent and slump measurements were taken along this section, respectively in the turbidites (Fa1g)
1483 and mass-transport deposits (Fa3p).

1484 Figure 8: Detailed views of the turbidite system's main architectural and sedimentary elements supporting the interpretation
1485 of the Sefton Hills 3D outcrop model (Figure 6). (a, b, g, h): thick to thin-bedded turbidites (Fa1g-c to Fa1g-a), comprising
1486 low-angle, concave-up, elongated bodies, sometimes slightly eroding into a basal mud drape and either showing fining and
1487 thinning upward trend or a simple mudstone cap; (a, d, e): contorted and dislocated turbidites between undeformed strata
1488 (Fa3l-s); (c, d): example of very thin- to medium-bedded turbidites from Fa1g-f; (e, f): example of sheet-like turbidites from
1489 Fa1s; (h): intra-turbidite debris flow mostly made of dislocated turbidites and some rare floating bioclasts (Fa3l-d).

1490 Figure 9: Detailed views of the shelf-derived mass-transport deposits (MTDs) main architectural and sedimentary elements
1491 supporting the interpretation of the Sefton Hills 3D outcrop model (Figure 6). (a, b, c, e, h): sharp, slightly erosional bases
1492 between distinct MTDs; (a): pluri-decamic turbidite raft incorporated in lithofacies MF-1 (second occurrence, MF-1b); (b,
1493 e): decamic mud clasts in lithofacies DF (second occurrence, DFb); (c): increasing mud clast content toward the top of
1494 lithofacies DF (first occurrence, DFa); (d): contorted thin-bedded turbidites in MF-2 (second occurrence, MF-2b); (f):
1495 overturned turbidite rafts and stratigraphic, locally structurally-controlled, contact between the MTDs and underlying turbidite
1496 system; (g): lateral continuity of the lithofacies MF-2 which can be traced over one kilometre to the south (Sefton Hills section
1497 s-2).

1498 Figure 10: Detailed description of the three main lithofacies (DF, MF-1 and MF-2) resulting from mass-wasting events that
1499 reworked shelf-derived material. Descriptions mainly summarise the observations made at the Sefton Hills locality (Whareama
1500 Basin) (Figure 6; Figure 7; Figure 9). Insights from the inland outcrops (Te Wharau Basin) were also incorporated. (a, h, n):
1501 matrix; (b, c, d, e, i, j, k, o): syn-subduction lithoclasts, *e.g.*, turbidites, mud clasts, shell bed clasts; (f, l): pre-subduction
1502 lithoclasts; (g, m): syn-subduction bioclasts, *i.e.*, skeletons from neritic faunal assemblages. Details in Table 1.

1503 Figure 11: Detailed views of Te Wharau Basin shelf-derived mass-transport deposits. (a): hinterland outcrop conditions,
1504 gravel-grade extraformational clasts within a silty mudstone matrix; (b): sub-angular cobble of shell bed clast and granules to
1505 pebbles of pre-subduction-dominated lithoclasts; (c): cobbles and boulders of pre- (*e.g.*, Torlesse material) and syn-
1506 subduction (*e.g.*, shell beds) lithoclasts; (d): chalky molluscan skeletons and lithoclasts from (predominantly) pre-subduction
1507 strata floating in a silty mudstone matrix; (e): oversized clast of bioclastic fine-grained sandstones from middle to outer shelf
1508 environments; (f): granules to cobbles of pre-subduction material that includes small, sub-rounded pebbles of already
1509 reworked Torlesse greywackes.

1510 Figure 12: Taphonomic characterisation of fossil remains described from 1x1 m area of outcrop at three different localities,
1511 using frequency histograms of the degree of alteration (e.g., low, moderate, high) for each category of skeleton damage (i.e.,
1512 fragmentation, abrasion, bioerosion) and encrustation. Lithofacies DF and MF-1 are described in details in Figure 10. Note
1513 that data for lithofacies MF-1 are only available for the finest skeletal fraction, coarser material being rare (n=3). Photographs
1514 of fossil remains illustrate the qualitative grading evaluation of taphonomic features in the field. Arrows in photographs 3 and
1515 4 point to bio-erosional features. Arrows in photographs 5 and 6 point to the analysed bioclasts. Scales in cm.

1516 Figure 13: Depositional processes and stratigraphic record of shelf-derived mass-wasting event at outcrop scale. Shelf failure
1517 will trigger both: (1) sediment mass-failure and mobilisation close to the source region(s), on the slope and (2) cohesive
1518 gravity flow deposition onto the basin floor: either as a single cohesive flow or eventually breaking down into a series of
1519 erosive, upward fining surges downslope. The wide range of lithofacies always incorporates reworked well-preserved to
1520 fragmented macrofaunal assemblages from neritic shelfal environments. They will also include extraformational clasts either
1521 (1) originating from the failed source area, (2) incorporated during the transport downslope and or (3) resulting from the
1522 partial destabilisation of the substratum upon which the shelfal environment was settling.

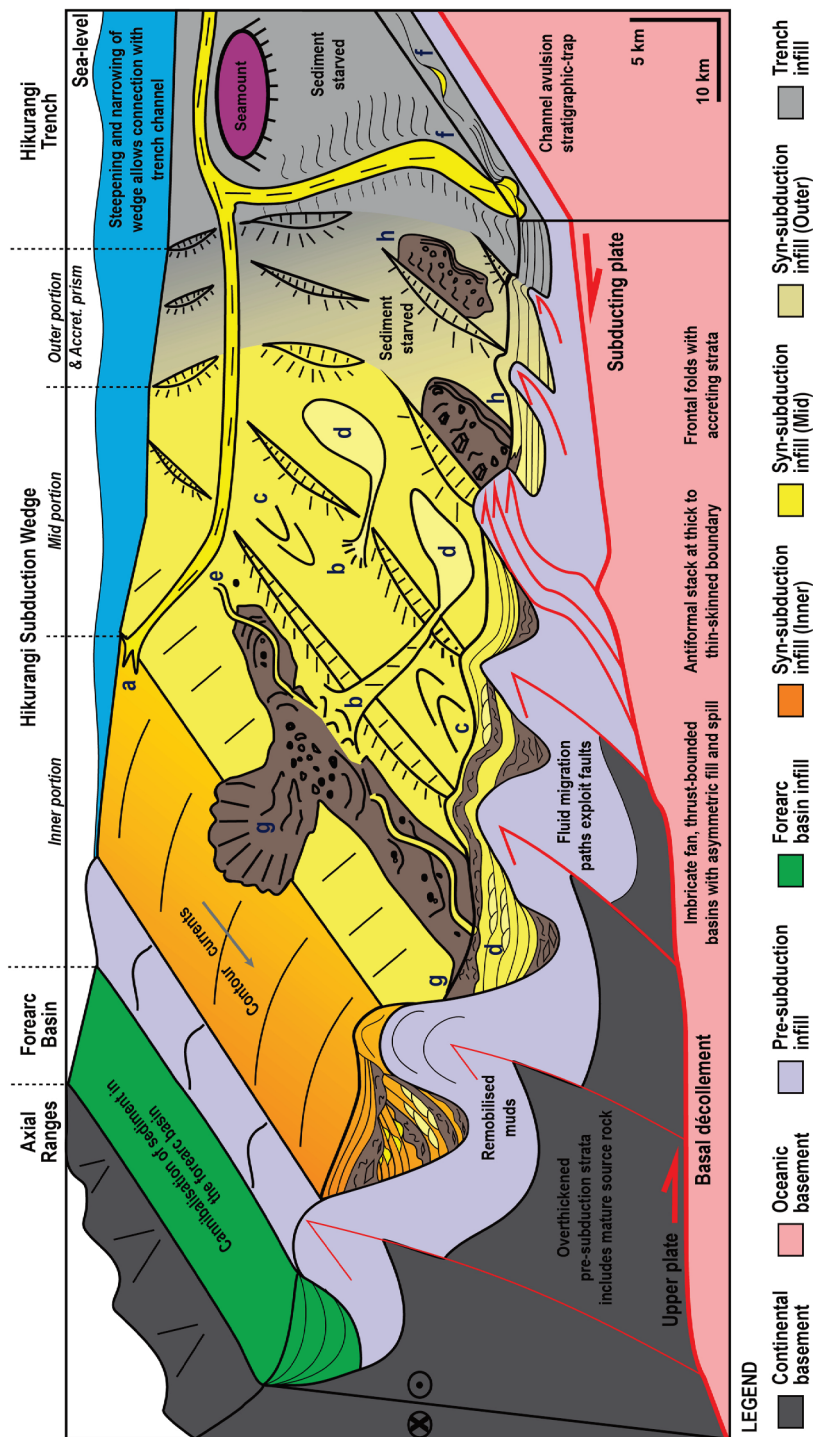
1523 Figure 14: Area vs length log-log plot showcasing the morphometric parameter values calculated for the mass-transport
1524 deposits (MTDs) described in this study using the sets of equations from [Moscardelli and Wood \(2015\)](#). See Appendix 4 for
1525 details on the equations, calculations and associated results for each of the occurrences. Whether using the general or specific
1526 set of equations, two main families of MTDs were identified using the nomenclature from [Moscardelli and Wood \(2015\)](#): (1)
1527 the Te Wharau Basin shelf-derived MTDs are best regrouped under the detached systems whereas (2) the Akitio and
1528 Whareama Basin shelf-derived MTDs under the attached systems.

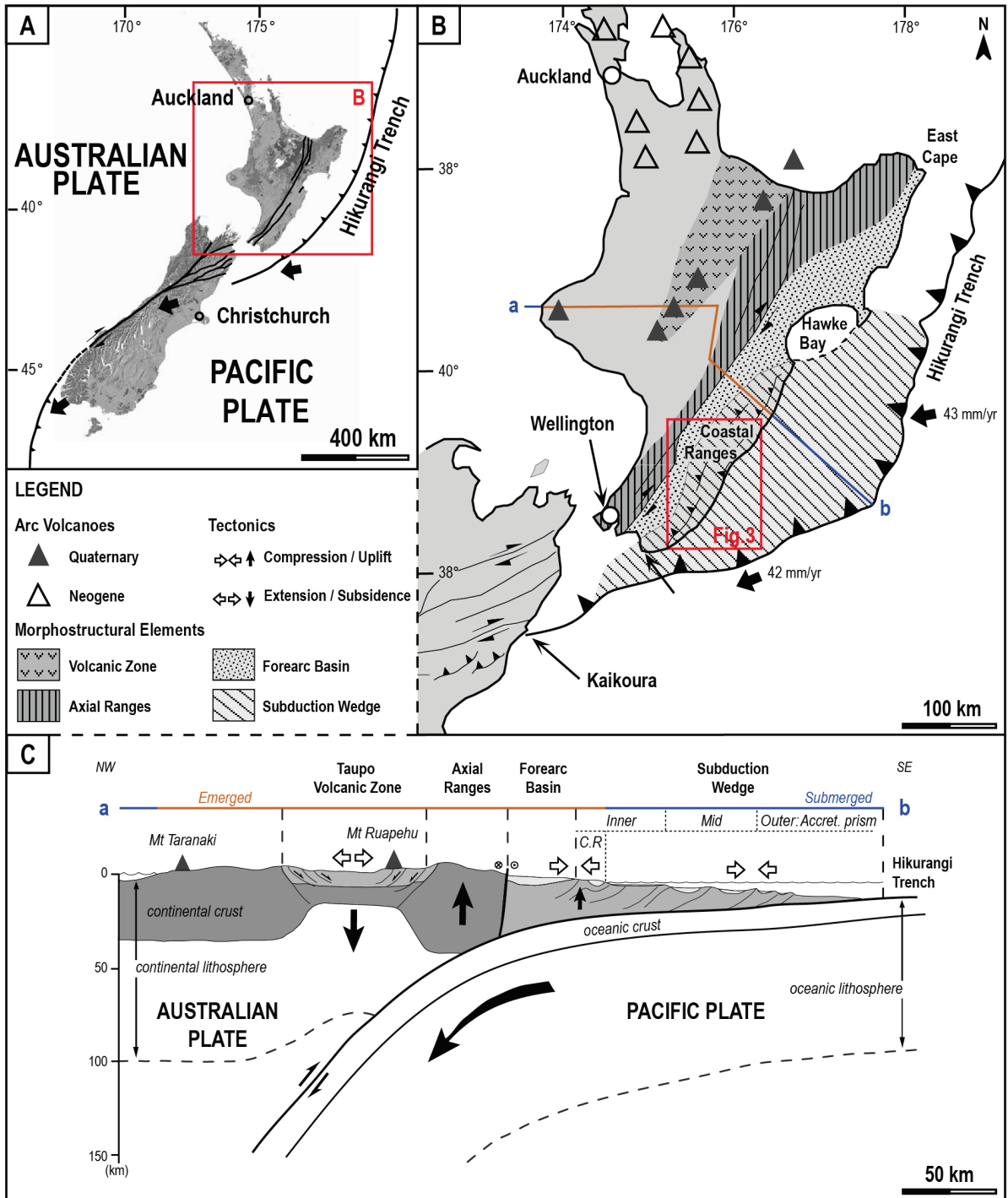
1529 Figure 15: Periods of repeated tectonic activity at basin-bounding structures will not only result in the development of neritic
1530 conditions and settlement of related faunal assemblages at shallow waters, but also favour the expansion of abrupt, unstable
1531 areas close to the shelf-margins installed above the thrust forelimb. The recurring generation and destruction of
1532 oversteepened slopes will in turn favour the repeated destabilisation and collapses of the shelves.

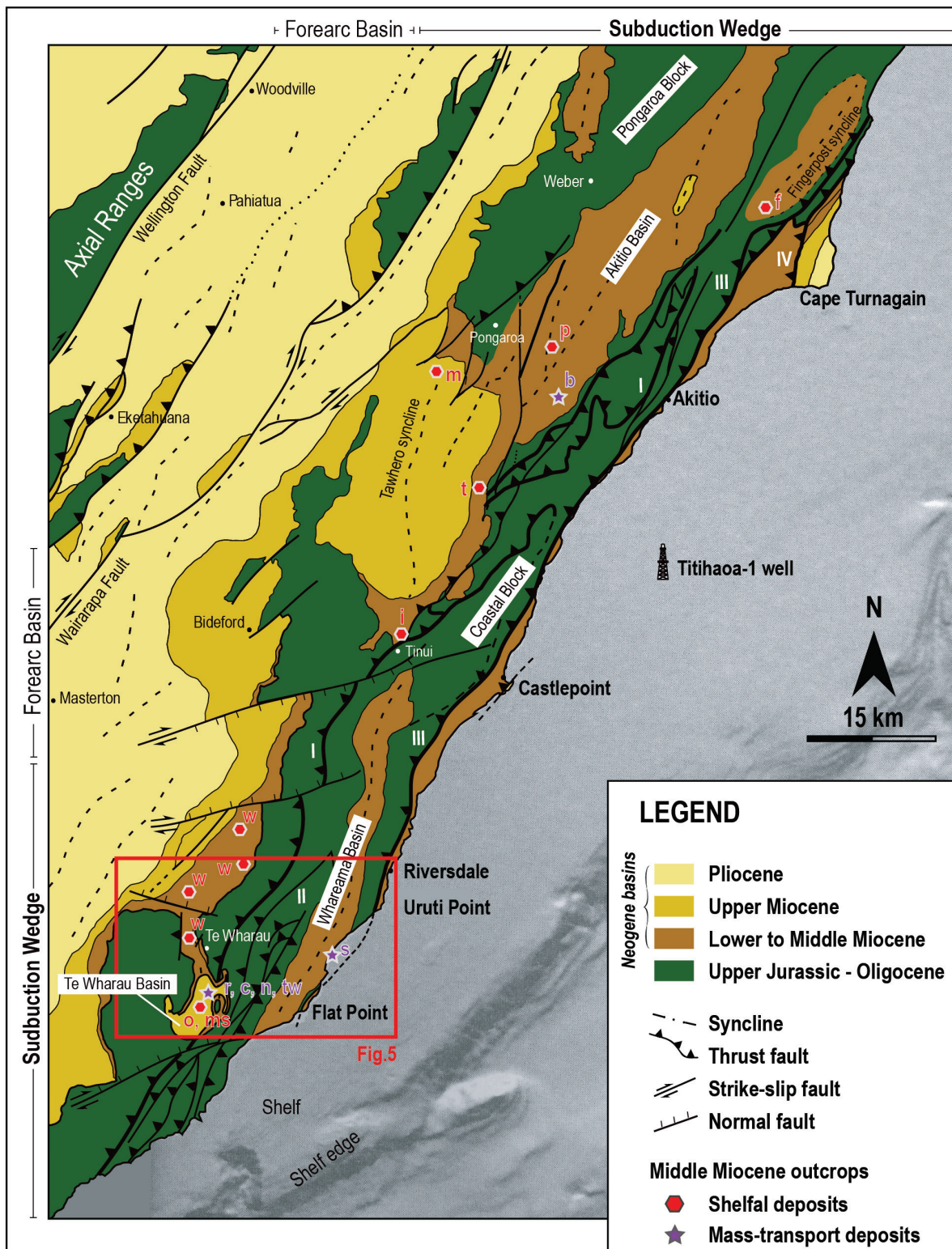
1533 Figure 16: Schematic palaeogeographic map of the south-western portion of the Hikurangi Margin (Coastal Ranges) during
1534 the Lillburnian. This period not only staged the development of regional shelfal domain(s) ([Crundwell 1987](#); [Chanier 1991](#);
1535 [Bailleul et al. 2007](#); [Bailleul et al. 2013](#)) but also recorded their concomitant destabilisation and failure(s). This(these) resulted
1536 in the emplacement of a multitude of MTDs, occluding the previously developing systems, such as the Sefton Hills turbidite
1537 systems in the Whareama Basin or the Kings canyon system (see [McArthur and McCaffrey \(2019\)](#) in the Akitio Basin. The
1538 development of the shelves occurred above substantially different substratum inherited from local tectonics, thereby allowing
1539 through the analysis of the reworked material to retrace the potential sourcing region(s) of the different MTDs (e.g., southern
1540 and northern shelfal domains). See Figure 3 for the name of the shelfal and MTD outcrops.

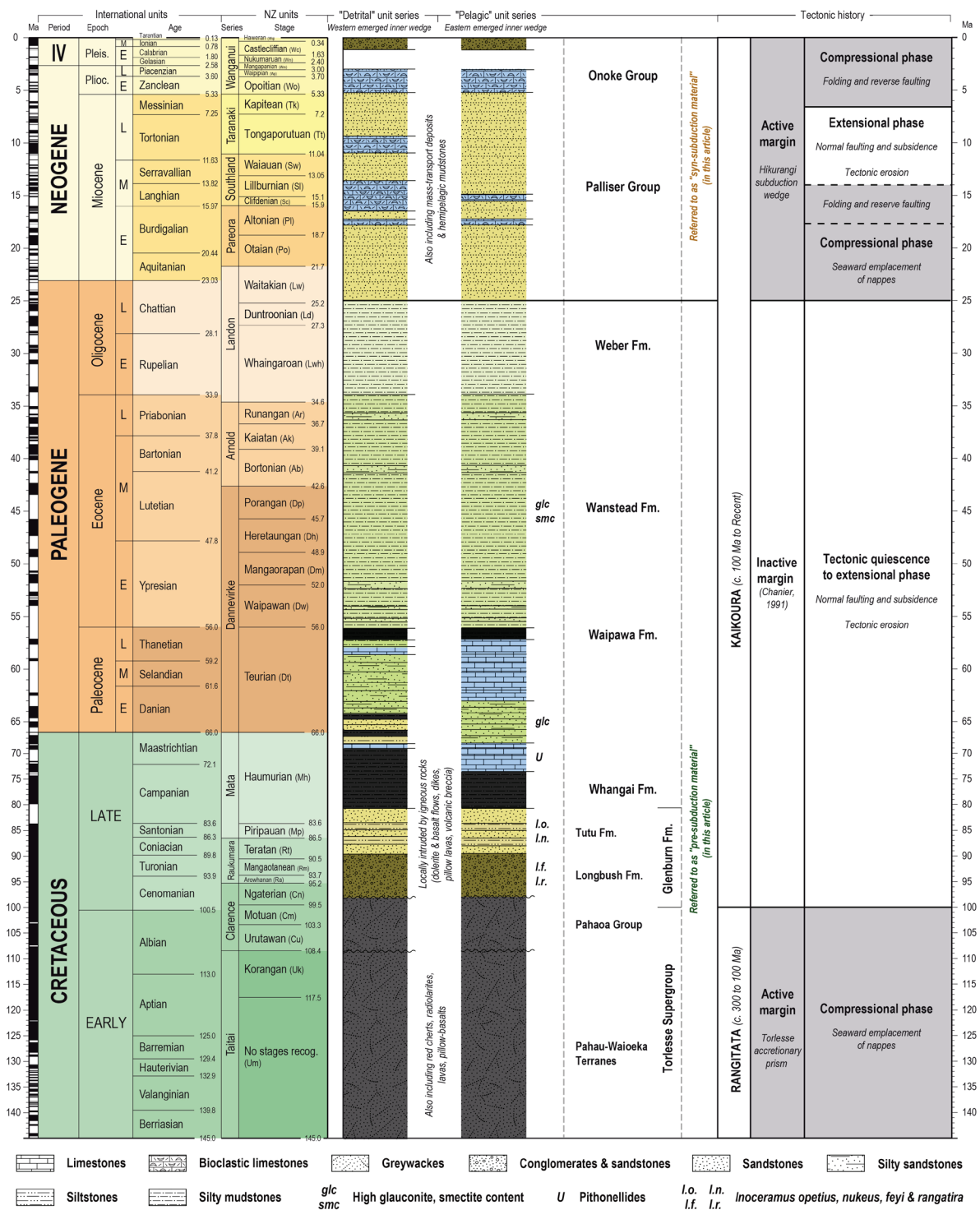
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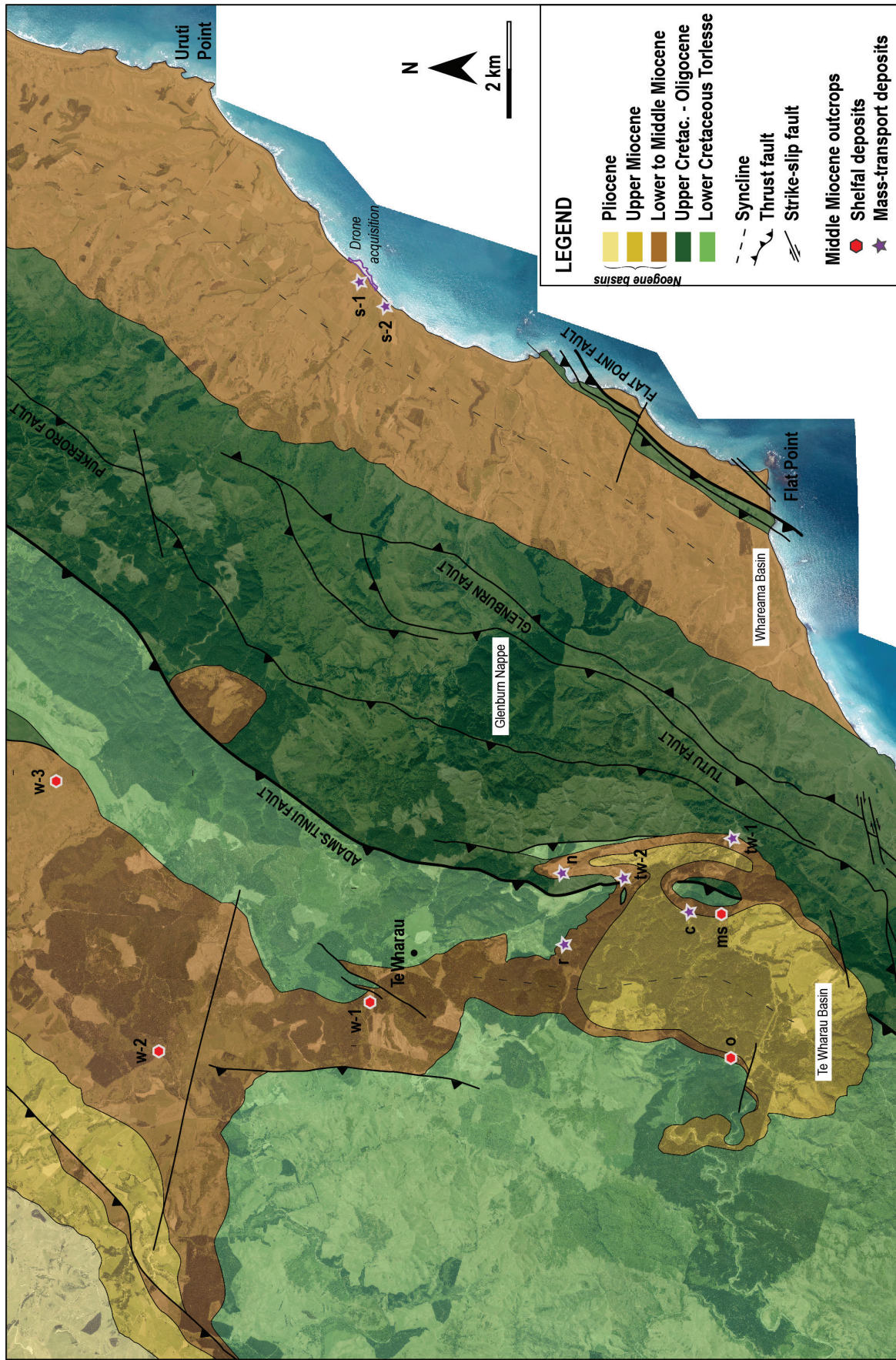
1542 Table 1: Characteristics and interpretation of the sedimentary facies for the turbidite systems (Fa1) and mass-wasting systems
1543 (Fa3) observed in the study area, mostly from the Sefton Hills outcrop (Whareama basin). The nomenclature is based upon
1544 the initial classification defined by [Bailleul et al. \(2007\)](#) and [Bailleul et al. \(2013\)](#). Pictures of the facies associations can be
1545 found in Figure 8, Figure 9, Figure 10; Figure 11.

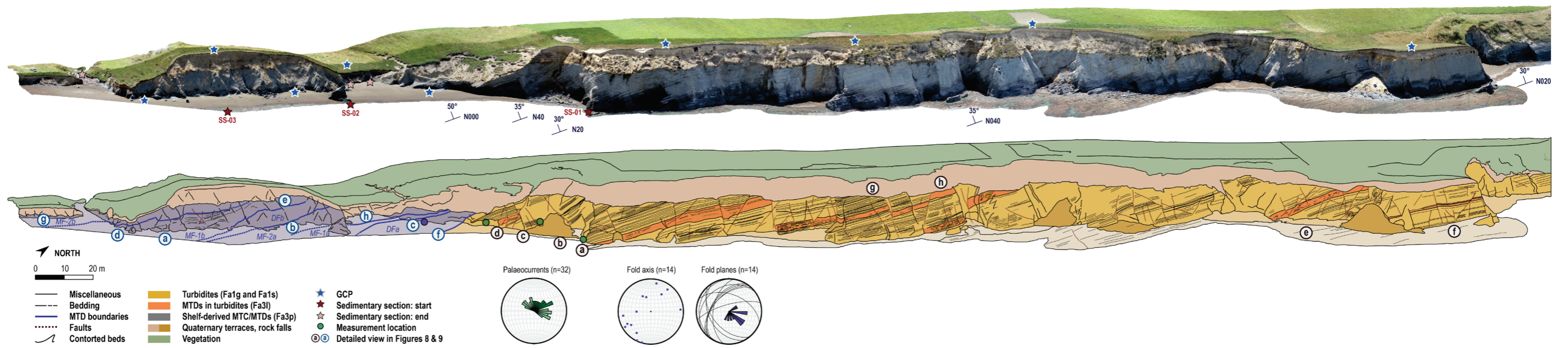


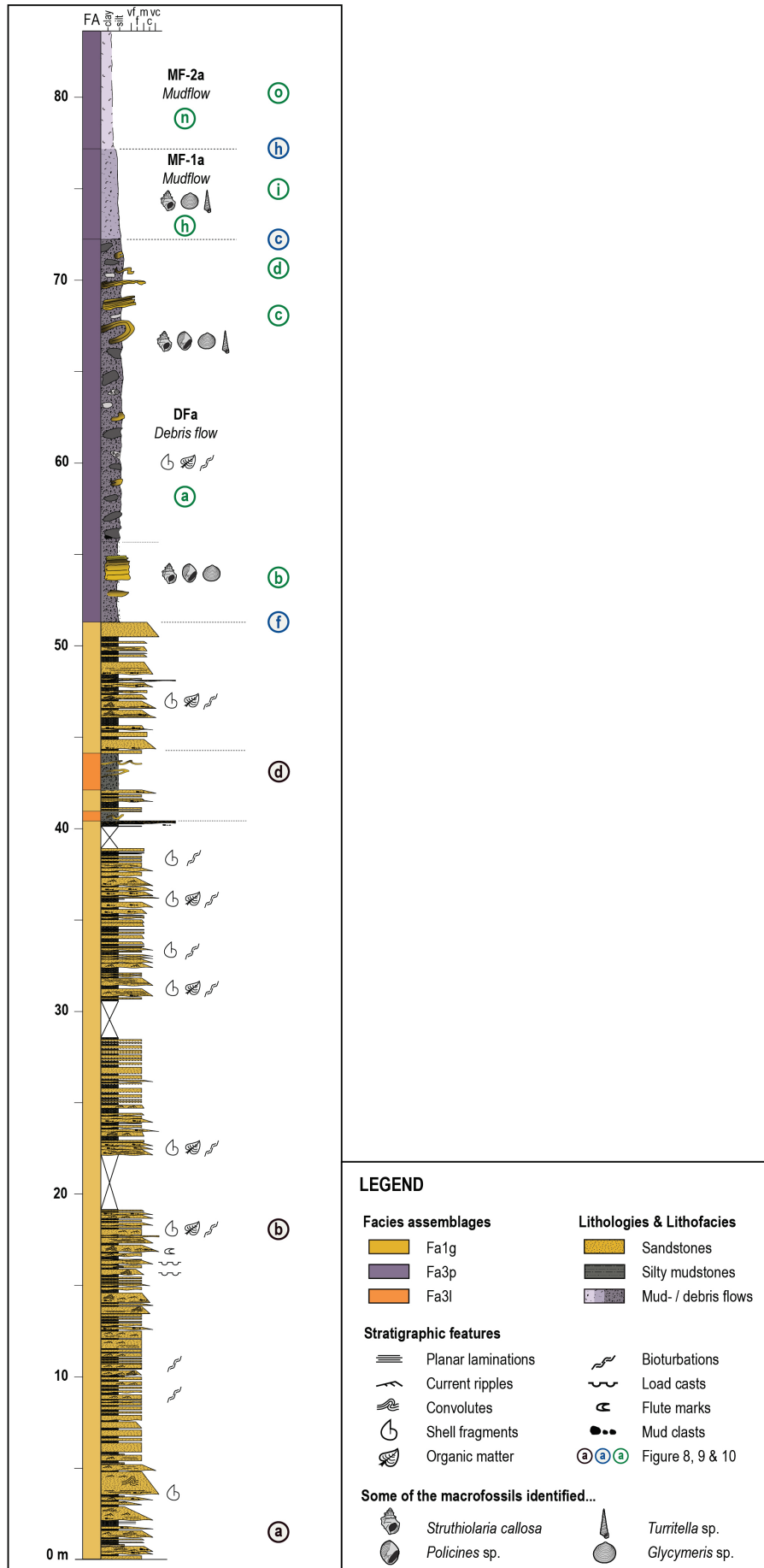


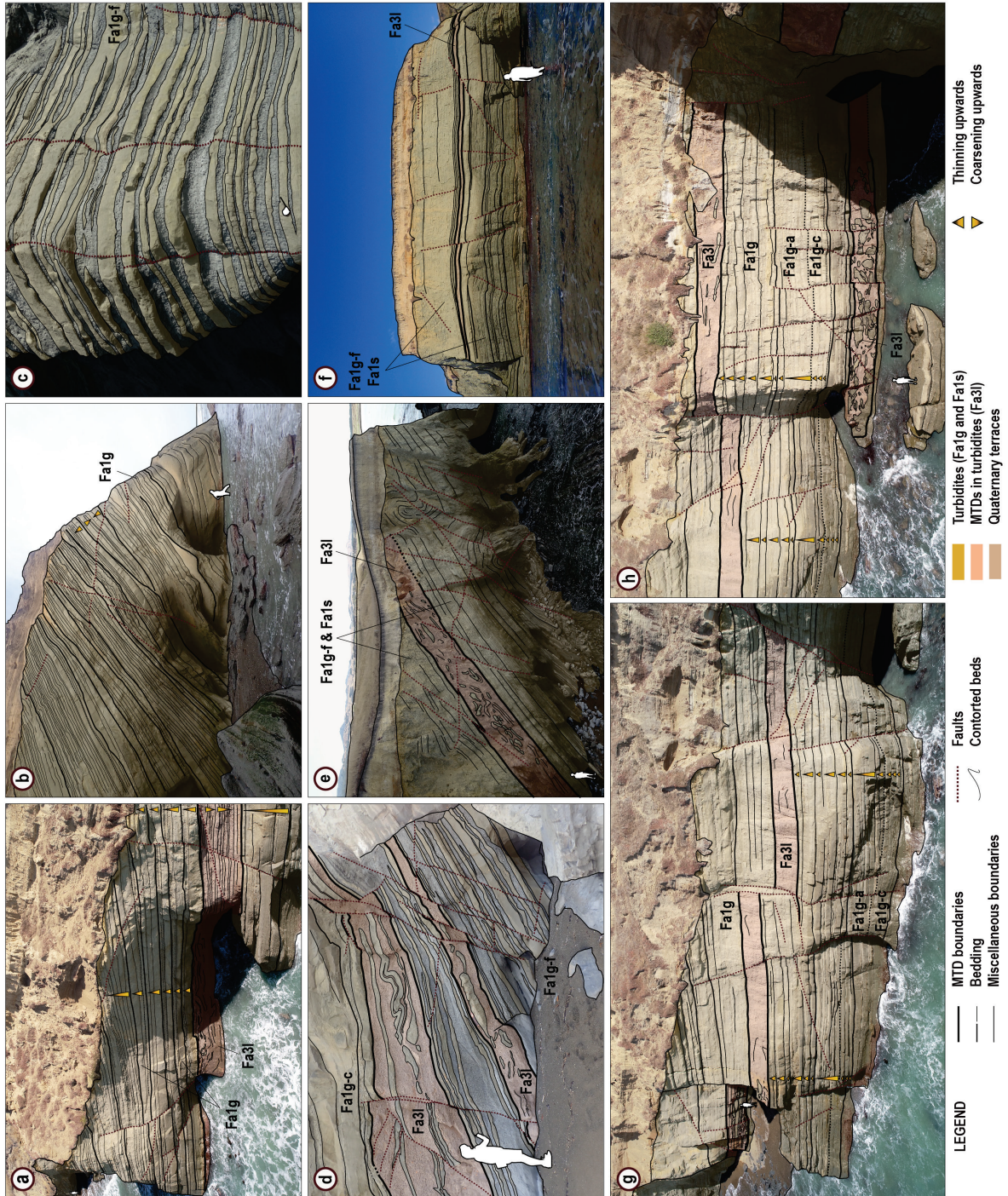


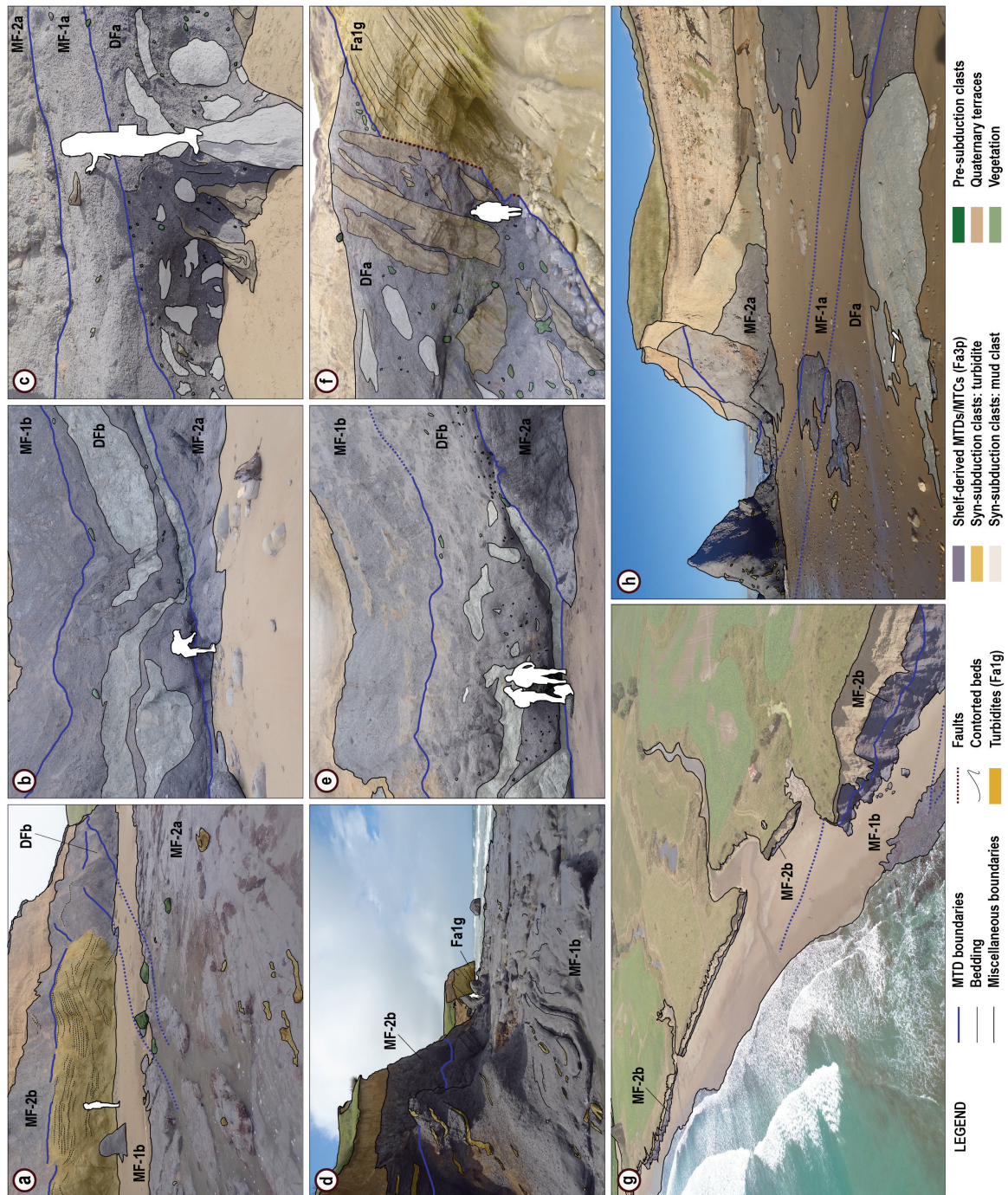


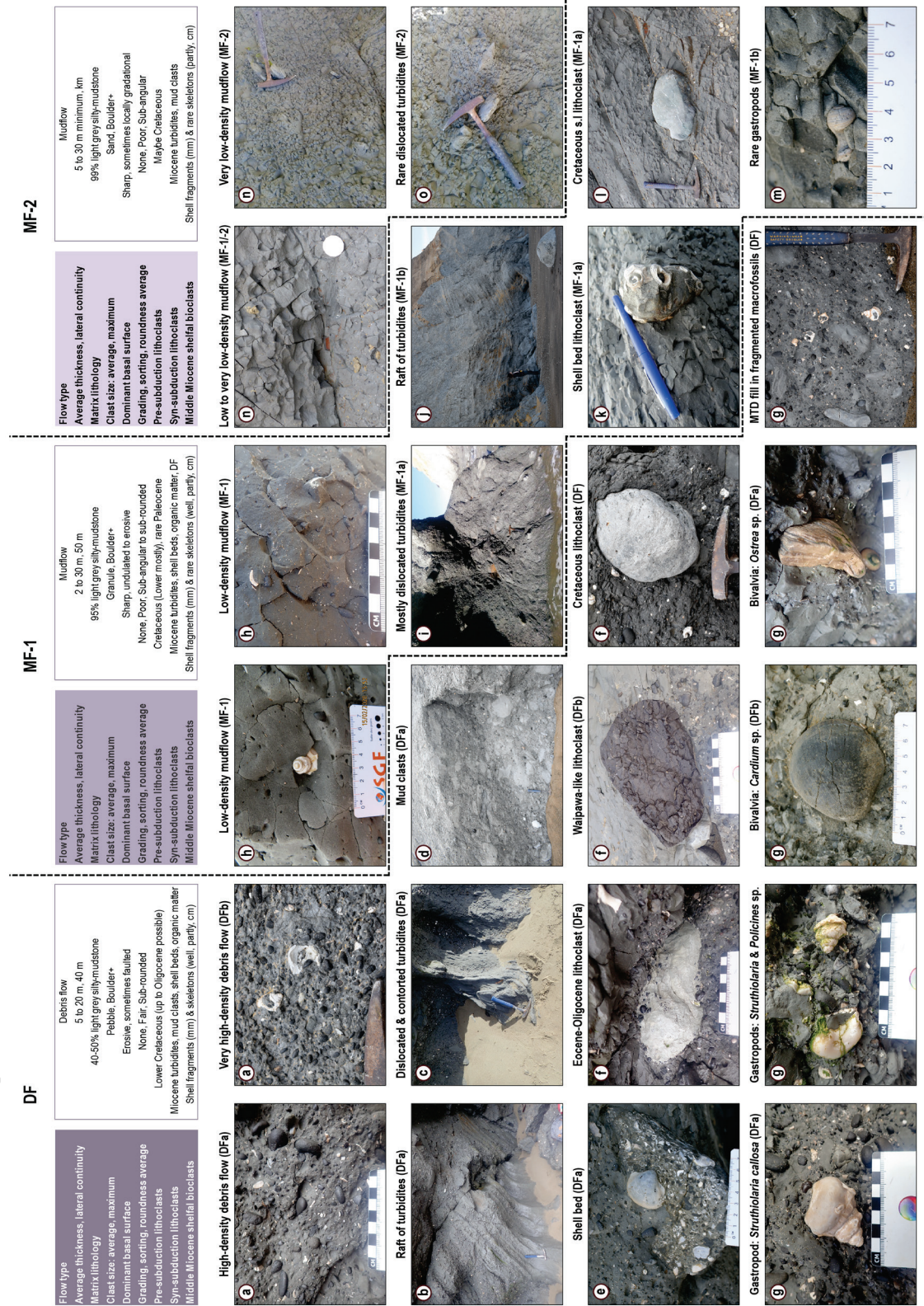


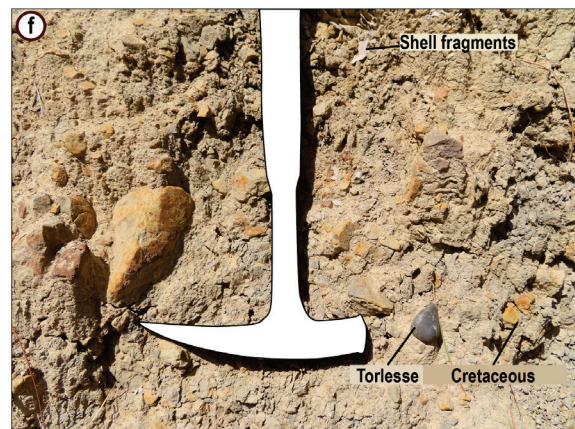
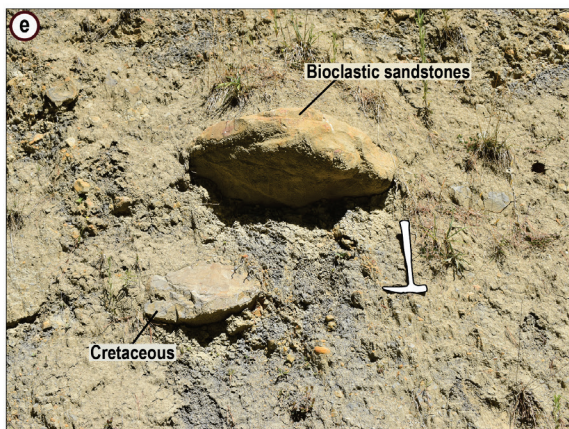
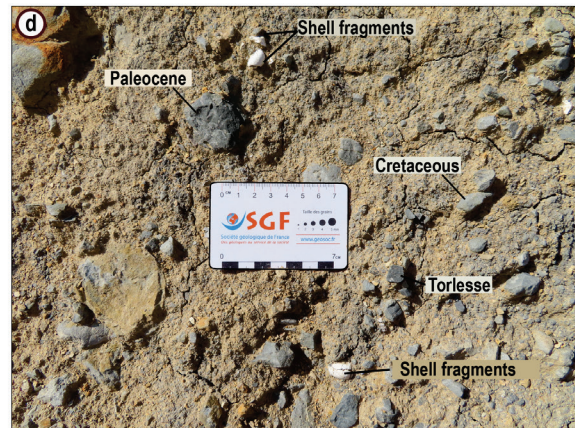
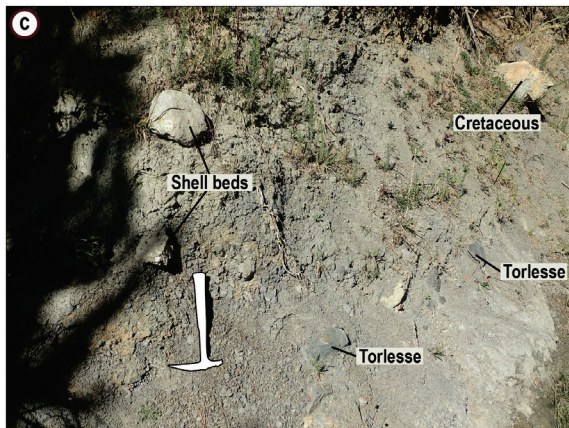
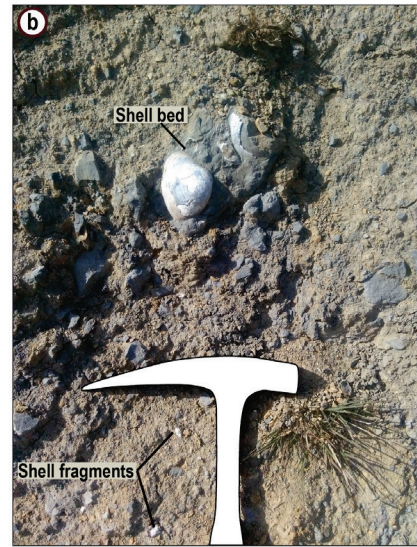






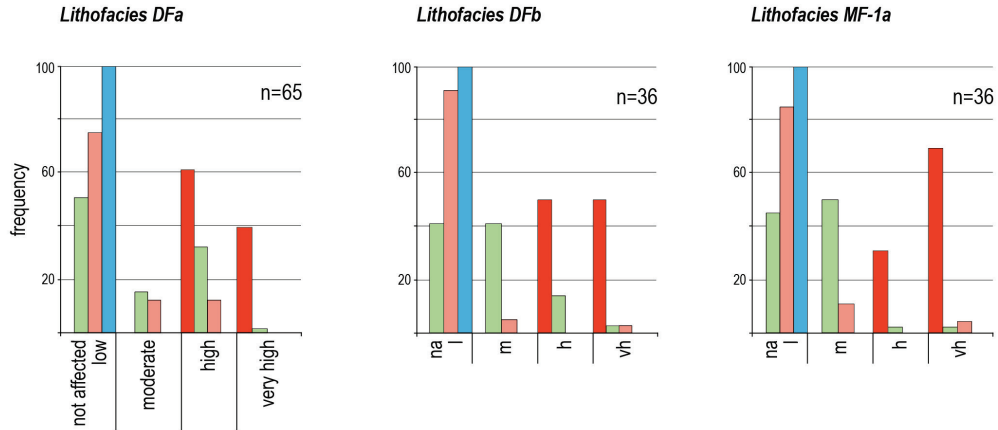




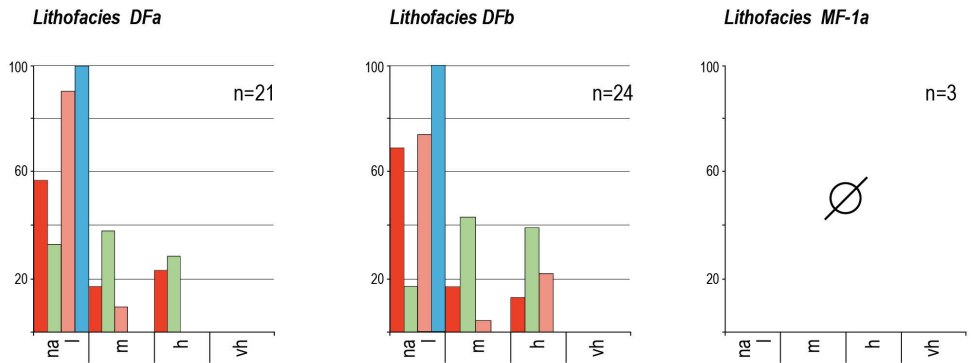


SEFTON HILLS OUTCROP - SECTION S-1

Bioclastic fraction (0.5 cm-3 cm)

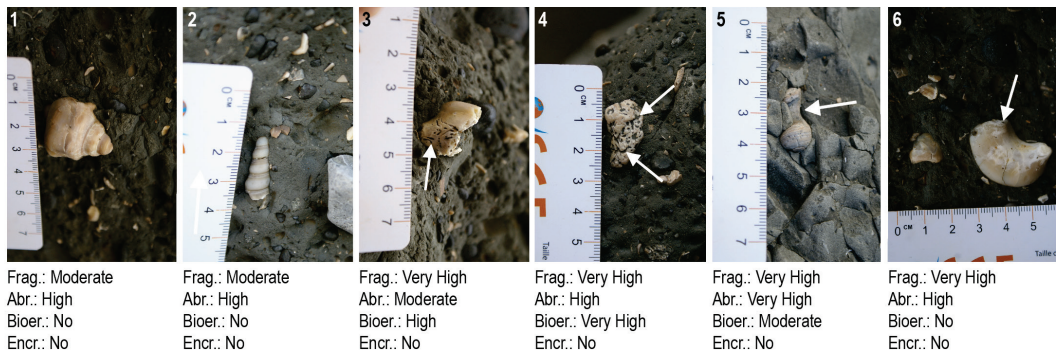


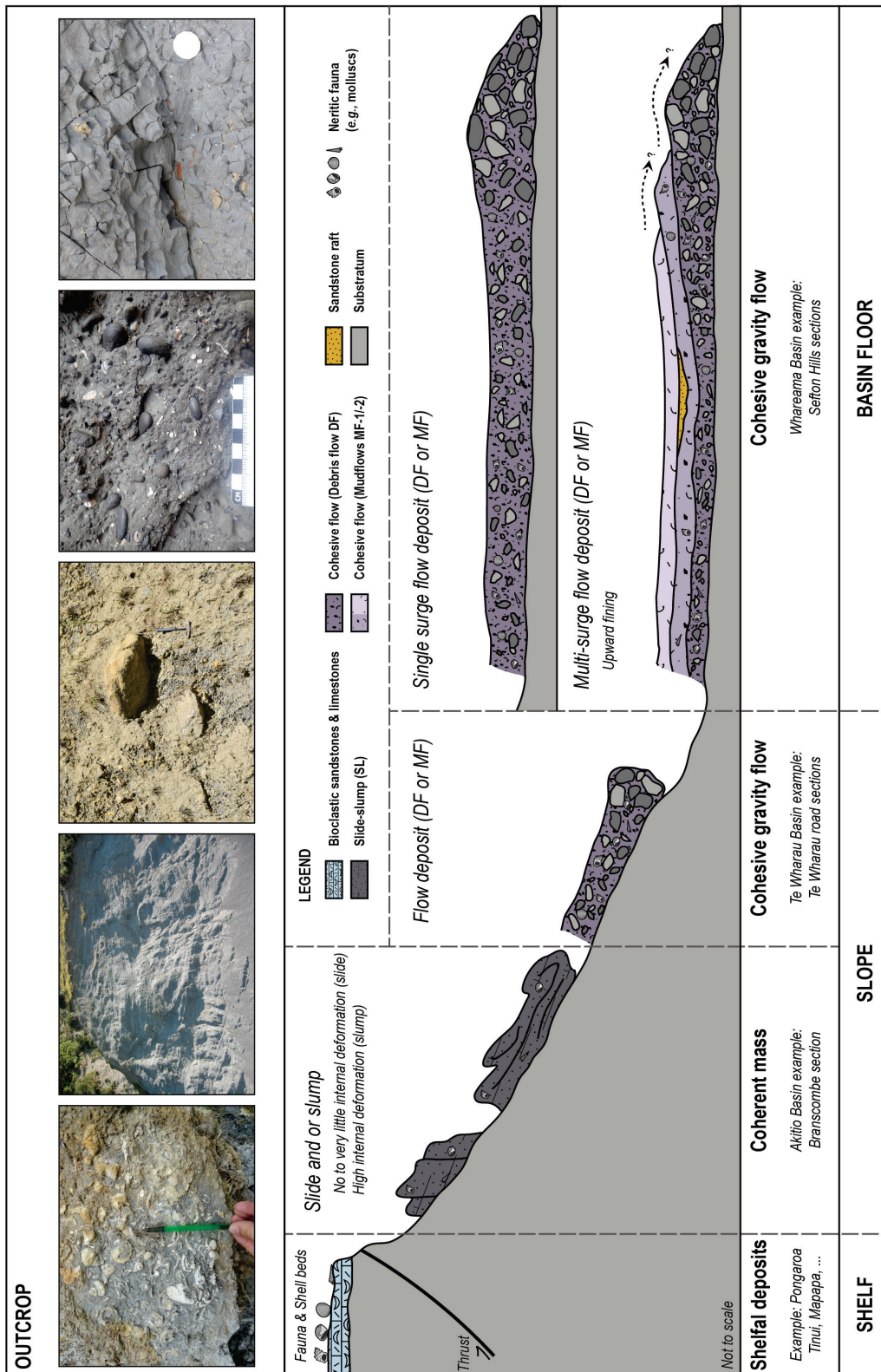
Bioclastic fraction (>3 cm)



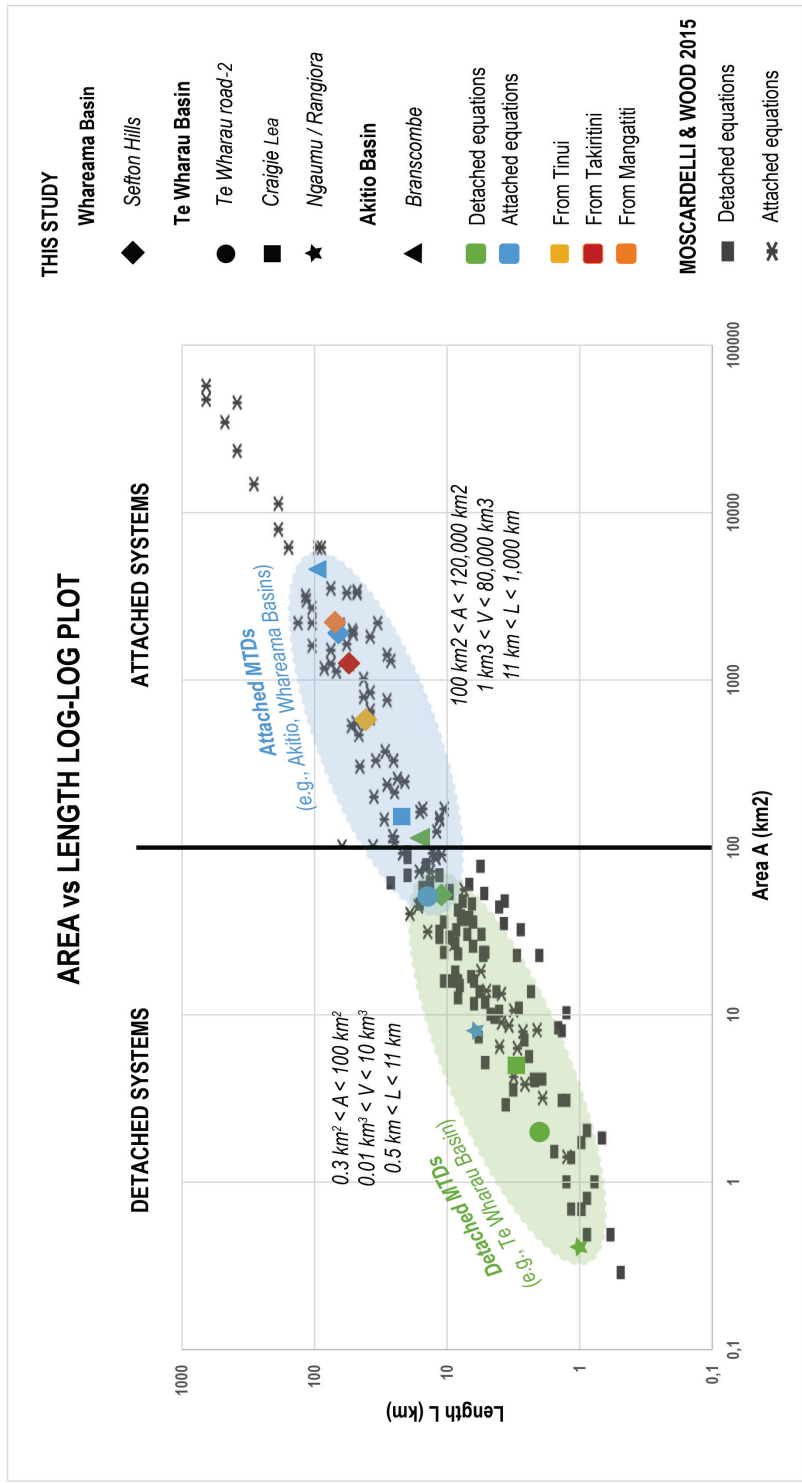
LEGEND ■ Fragmentation ■ Abrasion ■ Bioerosion ■ Encrustation

Field photographs showing examples of shell damages

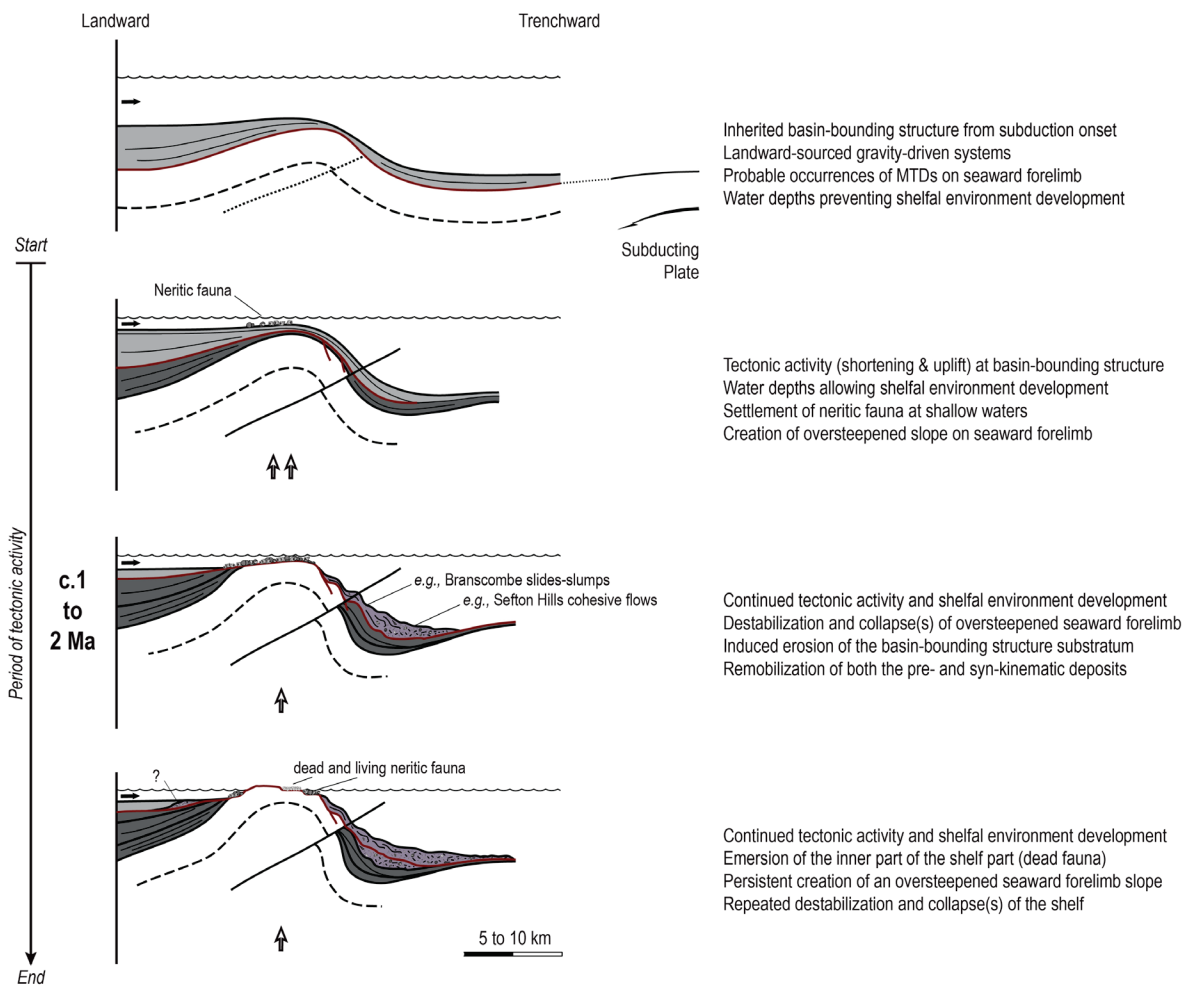












ACS

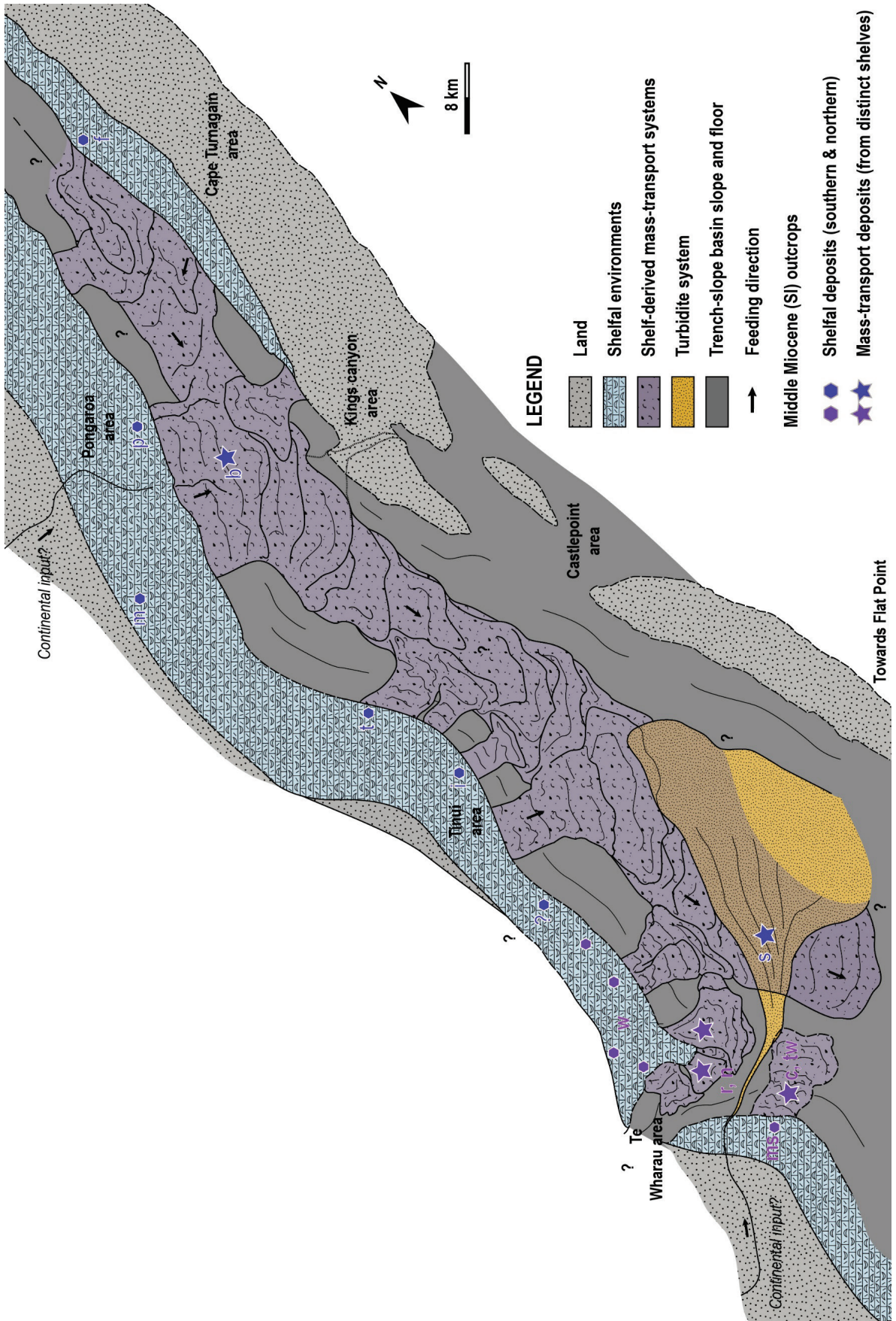


ACCEPTED MANUSCRIPT



LEGEND

- | | | | |
|---|---|---|--|
|  | Syn-subduction, syn-kinematic mass-transport deposits |  | Feeding direction, possible direct continental input |
|  | Syn-subduction, syn-kinematic undiff. gravity-driven deposits |  | Uplift |
|  | Syn-subduction, pre-kinematic undiff. gravity-driven deposits |  | Neritic fauna (e.g., molluscs) |
|  | Pre-subduction basement |  | Shell fragments |



| System code | Fa code | Lithology | Stratification | Internal bedding | Interpretations | Depositional environment |
|--|---------|---|--|---|--|--|
| Fa1 Turbidite systems Alternation of sandstones, siltstones and mudstones | Fa1g-c | Fine- to coarse-grained sandstones and siltstones, well-sorted, with mudstone cap. | Thin- to thick-bedded sandstones, thickness varies laterally, but remains relatively continuous, irregular incisional base with cm to dm scale incisions truncating underlying strata sometimes with channel-based drapes (CBDs), gradational to sharp tops. | Medium to coarse-grained Ta in thicker beds, commonly massive / structureless, with mud clasts, shell and plant fragments, sometimes displaying sole marks such as flute casts. Planar laminations (Tb), often dewatering or soft sedimentation deformation structures above well-developed climbing ripples (Tc). Lamination often highlighted by organic rich, carbonaceous and shell fragments. Common amalgamation and some aggradational successions. Rare bioturbation in mudstone cap. Possible stack of several set-scale cycles with intrachannel mudstones. | High sedimentation rate with rapid suspension fall-out from high density, mostly erosive turbidity currents (Lowe, 1982; Kneller, 1995). Small-scale incisional features suggesting small erosional channels and discontinuous scours developing on the surface of a lobe (Burgreen and Graham, 2014). CBDs resulting from the channel fills (Barton et al., 2010). Fragment content suggests that flow initiated in shallow marine environment. | Distributary channels and scours. Lobe off-axis, proximal to medial region. |
| | Fa1g-a | Very fine- to medium-grained sandstones and siltstones, well-sorted, with mudstone cap. | Thin- to medium-bedded sandstones, fining and thinning upwards, lateral continuity good lateral continuity yet pinches out, sharp or slightly irregular bases and gradational to sharp tops. | Rare basal coarse Ta intervals, occasional planar laminations (Tb) passing into climbing ripples (Tc), mostly climbing ripples passing into massive (due to bioturbation?) / structureless facies. Lamination often highlighted by organic rich, carbonaceous and shell fragments. Rare amalgamation. Very common bioturbation in mudstone cap. (2011). | Slow deposition from a mostly non-erosive, waning, high- to low-density turbidity currents (Lowe, 1982; Kneller, 1995). Fragment content suggests that flow initiated in shallow marine environment. Upward fining and thinning suggest abandonment of the channel and filling of the unfilled relief (McHargue et al., 2011). | Abandonment / Spill of distributary channels. Lobe off-axis, proximal to medial region. |
| | Fa1g-f | Very fine- to fine-grained sandstones and siltstones, well-sorted, with bioturbated mudstone cap. | Very thin- to medium-bedded sandstones, thinning or thickening upwards, lateral continuity yet pinching out possible, mostly slightly irregular bases and gradational to sharp tops, local low-displacement slumps and slump scours (Fa3l-s). | Mostly weathered or bioturbated, occasional planar laminations (Tb) passing into climbing ripples (starved) and rare convolutes (Tc). Sometimes alternation of parallel-ripple-laminated sandstone to siltstone. Rare incisional features with coarser material and occasional bioclastic grits. Lamination often highlighted by organic rich, carbonaceous and shell fragments. Variable degree of bioturbation, tends to be highly bioturbated. | High sedimentation rate with deposition from a mostly non-erosive, waning, low-density turbidity currents (Lowe, 1982; Kneller, 1995). Alternation of waxing then waning flow possibly indicating hyperpycnal flows (Mulder et al., 2003). Fragment content suggests that flow initiated in shallow marine environment. | Lobe fringe, medial to distal region. |
| Fa3 Mass-wasting systems Disorganized gravels, sandstones, siltstones and mudstones | Fa3l | Matrix-supported, siltstones to silty mudstones with varying quantity of granule- to boulder-grade syn-subduction extraformational clasts. | Thin- to very thick-bedded, tabular (sheets), good lateral continuity, sharp erosional bases and gradational to sharp tops, local low-displacement slumps and slump scours (Fa3l-s). | Commonly massive, sometimes planar laminations (Tb), rare ripples and convolutions (Tc), intra-beds erosional to non-erosional amalgamation surfaces. Lamination can be highlighted by organic rich, carbonaceous and shell fragments. Mostly a sandy, succession. | Unconfined turbidity currents. Deposition from waning, low density turbidity currents (Lowe, 1982; Kneller, 1995). | Sheet-lobe, distal region. Sheet-like turbidites. |
| | Fa3l-d | Disorganized interbedded sandstones, siltstones and mudstones. Silty mudstone background facies with occasional granule- to boulder-grade intraformational clasts. | Sharp and planar base and sharp sometimes undulated top, laterally continuous with sometimes the undeformed interval laterally available and visible, usually between 1 to 5 m thick interval. | Ungraded, disorganized. Syn-subduction lithoclasts (sandstone to siltstone). Rare syn-subduction bioclasts. Possible recumbent folds, shear and load structures. | Cohesive flow: debris flow or mudflow (Nardin et al., 1979; Mulder & Alexander, 2001). Possible flow transformation of Fa3l-s. Located within a deep-marine turbidite system thereby suggesting a local destabilization. Punctual bioclastic material could result from storms. | Locally-sourced mass-transport deposits. |
| | Fa3l-s | Disorganized interbedded sandstones, siltstones and mudstones. Silty mudstone background facies with occasional granule- to boulder-grade intraformational clasts. | Sharp and planar base and sharp sometimes undulated top, laterally continuous with sometimes the undeformed interval laterally available and visible, usually between 1 to 5 m thick interval. | Contorted (recumbent folds) remobilized. Possible scattered, syn-subduction lithoclasts (dislocated turbidites). Syn-sedimentary deformation. | Cohesive mass of sediment that moves along a glide plane internal deformation. Slide or slump (function of basal shearing surface). Located within turbidite system thereby suggesting local destabilization. | Locally-sourced mass-transport deposits. |
| Fa3p - Shelf-derived | Fa3p-d | Matrix-supported, siltstones to silty mudstones with varying quantity of granule- to boulder-grade pre- and syn-subduction extraformational clasts. | Slightly to highly erosive base and sharp to undulated top, sometimes gradational top, laterally discontinuous, variable thickness (m to dm). | Ungraded, disorganized. Pre- and syn-subduction lithoclasts. Syn-subduction bioclasts, either as skeletons (gastropods, bivalvia, corals) and or shell fragments. Common recumbent folds, shear and load structures. | Cohesive flow: debris flow or mudflow (Nardin et al., 1979; Mulder & Alexander, 2001). Macrofaunal assemblages suggest that mass-wasting initiated in shallow marine environment. | Shelf-derived mass-transport deposits. |
| | Fa3p-s | (Dis)organized interbedded sandstones, siltstones and mudstones. Sandy to silty mudstone background facies with granule- to boulder-grade pre- and syn-subduction extraformational clasts (litho- & bioclasts). | Sharp and planar base and sharp sometimes undulated top, laterally continuous with sometimes the undeformed interval laterally available and visible, usually 10s of m thick intervals. | Cohesive to contorted (recumbent folds), remobilized. Pre- and syn-subduction lithoclasts. Syn-subduction bioclasts, either as skeletons (gastropods, bivalvia, corals) and or shell fragments. Syn-sedimentary deformation. | Cohesive mass of sediments that moves along a glide plane internal deformation. Slide or slump (function of basal shearing surface). Macrofaunal assemblages suggest that mass-wasting initiated in shallow marine environment. | Shelf-derived mass-transport deposits. |