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## **Early stages of trench-slope basin development: Insights from mass-transport deposits and their interactions with turbidite systems (southern Hikurangi margin, New Zealand)**

B. Claussmann, J. Bailleul, F. Chanier, G. Mahieux, A.D. Mearthur, B.C. Vendeville

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1 **Early stages of trench-slope basin development: insights from**  
2 **mass-transport deposits and their interactions with turbidite**  
3 **systems (southern Hikurangi margin, New Zealand)**

4 Clausmann B.<sup>1,2,\*</sup>, Bailleul J.<sup>2</sup>, Chanier F.<sup>3</sup>, Mahieux G.<sup>4</sup>, McArthur A. D.<sup>5</sup>, Vendeville B. C.<sup>3</sup>

5  
6 1. SLB, Digital Subsurface Solutions, Abingdon, OX14 4RU, United Kingdom

7 2. U2R 7511, Basins-Reservoirs-Resources (B2R), Geosciences department, UniLaSalle - University of Picardie Jules Verne, 60026, Beauvais, France

8 3. University of Lille, CNRS, ULCO, UMR 8187, Laboratory of Oceanology and Geosciences (LOG), Lille, France

9 4. U2R 7511, Basins-Reservoirs-Resources (B2R), University of Picardie Jules Verne - UniLaSalle, 80039 Amiens, France

10 5. School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom

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23 \*Correspondence: [bclausmann@slb.com](mailto:bclausmann@slb.com)

25 Geological complexity, progressive tectonic overprint and prevailing submarine location of subduction  
26 margins generally hinder investigating the early stages of development of their oldest trench-slope  
27 basins, witnesses of subduction initiation and early history. Along the eastern North Island of New  
28 Zealand, the inner portion of the Hikurangi subduction wedge is emerged, thereby offering a unique  
29 opportunity to examine, at outcrop-scale, the tectonostratigraphic evolution of a trench-slope basin  
30 (Castlepoint trench-slope basin) that was linked to the onset of subduction. We present new  
31 occurrences of lowermost Miocene gravity-driven systems, suggesting a more intricate depositional  
32 framework to the ones previously inferred during this key period. Results show that the early stages of  
33 development of a trench-slope basin coeval with the birth of a subduction margin may deviate from  
34 traditional models either comprising (1) sustainable sediment sources connected to the basin very early  
35 in the history of the margin and (2) a sedimentation-deformation feedback mechanism promoting the  
36 long-term development of an aggradational turbidite system downslope. Analysis of the mass-transport  
37 deposits (MTDs) also revealed that the outboard migration of deformation was discontinuous and  
38 uneven along the margin during the earliest Miocene. Two major tectonic events, separated by a period  
39 of reduced tectonic activity, were recorded at the inboard border of the Castlepoint trench-slope basin,  
40 each resulting in seaward motion, oversteepening and frontal denudation of a thrust sheet. Each thrust  
41 sheet provided contrasting failed material and morphometric characteristics to the associated deposits,  
42 thereby allowing us to discriminate the nature of the nappe and related controls responsible for  
43 shedding each MTD as well as refine the timing of nappe emplacement along this part of the margin.  
44 Overall, this study draws new insights on the early structural evolution and stratigraphic infill during the  
45 birth of subduction zones, insights which may, in turn, help improve understandings of active margin  
46 settings.

47 **Keywords:** active margin, gravity-driven deposits, mass-wasting system, confined basins, trench-slope  
48 basins, thrust forelimb, channel levee system, olistostrome

49

## 50 1. INTRODUCTION

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51 Trench-slope basins are confined intra-slope basins that develop along all subduction margins (*e.g.*,  
52 Karig and Sharman 1975; Moore and Karig 1976; Smith et al. 1979; Karig et al. 1980; Moore et al. 1980;  
53 White and Louden 1982; Stevens and Moore 1985; Underwood and Norville 1986; Okada 1989;  
54 McCrory 1995; Underwood and Moore 1995) and more particularly on their subduction wedge (*sensu*  
55 Bailleul et al. 2013). Trench-slope basins typically form narrow, elongate and trench-parallel structural  
56 depressions separated by tectonically active bathymetric highs that are by-products of seaward-verging  
57 thrust faulting and asymmetrical folding (Moore and Karig 1976; Karig et al. 1980; Moore et al. 1980;  
58 Stevens and Moore 1985; Okada 1989; Underwood and Moore 1995).

59 Located between the trench and the trench-slope break (*i.e.*, on the lower trench-slope of a margin),  
60 these intra-slope basins are progressively uplifted and migrate upslope through time, moving away from  
61 the deformation front, owing to the seaward expansion and growth of the subduction wedge  
62 (Underwood and Moore 1995). As a result, at their early stages of development, trench-slope basins are  
63 generally located towards the base of the lower trench-slope. There, they are more likely to be  
64 sedimentologically 'immature' (*sensu* Underwood and Bachman 1982), being disconnected from the  
65 main sediment pathways that cross the margin, and thus typically comprise hemipelagic deposits or  
66 remobilized material, slumped off from the adjacent bathymetric highs (Moore and Karig 1976). As they  
67 migrate upslope however, they generally become sedimentologically 'mature' (*sensu* Underwood and  
68 Bachman 1982) being connected to the terrigenous sediment input and thus, chiefly trap coarser-  
69 grained, gravity-driven material.

70 In the past twenty years, numerous studies highlighted that owing to the strong interplay that exists  
71 between deformation and sedimentation in such tectonically active settings, more diversified and  
72 complicated frameworks could be drawn for the tectonostratigraphic evolution of trench-slope basins  
73 (*e.g.*, Underwood et al. 2003; Bailleul et al. 2007; Vinnels et al. 2010; Bailleul et al. 2013; Noda 2018;  
74 McArthur et al. 2019). Indeed, their development, distribution, geometry and stratigraphic infill were  
75 recurrently observed to be strongly influenced by the contemporaneous structural growth of the  
76 subduction wedge driven by subduction processes and their variations through time (*e.g.*, Bailleul et al.  
77 2013; Ghisetti et al. 2016; Noda 2018).

78 Despite numerous studies of subduction margin settings, their complexity, progressive tectonic overprint  
79 and prevailing submarine location hinder investigating the early stages of development of the margins'  
80 oldest trench-slope basins. Therefore, bringing new elements to address this knowledge gap may

81 constitute a milestone for the understanding of active margins, and more particularly for those trench-  
82 slope basins that are contemporaneous with the birth of subduction zones.

83 Along the eastern North Island of New Zealand, the western, exhumed, inner portion of the Hikurangi  
84 subduction wedge (*i.e.*, the coastal ranges) is partly emerged (Figure 1), and therefore offers an  
85 opportunity to investigate, at outcrop-scale, the tectonostratigraphic evolution of the first trench-slope  
86 basins (*e.g.*, the Castlepoint trench-slope basin) that were linked to the onset of subduction in the  
87 earliest Miocene (eventually latest Oligocene) (*e.g.*, van der Lingen and Pettinga 1980; van der Lingen  
88 1982; Chanier and Ferrière 1991; Neef 1992a; Lewis and Pettinga 1993; Bailleul et al. 2007; Bailleul et  
89 al. 2013; McArthur et al. 2019). Previous outcrop-based studies revealed that the abrupt changes of  
90 structural and sedimentation styles recorded during this short period of intense deformation (~3-5 Myr)  
91 resulted from (1) the seaward emplacement of a succession of thrust sheets underwater and (2) sudden  
92 high sediment input of detrital material, primarily distributed through gravity-driven systems into the  
93 newly formed trench-slope basins (Chanier and Ferrière 1991; Rait et al. 1991).

94 The associated lowermost Miocene deposits, known as the Whakataki Formation, were extensively  
95 described in the coastal ranges, and more particularly within the coastal Castlepoint trench-slope basin  
96 (Van den Heuvel 1960; Johnston 1980; Chanier and Ferrière 1991; Neef 1992; Neef 1995; Neef 1995;  
97 Edbrooke and Browne 1996; Delteil et al. 1996; Field et al. 1997; Neef 1997; Lee and Begg 2002; Field  
98 2005; Delteil et al. 2006; Bailleul et al. 2007; Bailleul et al. 2013; Down 2016; Malie et al. 2017; Sloss et  
99 al. 2021). They mostly comprise deep-marine, fine-grained turbidites occasionally interrupted by mass-  
100 transport deposits (MTDs), at the base or near the base of the series, ascribed to result from the frontal  
101 erosion of the advancing thrust sheets before turbiditic sedimentation took over (*e.g.*, Johnston 1980;  
102 Chanier and Ferrière 1991; Lee and Begg 2002; Field 2005).

103 In this study, we report newly described occurrences of the lowermost Miocene sediments in the  
104 Castlepoint trench-slope basin, which suggest a more complicated depositional framework. The  
105 associated deposits are superbly exposed at low tide to the south of the Castlepoint area, along more  
106 than 14 kilometers of wavecut platform. These successions record both the long-term development of a  
107 several hundreds of meters thick aggradational channel-levee complex system and the emplacement of  
108 three distinct styles of large-scale MTDs.

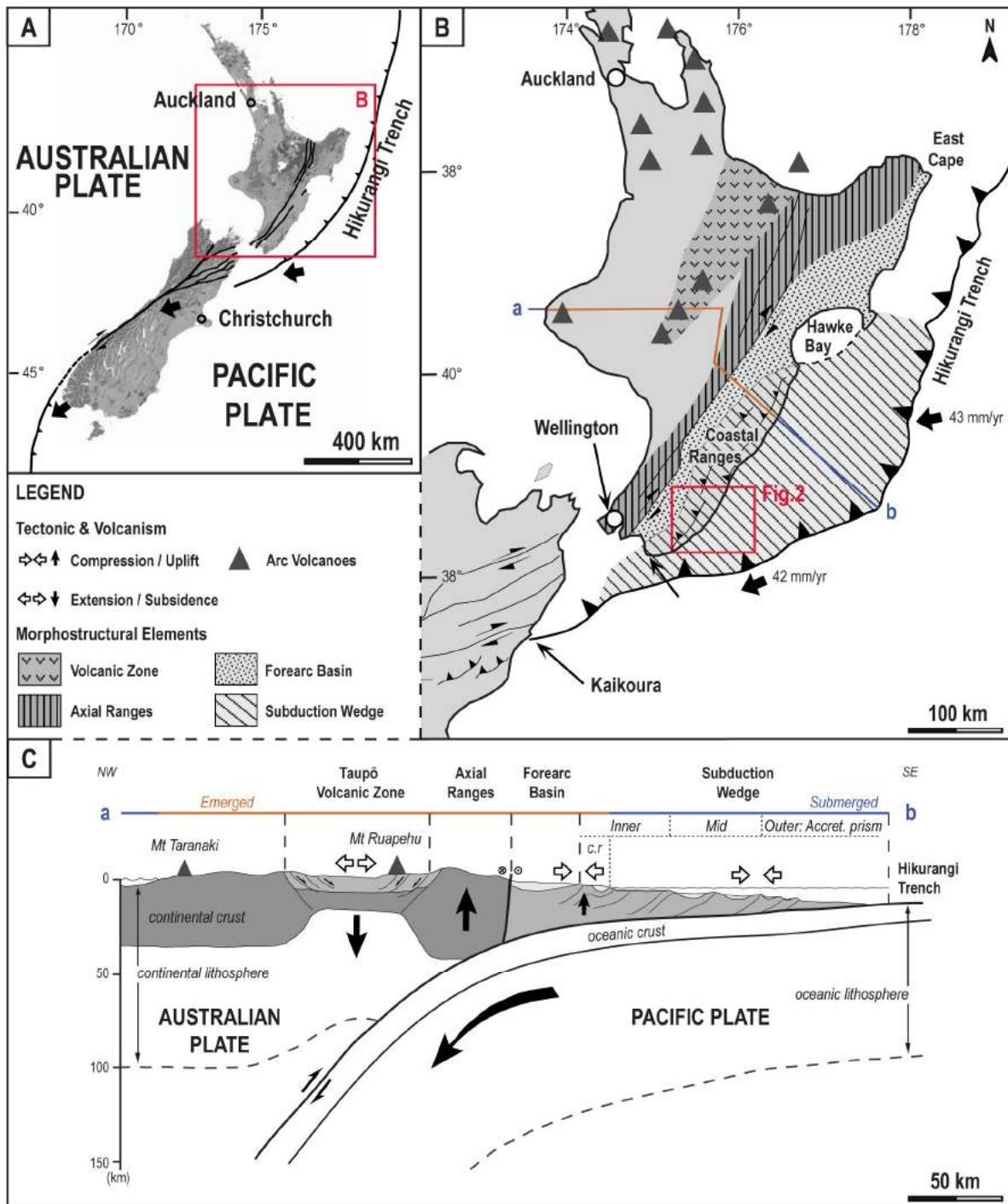
109 This study aims to combine these new insights with previous studies along an 80 kilometer-long coastal  
110 transect across the partially emerged Castlepoint trench-slope basin (Figure 2) to (1) better comprehend  
111 the early stages of tectonostratigraphic development of a trench-slope basin contemporaneous with the

112 birth of a subduction zone and (2) investigate the role of MTDs as spatial-temporal markers of geologic  
113 events in such a context.

114 Here, the lateral and vertical variabilities of the MTDs as well as their interactions with the turbidite  
115 systems not only suggest that different controlling parameters influenced their styles but also that the  
116 subsequent deposits captured the lateral and longitudinal evolution of the trench-slope basin-bounding  
117 structures (e.g., thrusts and growing anticlines).

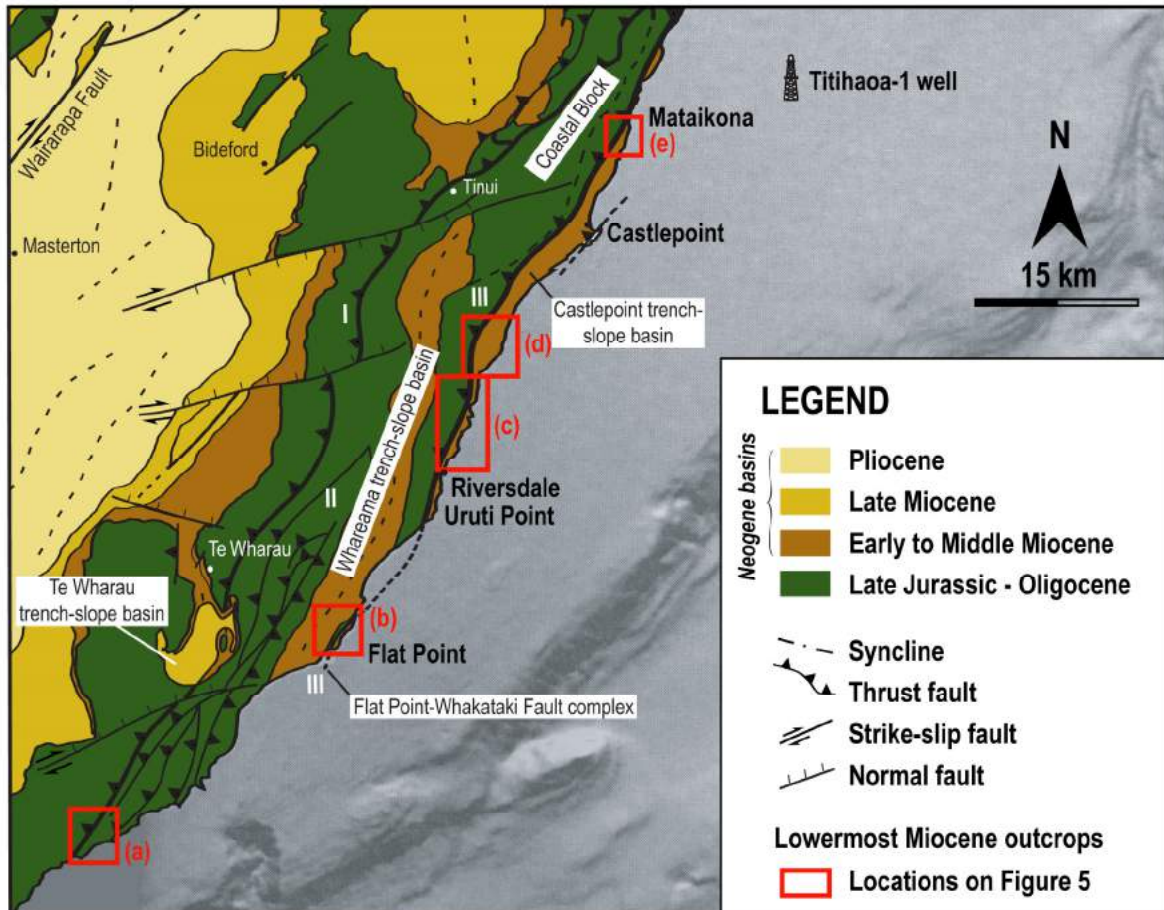
118 Specific objectives are to:

- 119 • Describe the internal characteristics and architectures of different styles of gravity-driven  
120 systems, which can occur in the early-stage fill of a trench-slope basin.
- 121 • Document the diversity of MTDs, which can develop at the front of thrust faults to gain new  
122 insights into the different mass-wasting processes and causal mechanisms, which were  
123 involved in their development, emplacement and preservation.
- 124 • Use detailed analysis of the MTDs, their failed material and their interactions with the  
125 turbidite systems as a tool to discriminate the nature of the thrust sheets involved in each of  
126 the MTDs and specify the timing of nappe emplacement along the Hikurangi Margin.
- 127 • Construct a generic depositional model capturing the distribution, styles as well as the  
128 processes and controls that influence MTDs at the front of thrust faults.



129

130 Figure 1: (A): Plate tectonic setting of New Zealand. (B): Major subduction-related morphostructural features of the Hikurangi  
 131 active margin, North Island of New Zealand. Black arrows show present-day relative plate motion between Pacific and  
 132 Australian plates from Beavan et al. (2002). See (C) for the a – b general cross-section of the Hikurangi subduction complex  
 133 (c.r – coastal ranges). Modified after Chanier et al. (1999), Bailleul et al. (2007) and Bailleul et al. (2013).



134

135 Figure 2: Bathymetric map (Lewis et al. 1999) and onshore structural map (modified from Chanier et al. (1999), Lee and  
 136 Begg (2002) and Bailleul et al. (2013)) of the southern Hikurangi subduction wedge. The offshore area includes the location  
 137 of the well Titihaoa-1 (Biros et al. 1995; Griffin et al. 2022). Locations of the fault complexes = (I): Adams-Tinui Fault  
 138 complex, (II): Pukeroro Fault, (III): Flat Point-Whakataki Fault complex to the south, known to evolve into the Whakataki-  
 139 Turnagain Fault complex to the north. Locations of the lowermost Miocene [NZ stage: late Waitakian-Otaian] coastal  
 140 sections = (a): Pahaoa section, (b): Flat Point section, (c): Orui sections, (d): Waimimi sections and (e): Suicide Point-  
 141 Mataikona section.

143 **2.1. Tectonostratigraphic record of the Hikurangi subduction onset**

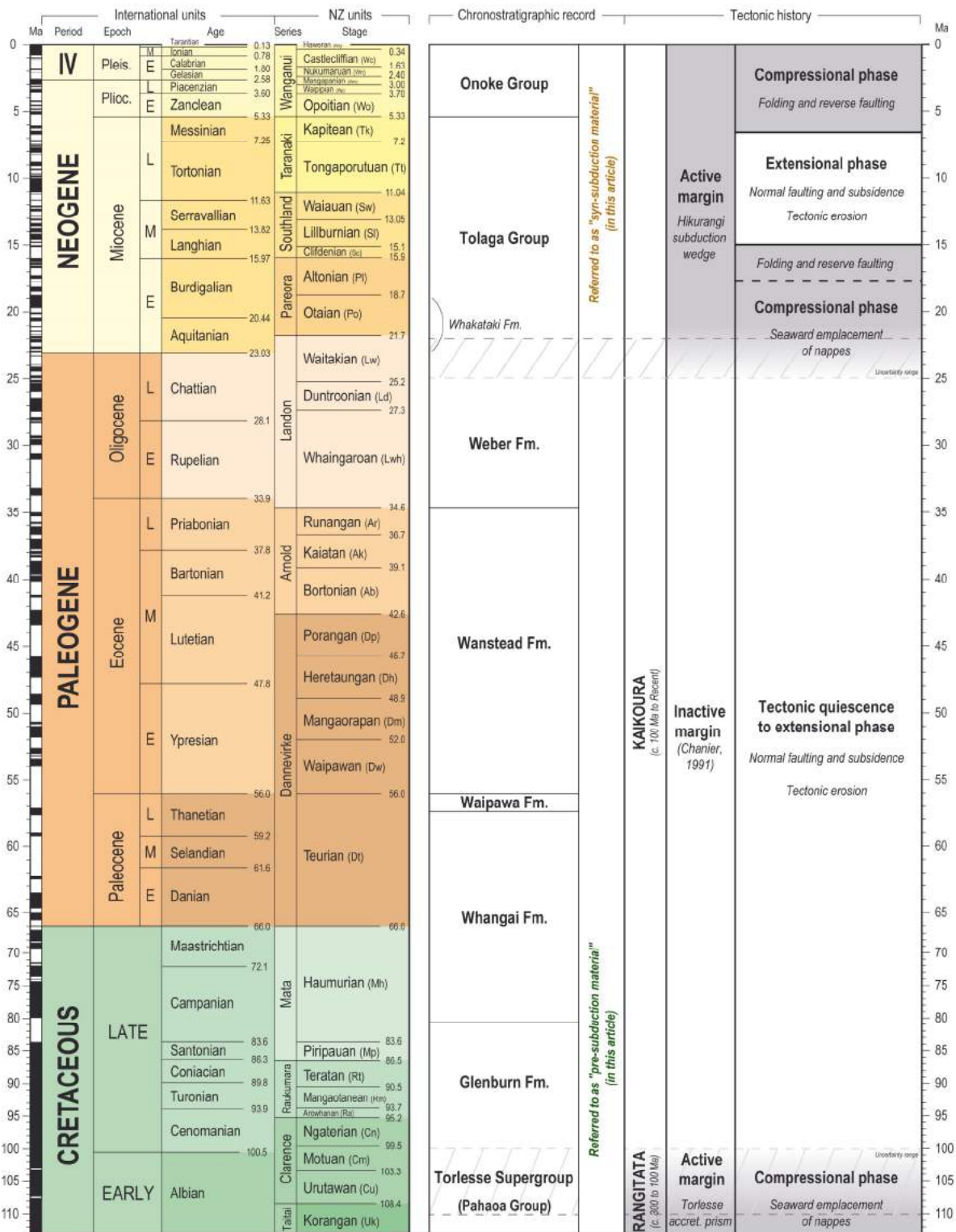
144 About 25-21 Ma ago, the eastern North Island of New Zealand was the scene of a major geodynamic  
145 change, transitioning from a tectonically passive to active setting (Chanier 1991; Rait et al. 1991; King  
146 2000; Hayward et al. 2001; Nicol et al. 2007; Bland et al. 2022; Hines et al. 2022). The westward  
147 subduction of the Pacific Plate beneath the Australian Plate (1) marked the end of a sustained period of  
148 tectonic quiescence that lasted from the Late Cretaceous to the Oligocene and (2) controlled the  
149 complex and polyphase tectonostratigraphic development of the Hikurangi subduction wedge from its  
150 onset in the earliest Miocene (or eventually latest Oligocene) (Figure 1; Figure 3) (Ballance 1976; Spörl  
151 1980; Pettinga 1982; Chanier and Ferrière 1991; Rait et al. 1991; Field et al. 1997; Nicol et al. 2007).

152 Bounded by the Hikurangi Trench to the east and the forearc basin *sensu stricto* to the west, the  
153 Hikurangi subduction wedge is composed of a series of elongated sedimentary basins (*i.e.*, trench-slope  
154 basins (*sensu* Underwood and Moore 1995)) separated by trench-parallel structural ridges that exert or  
155 have exerted a crucial control on their Miocene-to-Recent stratigraphic infills (Figure 1) (Chanier and  
156 Ferrière 1991; Lewis and Pettinga 1993; Bailleul et al. 2013; Bland et al. 2015; Ghisetti et al. 2016;  
157 McArthur et al. 2019; Claussmann et al. 2021; Claussmann et al. 2022; Griffin et al. 2022).

158 The development of the Hikurangi subduction wedge started at the onset of subduction with a major  
159 episode of SE-directed compressional deformation that resulted in the seaward emplacement of a  
160 succession of thrust sheets involving the Lower Cretaceous to Oligocene series of the pre-subduction  
161 margin (Figure 3; Figure 4) (Pettinga 1982; Chanier and Ferrière 1989; Chanier and Ferrière 1991; Rait  
162 et al. 1991). At the onset of subduction, the plate convergence was rapid (~80 millimeters/year)  
163 (Chanier 1991), with an estimated total shortening across the margin in excess of 25 kilometers (Nicol et  
164 al. 2007; Hines et al. 2022). The remobilized pre-subduction margin series eventually formed a  
165 succession of superposed nappes (each between 0.2-1.5 kilometers thick) with eastward overthrusting  
166 of the Lower Cretaceous over the Upper Cretaceous to Oligocene proximal units, themselves  
167 overthrusting more distal units (Figure 4A) (Chanier and Ferrière 1989; Chanier and Ferrière 1991; Rait  
168 et al. 1991).

169 Abrupt changes of sedimentation styles and rates were also recorded during this particular period of  
170 nappe emplacement, with a syn-subduction detrital sedimentation dominated by deep-marine gravity-

171 driven systems that radically contrasts with the previous Eocene-Oligocene pelagic sedimentation  
 172 (Chanier and Ferrière 1991; Field et al. 1997; Morgans 2016).



173  
 174 Figure 3: Chronostratigraphic chart for the southern emerged portion of the Hikurangi subduction wedge. Stratigraphy of the  
 175 pre- and syn-Hikurangi subduction series adapted from (Chanier 1991; Chanier and Ferrière 1991; Field et al. 1997; Lee  
 176 and Begg 2002; Bland et al. 2015; Bland et al. 2022). Regional tectonism adapted from Chanier et al. (1999), Bailleul et al.

177 (2013) and Malie et al. (2017). New Zealand stages after Raine et al. (2015) showing the equivalence with the international  
178 stages.

179 The resulting deposits date from the earliest Miocene, late Waitakian to Otaian (Aquitainian to Early  
180 Burdigalian, 23.03 – 18.7 Ma) and belong to the Whakataki Formation (Johnston 1980). They  
181 characteristically consist of up to 1,500 meters of deep-marine, mainly fine-grained, turbidites  
182 occasionally interrupted by a few meters up to several hundred of meters thick MTDs at or near the  
183 base of the formation (e.g., Johnston 1980; Chanier and Ferrière 1991; Lee and Begg 2002; Field  
184 2005). The Whakataki Formation locally overlies the pre-subduction margin series conformably, thereby  
185 suggesting that its deposition was closely linked to the event of thrust sheets' emplacement, for which  
186 propagation lasted about three to five million years (from late Waitakian to late Otaian) (Chanier and  
187 Ferrière 1991; Rait et al. 1991).

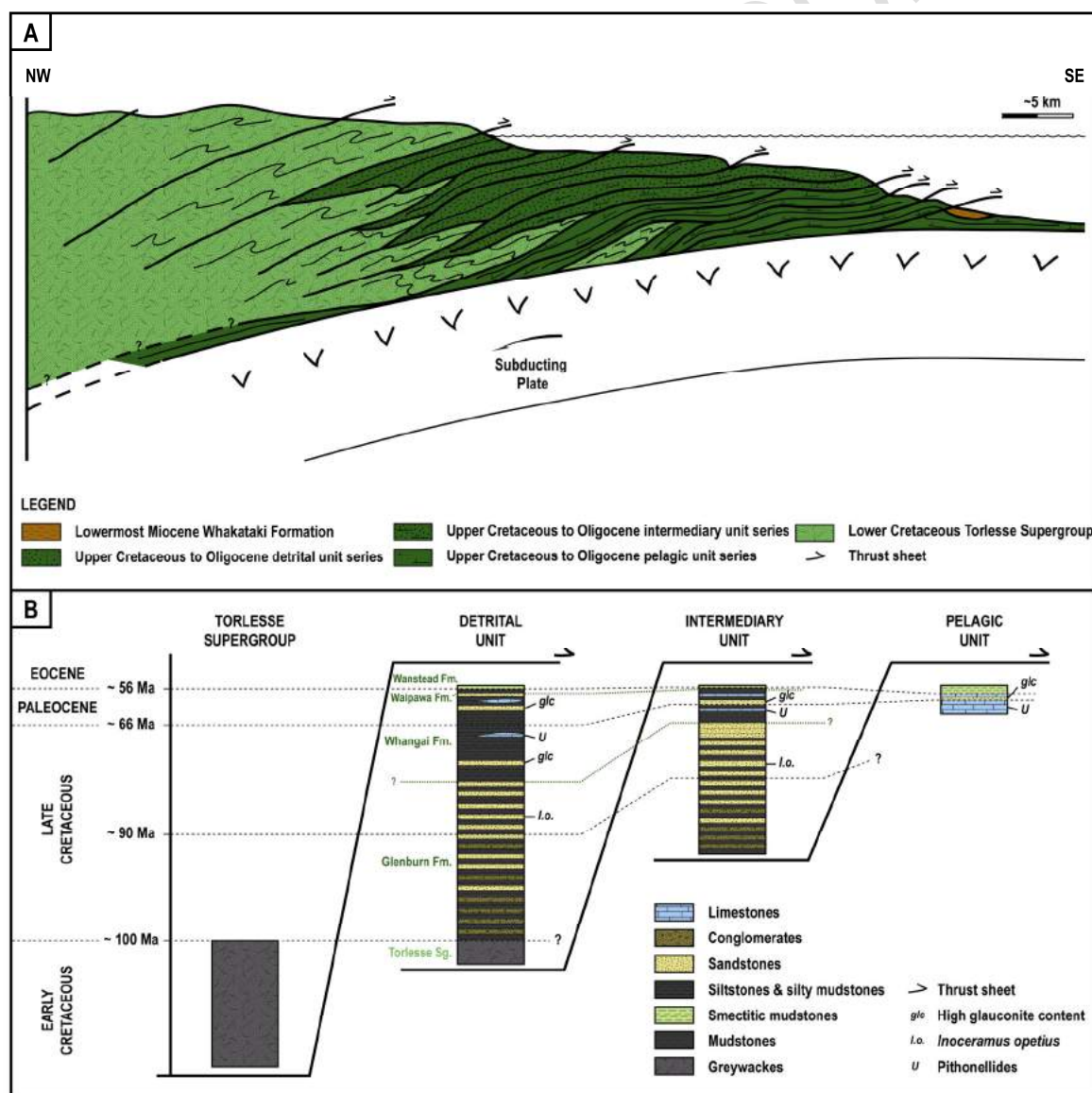
## 188 **2.2. Stratigraphy of the pre-subduction margin series**

189 The pre-subduction margin series comprise (1) the Upper Cretaceous to Oligocene passive margin  
190 strata, which shows an eastward evolution from detrital (proximal, to the west) to pelagic (distal, to the  
191 east) sedimentation (Figure 4) (Johnston 1980; Moore 1986; Chanier 1991; Chanier and Ferrière 1991;  
192 Crampton 1997; Field et al. 1997; Lee and Begg 2002; Morgans 2016; Hines 2018) and (2) the Jurassic  
193 to Lower Cretaceous Torlesse Supergroup (Figure 3; Figure 4) (Suggate 1961; George 1990; George  
194 1992), remnant of an older accretionary prism that forms the underlying basement (Figure 4B) (Spörli  
195 1980; Bradshaw 1989; Mortimer 2004; Mortimer et al. 2014; Bland et al. 2015).

196 The Torlesse Supergroup is composed of metasedimentary rocks that mainly include heavily deformed  
197 and indurated sandstones and mudstones (greywackes and argillites) as well as sporadic red cherts,  
198 radiolarites and basalts (Spörli 1980; Bradshaw 1989; Barnes and Korsch 1990; Barnes and Korsch  
199 1991; Mortimer 1994; Field et al. 1997). Considered a former thick sedimentary oceanic plateau, the  
200 Torlesse was strongly deformed during its subduction and accretion along the New Zealand crust (i.e.,  
201 former eastern Gondwana margin) until late Early Cretaceous times (e.g., Spörli 1978; Bradshaw 1989;  
202 George 1992; Mortimer 2004).

203 Following that major orogenic period, Upper Cretaceous to Oligocene strata were deposited on top of  
204 the Torlesse basement. They can be subdivided into five main stratigraphic units: (1) the Upper  
205 Cretaceous Glenburn Formation, which can locally reach up to 1,000 meters in thickness and mostly  
206 consists of coarse detrital sedimentary rocks characterized by alternating conglomerates, sandstones  
207 and siltstones; (2) the Upper Cretaceous to Paleocene Whangai Formation, which represents about 100

208 to 500 meters of massive siltstones and silty mudstones, occasionally disturbed by pebbly  
 209 conglomerates, calcareous concretions, azoic glauconitic sandstone beds, sedimentary dykes,  
 210 limestone lenses, and evolving from being mostly siliceous during the Upper Cretaceous to being mostly  
 211 carbonated during the Paleocene; (3) the Upper Paleocene Waipawa Formation, which corresponds to  
 212 a few meters up to 50 meters of organic-rich silty mudstones; (4) the Eocene Wanstead Formation,  
 213 which characteristically comprises 100 to 200 meters of now weakly indurated light green, red or black  
 214 calcareous and smectitic mudstones, occasionally interbedded with glauconite-rich sandstones; and  
 215 finally (5) the Oligocene Weber Formation, about 200 to 340 meters thick, and generally consisting of  
 216 whitish pelagic marls and limestones (Figure 3; Figure 4B) (Van den Heuvel 1960; Moore 1980; Moore  
 217 1986; Chanier and Ferrière 1991; Crampton 1997; Field et al. 1997; Lee and Begg 2002; Hines et al.  
 218 2013; Hollis et al. 2014; Bland et al. 2015; Morgans 2016; Crampton et al. 2019).



219

220 Figure 4: [previous page] (A): Schematic cross-section from Chanier (1991) representing the development of the Hikurangi  
221 subduction wedge at the onset of subduction in the earliest Miocene. This onset was marked by the seaward emplacement  
222 of a series of thrust sheets that involved and stacked the pre-subduction margin series. (B): The pre-subduction margin  
223 series can be divided into (1) the Lower Cretaceous Torlesse greywackes and (2) the Upper Cretaceous to Oligocene strata,  
224 evolving from detrital to intermediary to pelagic sediments eastward (Johnston 1980; Spörl 1980; Moore 1986; Bradshaw  
225 1989; Chanier 1991; Chanier and Ferrière 1991; Mortimer 1994; Crampton 1997; Field et al. 1997; Lee and Begg 2002; Lee  
226 and Begg 2002; Mortimer et al. 2014).

227 The easternmost pelagic series of the passive margin typically comprises (1) up to 10 meters of white to  
228 pink-grey micritic and Pithonellid-bearing limestones in the Late Cretaceous (Chanier et al. 1990) as  
229 well as (2) 20 to 90 meters of whitish micritic limestones (Kaiwhata limestones) in the Paleocene (Figure  
230 4B, pelagic unit) (Van den Heuvel 1960; Chanier and Ferrière 1991; Lee and Begg 2002; Hines et al.  
231 2013).

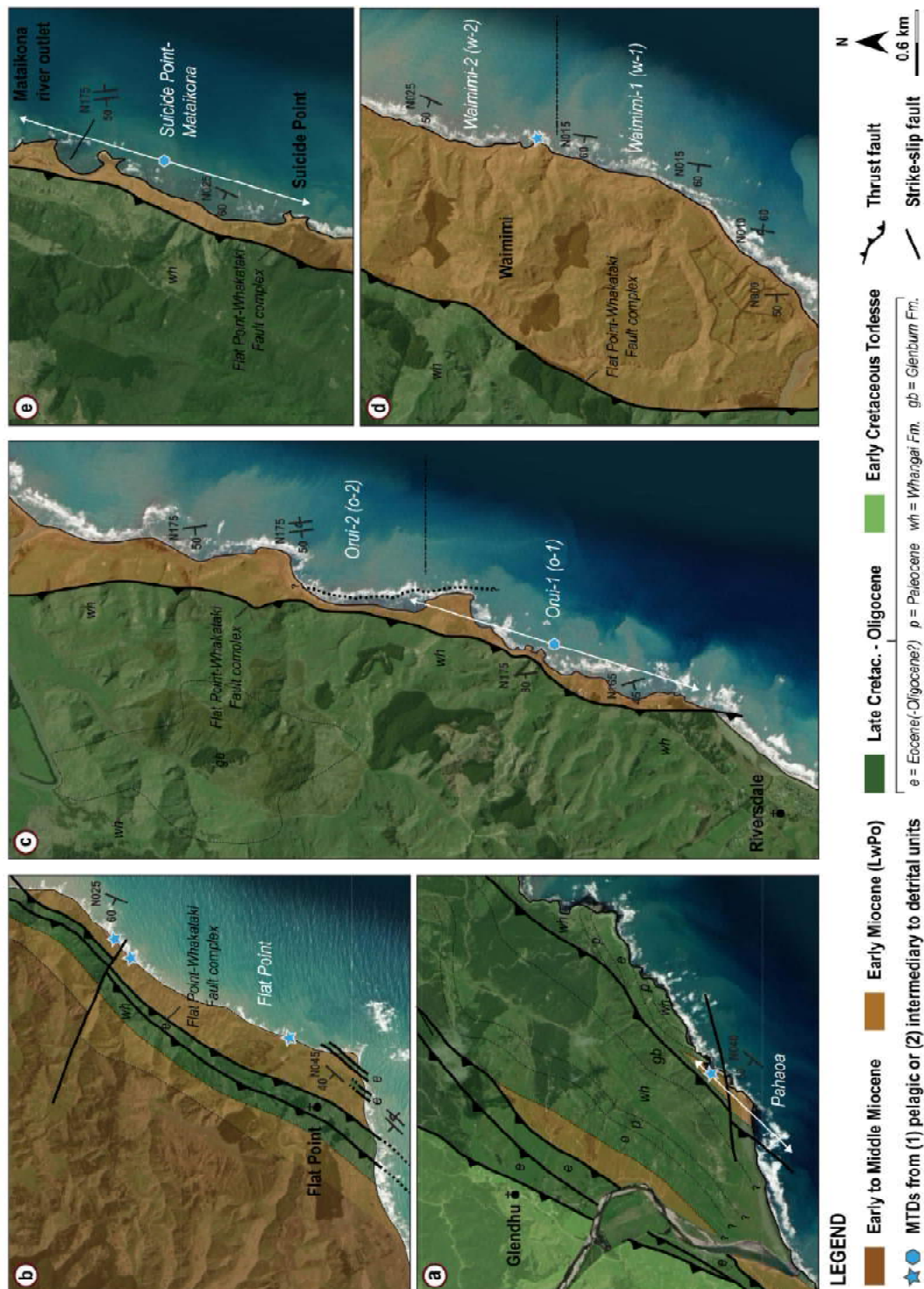
### 232 2.3. Syn-subduction lowermost Miocene MTDs

233 In this study, we specifically focus on the lowermost Miocene mass-wasting processes that remobilized  
234 the pre-subduction margin series. Previous field studies informed that the related MTDs (*i.e.*,  
235 olistostromes (*sensu* Flores 1955) or sedimentary mélanges (*sensu* Raymond 1984)) are mappable  
236 units of matrix-supported pebbly conglomerates that essentially rework pre-subduction material,  
237 randomly scattered within a silty mudstone- to siltstone-dominated matrix (Chanier and Ferrière 1991;  
238 Lee and Begg 2002). These studies also led to recognition of several styles of MTDs in the lowermost  
239 Miocene Whakataki Formation: (1) either mostly reworking the pelagic unit (Chanier and Ferrière 1991;  
240 the Pahaoa and Flat Point olistostromes) or the intermediary to detrital units from the Upper Cretaceous  
241 to Oligocene series (Neef 1995; Delteil et al. 2006; Down 2016; the Suicide Point and Mataikona  
242 breccias); (2) representing single or several events of mass wasting (Chanier and Ferrière 1991; the  
243 Flat Point olistostrome vs the Pahaoa olistostromes); (3) comprising varying interactions with the  
244 contemporaneously developing Whakataki turbidites (*e.g.*, Chanier and Ferrière 1991; the interbedded  
245 Flat Point olistostrome).

### 246 2.4. Castlepoint trench-slope basin

247 The study area is located on the western limb of the Castlepoint trench-slope basin, a newly identified  
248 sub-basin to the East Coast Basin domain. Partially emergent at present day, the Castlepoint trench-  
249 slope basin is a narrow (currently two to four kilometers wide at the outcrop, possibly up to 15-20  
250 kilometers depending on the exact location of its outboard basin boarder), elongated (~120 kilometers

251 long) and trench-parallel (NE-SW) intra-slope basin of the Hikurangi subduction wedge (Figure 2). Its  
252 landward margin is controlled by the seaward-directed Flat Point-Whakataki Fault complex (Figure 2;  
253 Figure 5) which transported pre-Miocene strata on its back (*i.e.*, the Glenburn Nappe in [Chanier and  
254 Ferrière 1991](#)) thrusting over the contemporaneously developing syn-subduction strata (*e.g.*, lowermost  
255 Miocene Whakataki Formation) (Figure 2; Figure 5; Figure 6). The Flat Point-Whakataki Fault complex  
256 and its associated thrust ridge formed and still forms its inboard basin-bounding structure, separating it  
257 from the 'Whareama trench-slope basin' to the south and the 'Akitio trench-slope basin' to the north  
258 (Figure 2). The location of its seaward margin remains uncertain however, being underwater. The  
259 Turnagain Fault could be a candidate ([see Figure 2 and 6 of Malie et al. 2017](#)).



260

261 Figure 5: Satellite maps from World Imagery (ESRI), and onshore geological maps adapted from Chanier (1991) and 1:250  
 262 000 Geological Map of New Zealand (QMAP) of Wairarapa (<https://www.gns.cri.nz/>) for each of the lowermost Miocene [NZ  
 263 stage: late Waitakian-Otaian] coastal sections = (a): Pahaoa section, (b): Flat Point section, (c): Orui sections, (d): Waimimi  
 264 sections and (e): Suicide Point-Mataikona section. Location (symbol) and extent (arrows, if applicable) of the mass-transport  
 265 deposits that essentially rework pre-subduction margin series in each section localities. Due to outcrop extent and  
 266 contrasting stratigraphic features, the Orui (o) and Waimimi (w) outcrops were both subdivided into two sections,  
 267 corresponding to the southern (o-1, w-1) and northern (o-2, w-2) exposures.

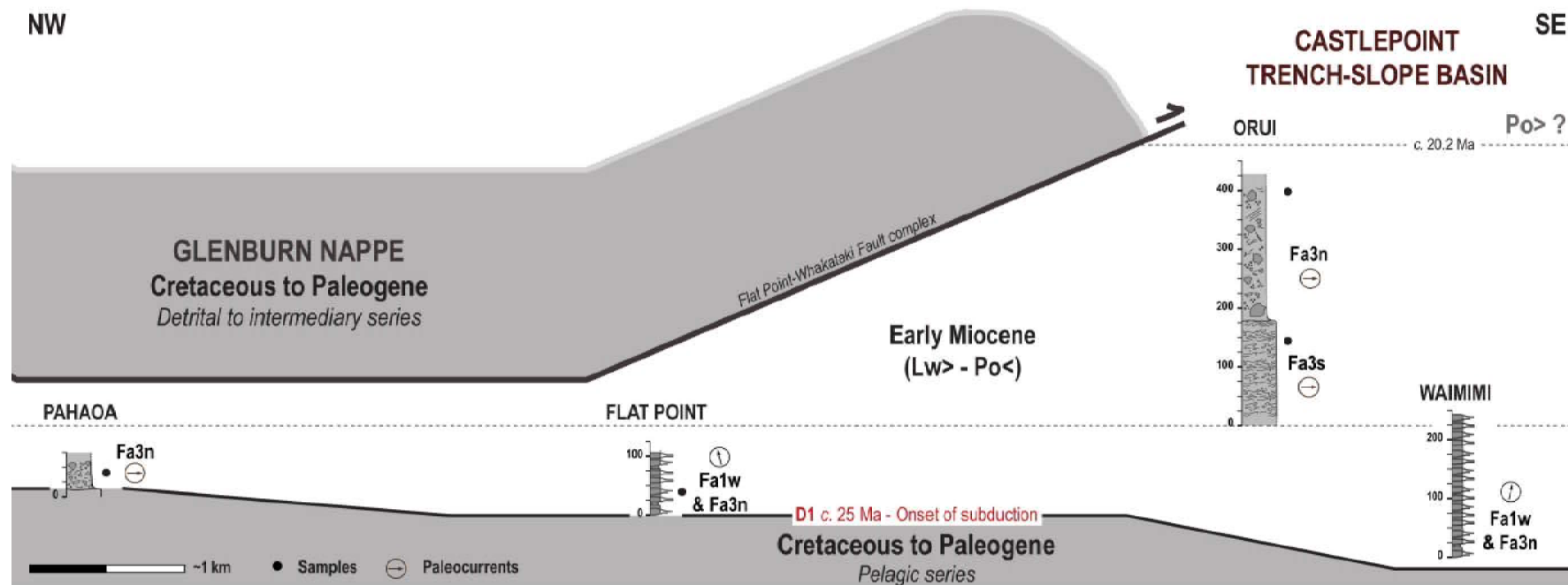


Figure 6: NW-SE correlations of the lowermost Miocene [NZ stage: late Waitakian-Otaian] Whakataki Formation gravity-driven deposits. Sedimentological vertical sections were collected along the Castlepoint trench-slope basin, to the east of its landward basin-bounding structure (*i.e.*, Glenburn Nappe) controlled by the underlying seaward-directed Flat Point-Whakataki Fault complex.

The template used follows the one that was previously built by (Bailleul et al. 2013) for the Akitio trench-slope basin. Fa1w – refers to channel-levee system; Fa3n – to mass-wasting system mostly reworking pre-subduction margin series; Fa3s – to mass-wasting system reworking syn-subduction margin series. Location of coastal sections shown on Figure 5 : (a): Pahaoa section, (b): Flat Point section, (c): Orui sections, (d): Waimimi sections. See Appendix 3 for sampling details.

269 This outcrop-based study examines the lowermost Miocene Whakataki Formation cropping out in the  
270 Castlepoint trench-slope basin of the southern coastal ranges of the North Island. In this context, three  
271 field campaigns (2018, 2019, 2020) were carried out acquiring high-resolution sedimentological,  
272 structural and photogrammetric data along 80 kilometers of the coast. Five main localities were  
273 analyzed, three of which were previously partly described by Chanier and Ferrière (1991) (Pahaoa and  
274 Flat Point sections; Figure 2a, b; Figure 5a, b; Figure 6), Neef (1995), Delteil et al. (2006) and Down  
275 (2016) (Suicide Point-Mataikona section; Figure 2e; Figure 5e; Figure 6); and two of which remained  
276 undescribed until now (14 kilometers of coastline to the north of Riversdale, Orui and Waimimi sections;  
277 Figure 2c, d; Figure 5c, d; Figure 6).

### 278 **3.1. Outcrop data**

279 Field mapping data were recorded with a Trimble ® TDC100 and integrated using ArcGIS software  
280 tools. Detailed sedimentary sections were measured at bed scale (1:50) to characterize the Whakataki  
281 Formation turbidites in this area, totaling 872 meters and summarized in Table 1, Figure 7, Figure 8 and  
282 Figure 9 and Figure 10. A dedicated diagnostic feature template was used to thoroughly describe each  
283 Whakataki Formation MTD occurrence in a standardized manner and completed using abundance  
284 charts for visual percentage (Terry and Chilingar 1955) (see pie charts in Figure 9 and Figure 11). The  
285 combination of the two allowed us to create a synthetic sedimentary section for the Orui locality  
286 presented in Figure 11. For the previously studied Pahaoa and Suicide Point-Mataikona localities, an  
287 overview of their deposits is provided on Figure 12.

288 A total of 123 structural measurements (e.g., ductile deformation analysis in both the MTDs and  
289 turbidites) as well as 481 paleocurrent indicators (measured from three-dimensional ripples, primary  
290 current lineations and sole marks within and at base of turbidite beds) were collected. The  
291 measurements were corrected using the geomagnetic models from GNS Science New Zealand and  
292 restored to pre-tilt position after back-tilting of bedding planes to initial horizontal position (assuming  
293 cylindrical folding). They are presented in context of their outcrops in Figure 8, Figure 9, Figure 10,  
294 Figure 13, Appendix 1 and Appendix 2.

295 Fieldwork data were complemented by micropaleontological analysis (foraminiferal content) conducted  
296 by GNS Science New Zealand to determine the age of the sedimentary units and related depositional  
297 paleobathymetries (Figure 6; Appendix 3). Samples were collected in the Orui and Waimimi sections to

298 supplement the Fossil Record Electronic Database FRED (<https://fred.org.nz/>) (Clowes et al. 2021)  
299 since these areas currently appear as Quaternary beach deposits on the 1:250 000 Geological Map of  
300 New Zealand (QMAP) of Wairarapa (<https://www.gns.cri.nz/>). For the Pahaoa, Flat Point and Suicide  
301 Point-Mataikona sections, we referred to previously collected samples, either available in FRED or in  
302 Chanier (1991). Thin-section analysis was performed on one of the samples in order to characterize the  
303 origin, but also the age of the associated rock on the basis of the micropaleontological content  
304 (Appendix 4).

305 High-resolution images were taken with a DJI Phantom 4 Pro drone (Figure 8; Figure 9; Figure 11;  
306 Figure 13). Georeferenced outcrop models in the form of triangulated meshes textured with the  
307 photographs were then created (Figure 8; Appendix 1; Appendix 2) to display the stratigraphic  
308 architectures and help the characterization of the facies organization.

### 309 3.2. Lithofacies and facies associations

310 A lithofacies scheme was developed for the five localities. Seven lithofacies were identified, based upon  
311 their dominant lithology and primary sedimentary features, and interpreted in terms of processes  
312 (summarized in Table 1 and represented in Figure 7).

313 Together, they form three facies associations (**Fa1w**, **Fa3n**, **Fa3s**) that are characterized by distinct  
314 architectures, lithofacies organization and depositional systems (Table 2). In this study, we leveraged on  
315 and complemented the initial trench-slope basin nomenclature that was defined by Bailleul et al. (2007)  
316 and Bailleul et al. (2013), and where **Fa1** are associated to turbidite systems and **Fa3** to mass-wasting  
317 deposits.

### 318 3.3. Ductile deformation analysis

319 In this tectonically active setting, particular attention was paid to the tectonic or sedimentary origin of the  
320 folds affecting the same poorly lithified material (facies association **Fa1w**). As previously highlighted by  
321 Waldron and Gagnon (2011), whether the driving forces that led to soft-sediment deformation (*sensu*  
322 Maltman 1984) are largely (1) “superficial, gravity-driven” or (2) “rooted, tectonic” processes remains a  
323 challenging question, and more particularly since they believe that a geologist examining the deformed  
324 rocks is unlikely to be able to tell the difference from outcrop evidences.

325 In this outcrop-based study however, the distribution of the fold axis and axial planes affecting the same  
326 poorly lithified material (facies association **Fa1w**) provided a first recognition criterion, either revealing

327 (1) a scatter of data, as sometimes observed in slump-related folds (Alsop and Weinberger 2020) with  
328 however a preferential dip direction, or (2) consistent patterns, similar to that of the Early Miocene  
329 regional paleostress field. The stratigraphic position(s) of the soft-sediment deformation has then  
330 allowed to reconcile these first observations with the larger geological settings. Clues for deciphering  
331 their dominant driving forces were therefore gained by combining insights from the ductile deformation  
332 analysis, the stratigraphic position of the related soft-sediment deformation and the regional tectonics.  
333 The extent (kilometers) of the outcrop exposures were critical, not only providing distorted and partial  
334 views of the fold profiles, but instead allowing a consistent mapping of the deformation.

## 335 4. LOWERMOST MIOCENE WHAKATAKI FORMATION

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### 336 4.1. Turbidites

#### 337 4.1.1. Fa1w: Axial channel-levee system

##### 338 Observations

339 **Fa1w** is characterized by (1) broadly lenticular, commonly very-thick bedded (average two to three  
340 meters), fine-grained clean sandstones capped with well-developed mudstones (**HDTC**), interbedded  
341 with (2) relatively continuous, flat and on average thin-bedded, fine sandstones and mudstones (**LDTC**)  
342 (Table 1; Table 2; Figure 7). The transition between these two lithofacies regularly shows angular  
343 relationships (e.g., downlaps, erosional truncations) (Figure 8a, a1, a3, a4; Figure 9a).

344 The thicker beds (**HDTC**) are frequently amalgamated (Figure 8a2, a3, b2, b4, c). Their concave up and  
345 erosional bases are usually coarse-grained, with mud clasts and sometimes trough cross-stratifications  
346 (Figure 7). They truncate the underlying thin-bedded strata (**LDTC**) with broad, metric, rarely decametric  
347 incisions, which can be traced across several tens of meters along the outcrop (Figure 8a1, a3, b1, b4).  
348 The percentage of bed amalgamation seems to proportionally increase with the size of the incision  
349 (Figure 8a2, a3); for example, the largest incision (up to 30 meters deep) records at least six distinct,  
350 semi-amalgamated channels. Most sandstone beds include several grain-size breaks, well-developed  
351 dewatering or soft sedimentation deformation structures, and frequently end with thick intervals of faint  
352 laminations, wispy convolute laminations and patchy silt pseudonodules in very fine-grained sandstones  
353 to siltstones (Figure 7; Figure 8c). The mud caps are particularly thick and regularly appear to fill the  
354 remaining lenticular relief (Figure 8a1, a4, b1, b4).

355 The associated thinner beds (**LDTC**) are commonly organized in packages about ten meters thick  
356 (Figure 8a1), occasionally several tens of metres thick (Figure 8b1). They are truncated at the top by the  
357 thicker sandstone beds (**HDTC**) (Figure 8a3, b1) and can show wedging geometries with low-angle  
358 downlap terminations onto the underlying mudstone cap of the thicker sandstone beds (**HDTC**) or within  
359 the interval itself (**LDTC**) (Figure 8a1, b1; Figure 9a; Appendix 1; Appendix 2). The structured sandstone  
360 beds are generally thin-bedded and can show disseminated fine to very fine plant debris. Occasional  
361 occurrences of medium-bedded intervals are present and tend to have sole marks, such as flute casts.

362 Paleocurrent measurements (with bedding restored to horizontal position) show consistent near-  
363 orthogonal relationship between the thicker (**HDTC**) and thinner sandstone beds (**LDTC**) and indicate  
364 currents that are dominantly northward-directed (Figure 8; Appendix 1; Appendix 2).

365 Shear zones are frequently observed in **Fa1w**, generally comprising shear and fault planes either  
366 resulting in flexural-slip features (Figure 8b, b3) or combined with remobilized (**SL-b**) and or contorted  
367 (**SL-a**) strata (Figure 8b1, b4; Figure 10). This dominantly ductile soft-sediment deformation affects both  
368 the **HDTC** and **LDTC** intervals, and sometimes results in localized repetition of the series (Figure 8b;  
369 Figure 10; Appendix 2). The associated folds are sometimes upright, mostly inclined to recumbent and  
370 generally hold meters to several meters' wavelength. They are characteristically NE-SW directed with  
371 their hinges preferentially dipping towards the east (Figure 10).

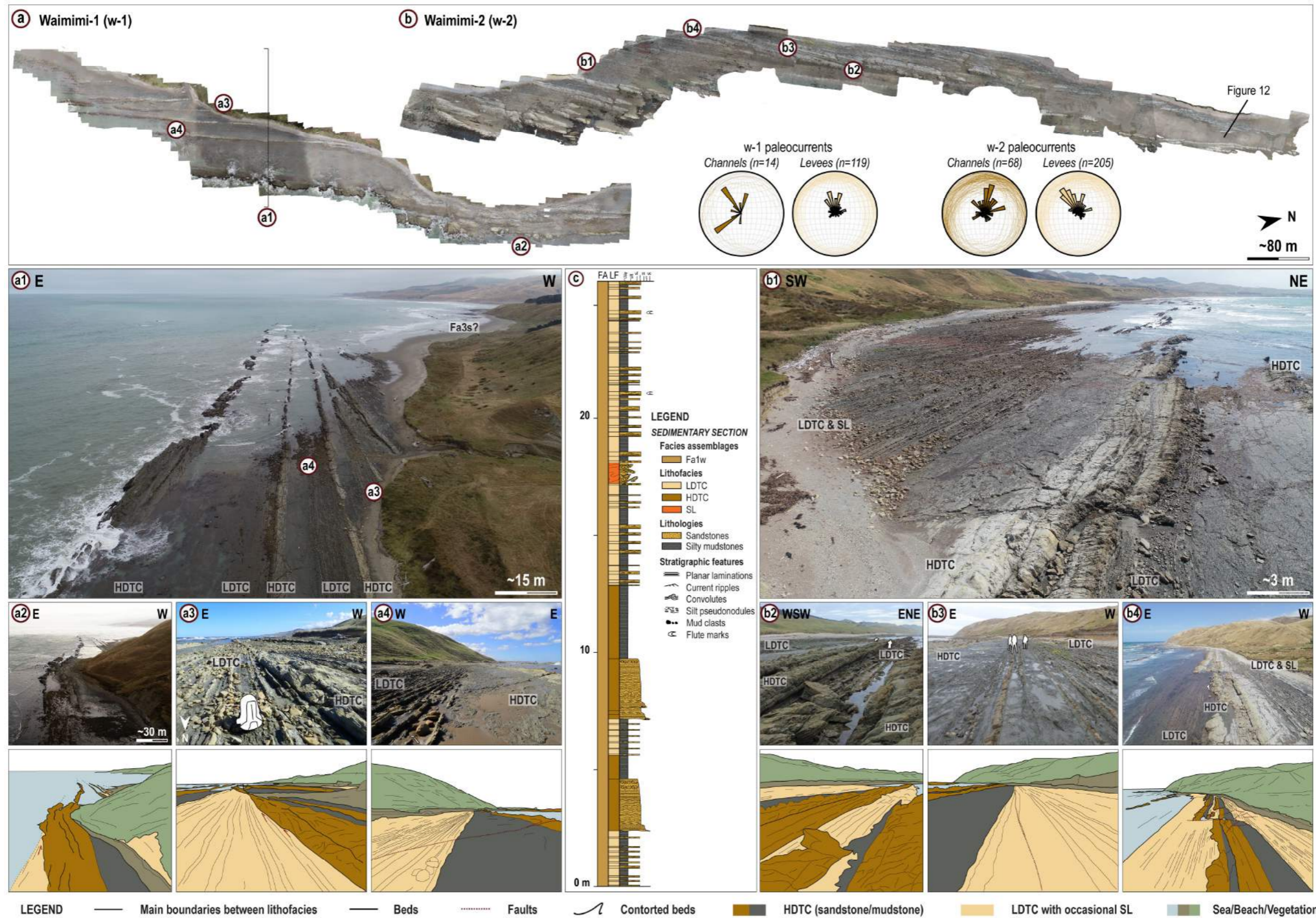
372 Finally, in three instances, very thick-bedded (up to three meters), disorganized, polymict and matrix-  
373 supported conglomerates (**DF**) were observed to interrupt these series (two of them illustrated on the  
374 logs of Figure 9). Their base is sharp and erosive into the mudstone caps, whereas their rugose  
375 topography is usually overlain by the **HDTC** sandstones that locally rework the conglomeratic content at  
376 their base or incorporate some of the outsized clasts (Figure 9b). These different deposits are discussed  
377 in detail below (see Section 4.2.1, facies association **Fa3n**).

378 At Waimimi, **Fa1w** reaches up to 270 meters in thickness to the south and over 400 meters to the north,  
379 and typically shows several kilometers of lateral continuity (Table 2; Figure 5d; Figure 6; Figure 8;  
380 Appendix 1; Appendix 2). Once corrected for post-depositional deformation, the thicker beds (**HDTC**)  
381 display a general dispersion of current directions from the SW to the N at Waimimi-1 whereas they  
382 indicate a fairly consistent NE direction at Waimimi-2. The thinner beds (**LDTC**) are preferentially  
383 directed to the NNW (Figure 8; Appendix 1; Appendix 2).



384

385 Figure 7: Representative photographs of the lithofacies summarized in Table 1 and encountered at the Pahaoa, Flat Point,  
 386 Orui, Waimimi and Suicide Point-Mataikona localities. See Table 1 for the description of the lithofacies codes.



387

388 Figure 8: 3D outcrop models, paleocurrent analysis as well as detailed photo interpretations of the lowermost Miocene channel-levee system (Fa1w) observed at Waimimi. This coastal outcrop is divided into two sections, namely section w-1 to the south and section w-2 to the north. The  
 389 letters (a) and (b) respectively refer to some of the architectural elements that characterize the w-1 and w-2 sections. The letter (c) captures a sedimentary section that synthesises the stratigraphic pattern of the channel-levee system. See Table 1 for the description of the lithofacies codes  
 390 (HDTC, LDTC, SL) and Table 2 for the facies association codes. See Appendix 1 and Appendix 2 for enlarged views of the Waimimi outcrop models, respectively the southern part (w-1) and the northern part (w-2).

391 At Flat Point, **Fa1w** is approximately one hundred meters thick, cropping out along several kilometers  
392 of coastline (Table 2; Figure 9). It conformably overlies the Eocene-Oligocene pre-subduction margin  
393 series and is overthrust by the seaward-directed Flat Point-Whakataki Fault complex (Figure 2b;  
394 Figure 5b; Figure 6). At Flat Point, the series includes a higher proportion of **HDTC** intervals, which are  
395 interbedded with smaller **LTDC** intervals that generally comprise sandier and thicker sandstone beds to  
396 that of Waimimi. The internal architecture is also more complex, displaying numerous sharp erosional  
397 truncations, concave-up geometries and downlap terminations (Figure 9a). The paleocurrents are  
398 dominantly directed to the NW (Figure 9a).

### 399 Interpretations

400 We interpret **Fa1w** to represent the development of an aggradational (minimum 230 meters thick at  
401 Waimimi) and laterally extensive (several tens of kilometers axially to the basin) turbidite-rich channel-  
402 levee complex system (Mutti and Normark 1991; Galloway 1998; Sprague et al. 2005; Kane and  
403 Hodgson 2011), which ran parallel to the trench-oriented basin bounding structures. The broadly  
404 lenticular, sandstone- to mudstone-rich deposits (**HDTC**) result from confined, waning turbidity currents  
405 and characterize the infilling of channel-forms, whereas the thinner-bedded heterolithic intervals  
406 represent the relatively unconfined portion of flows spilling over the channels and forming their levee-  
407 overbank deposits (**LDTC**, **SL-a**, **SL-b**) (Mutti and Normark 1991; Galloway 1998; Kane and Hodgson  
408 2011).

409 The channel fills (**HDTC**) characteristically provide greater preservation of the waning cycles and hold  
410 rather thin channel fills in comparison to their widths (Figure 8) (Mutti and Normark 1991; Galloway  
411 1998; Hodgson et al. 2016). Their internal organization is complex and record multiple cycles of sub-  
412 horizontal channel-fills (e.g., recurrent grain-size breaks), largely dominated by fine-grained  
413 sedimentation with an overall evolution from traction- through suspension fall out- to suspension-  
414 dominated depositions (e.g., Bouma 1962; Stow and Shanmugam 1980). We interpret these infills to  
415 result from a succession of (rather than a single) turbidity flow events.

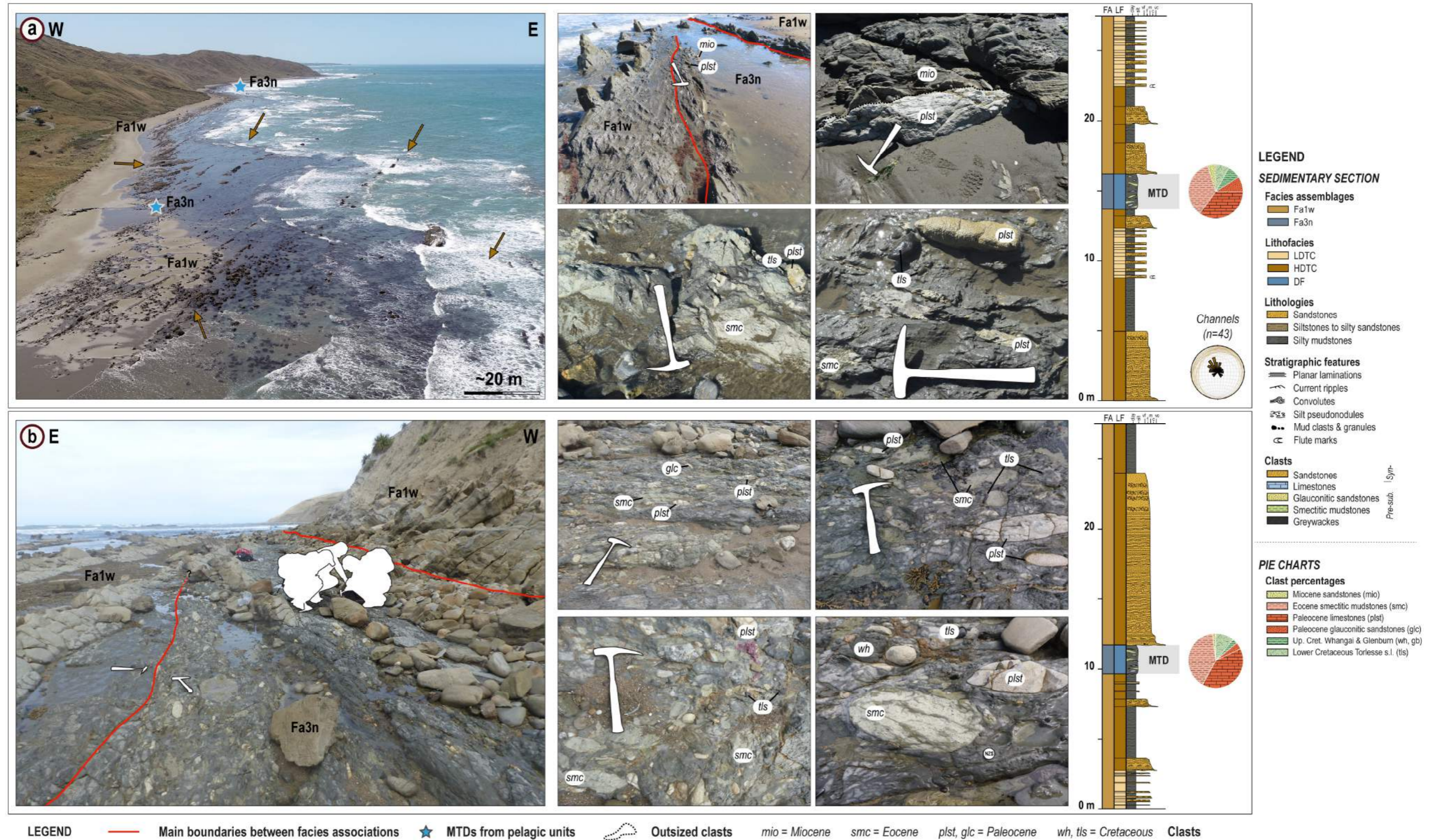
416 At both Flat Point and Waimimi, these channels are typically underfilled ending with very thick-bedded  
417 mudstone caps (likely substantially compacted already (Jones 1944)), reflecting their recurring  
418 abandonment, and possibly avulsion (Galloway 1998; Sylvester et al. 2011). Unfilled reliefs tend to  
419 strongly impact the location and morphology of the next channel, thereby favoring the development of  
420 organized stacking patterns with negligible channel offset such as the ones observed here (Figure 8)  
421 (Posamentier and Kolla 2003; McHargue et al. 2011).

422 The recurrent packages of thin-bedded turbidites (**LDTC**) are attributed to the levee-overbank deposits  
423 (Kane and Hodgson 2011; McArthur et al. 2016) needed for aggradation from one channel to another  
424 (Mutti and Normark 1991). Their generally uniform to progressively swinging paleocurrent directions  
425 (Figure 8), their sedimentary structures characteristics of simple waning flows (*i.e.*, partial Bouma  
426 sequences), their broad wedge geometry, varying thicknesses and downlap terminations all suggest  
427 deposition from unconfined overbank flows (Kane and Hodgson 2011).

428 The near-orthogonal relationships observed in the paleocurrent directions, well-expressed in Waimimi-  
429 2, are consistent with a turbidite channel-levee system and suggest channelized flows, though sparse,  
430 generally to the north along with longitudinal flows alternatively to the NW and NE at Waimimi. Although  
431 the micropaleontology analysis indicates that deposition occurred at deep bathyal depths (>800 meters)  
432 during the earliest Miocene, late Waitakian to Otaian (Aquitainian to Early Burdigalian, 23.03 – 18.7 Ma)  
433 (Appendix 3), the presence of terrigenous organic material highlights that the turbidity flows most likely  
434 initiated from shallow marine environments that were connected to a vegetated hinterland (Kuenen  
435 1964).

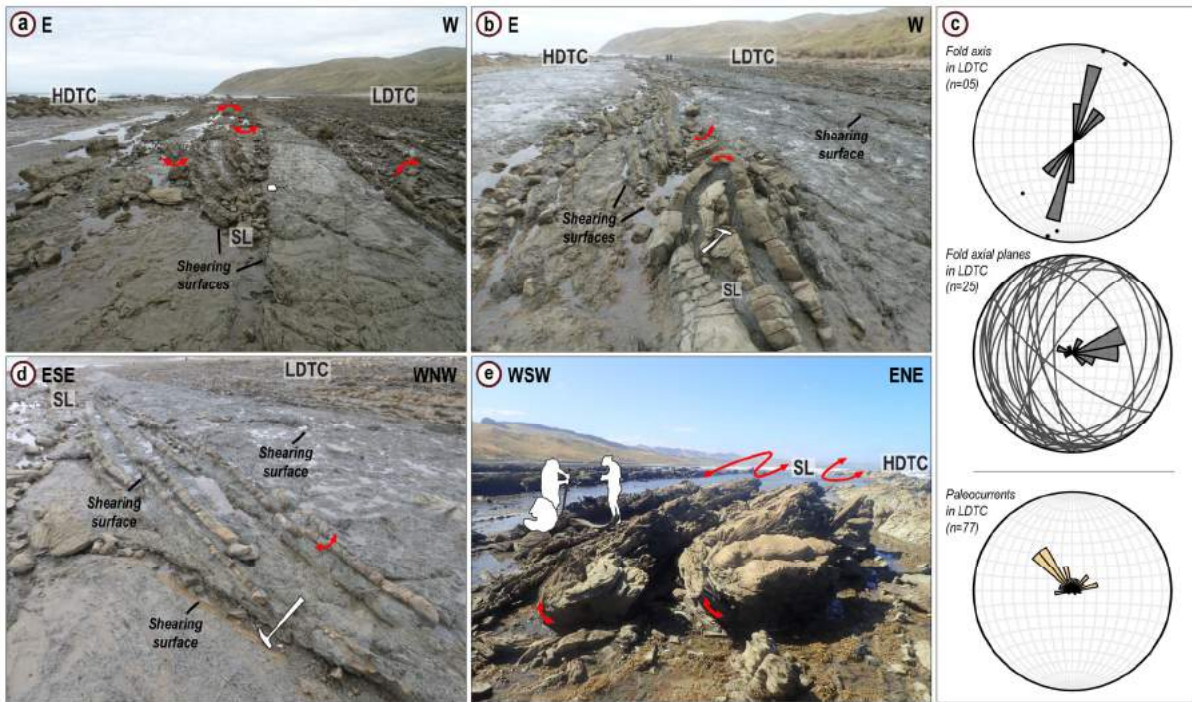
436 Contemporaneous turbidites similar to these (**LDTC**, disputably 750 to 1500 meters thick) have been  
437 described further north, to the north of Castlepoint (Figure 2). They were interpreted to result from  
438 medial and distal levee-overbank setting with longitudinal flow directions to the NNE (Field 2005),  
439 supplied from a sediment source close to the continent (*i.e.*, vegetated hinterland and nearshore/shelf  
440 environments) (Sloss et al. 2021; Griffin et al. 2022). The Flat Point and Waimimi **Fa1w** deposits could  
441 therefore represent relatively proximal expressions of such a channel-levee complex system, either  
442 sourced from one or multiple entry points, advancing and feeding the more distal deposits to the north.

443 Finally, we attribute the compressional features affecting the poorly lithified **Fa1w** deposits to result  
444 from post-depositional tectonic overprint related to the earliest Miocene period of regional NE-SW  
445 seaward thrusting (Chanier and Ferrière 1991). Although local gravity-driven slope instabilities are  
446 common in levee-overbank settings due to oversteepening (Posamentier and Walker 2006), these  
447 structures were observed to mutually affect the channel and levee-overbank settings, and also provide  
448 incoherent paleoslope direction to those of the related levee-overbank (Figure 10).



449

450 Figure 9: (a): Flat Point and (b): Waimimi mass-transport deposits (MTDs), interpreted to result from the frontal erosion of thrust sheets (Fa3n) developed in the pelagic units of the Hikurangi margin pre-subduction series and interrupting the lowermost Miocene channel-levee system  
 451 (Fa1w). Detailed views of the MTDs and their lithoclast content. The sedimentary sections are composite sections, capturing their stratigraphic relationship with the coeval channel-levee systems. The pie charts provide insights as to the nature and associated proportions of each lithoclast  
 452 style. *mio* = sandstones (e.g., Fa1w); *smc* = smectitic mudstones; *plst* = whitish sub-micritic limestones; *glc* = glauconitic sandstones; *wh* = calcareous or siliceous mudstones; *tls* = greywackes. The yellow-brown arrows on the top-left picture highlight the complex internal architecture of  
 453 Fa1w. See Table 2 for the description of the facies association codes.



454

455 Figure 10: (a, b, d, e): Soft-sediment deformation (SL) recorded in the poorly lithified sediments of the Waimimi channel-  
 456 levee system (Fa1w), interchangeably affecting the channel (HDTC) and levee-overbank (LDTC) settings. (c): Stereoplots  
 457 (Schmidt, lower hemisphere) after back-tilting of bedding planes to initial horizontal position (assuming cylindrical folding)  
 458 highlight the fold axis, axial planes and paleocurrent directions recorded in the levee-overbank settings presented here.  
 459 Fold measurements were taken in the deformed zone (SL on pictures a, b, d and e) whereas the paleocurrents were taken  
 460 in the structured intervals from the upper, undeformed zone (LDTC on pictures a, b and d). See Table 1 for the description  
 461 of the lithofacies codes (HDTC, LDTC, SL)

462

## 4.2. Mass-transport deposits

463

### 4.2.1. Fa3n: Reworked pre-subduction series

464

#### General observations

465

466 Facies association **Fa3n** is characterized by disorganized, polymict and matrix-supported  
 467 conglomerates (**DF**, **MF**) that rework randomly distributed pebble- to boulder-grade and outsized (deci-  
 468 to pluri-decamic) extraformational lithoclasts derived from the pre-subduction margin series (Table 1;  
 469 Table 2; Figure 7; Figure 9; Figure 11; Figure 12). Intraformational lithoclasts from the  
 470 contemporaneously developing syn-subduction strata (*i.e.*, lowermost Miocene Whakataki Formation)  
 471 were also sporadically observed. Clasts are supported by a light grey, silty mudstone matrix, which can

472 locally show a higher siltstone content, as observed at Pahaoa (Chanier and Ferrière 1991) or at Orui  
473 (Figure 11c).

#### 474 General interpretations

475 We interpret **Fa3n** to result from slope failure and mass-wasting processes that destabilized and  
476 reworked a paleogeographic domain(s) or structural unit(s) dominated by pre-subduction margin strata.  
477 The resulting deposits are therefore interpreted to represent mass-transport deposits (MTDs). They  
478 were likely produced by cohesive flows (*sensu* Mulder and Alexander 2001). The foraminiferal analyses  
479 of their matrix content indicate that deposition here occurred at minimum in middle bathyal (>800  
480 meters) or possibly lower bathyal water depths (>1000 meters) during the earliest Miocene, late  
481 Waitakian to Otaian (Aquitanian to Early Burdigalian, 23.03 – 18.7 Ma) (Appendix 3). The  
482 contemporaneous onset of subduction and initial structural development of the subduction wedge  
483 resulted in the intense deformation of the passive margin, with the seaward emplacement of a  
484 succession of thrust sheets (Figure 4) (Chanier and Ferrière 1991; Rait et al. 1991). This, in turn,  
485 subaqueously exposed the rocks from the older pre-subduction substratum, ready to be reworked and  
486 incorporated into the subsequent mass-wasting processes. We therefore interpret **Fa3n** to derive from  
487 advancing thrust sheets (*sensu* Festa et al. 2010 and references therein).

488 In the study area, despite common characteristics such as the dominant lithology (*e.g.*, conglomerate),  
489 nature of the matrix (*e.g.*, silty mudstone) and of the clasts (*e.g.*, pre-subduction), significant differences  
490 exist, both in terms of their morphometric characteristics (*e.g.* size, extent) and their lithoclast content  
491 (*e.g.*, grade, roundness, age, detrital or pelagic origin). We here use the lithoclast nature (pre-  
492 subduction) and origin (thrust sheet unit) as a dividing criterion to further characterize the **Fa3n** MTDs  
493 and their source areas (Nemec and Steel, 1984). As a result, we identified two main recurrent yet  
494 distinct styles within the **Fa3n** facies association. These two styles are detailed below.

#### 495 **4.2.1.1. Reworking of pelagic units**

##### 496 Observations

497 The first style of **Fa3n** is encountered at Pahaoa (Figure 5a; Figure 12a), Flat Point (Figure 5b; Figure  
498 9a) and Waimimi (Figure 5d; Figure 9b; Appendix 2).

499 In this first style (Table 2), the associated conglomerates comprise ~50 to 80% matrix content, with  
500 chaotically distributed lithoclasts (**DF**). They mostly (>80%) consist of sub-angular to sub-rounded  
501 pebbles to boulders of Paleocene limestones (*i.e.*, white micritic Kaiwhata limestones) and light green

502 Eocene calcareous smectitic mudstones (Figure 9; Figure 12a). At Pahaoa, the clasts of Paleocene  
503 rocks are frequently several meters long (Figure 12a). Both characteristically present elongated,  
504 lenticular, sometimes sigmoidal shapes (Figure 9; Figure 12a). For the Eocene strata however, the very  
505 flat shapes are systematically oriented parallel to the matrix bedding.

506 For the remainder of the pre-subduction clasts, their content varies slightly at the different locations  
507 (Figure 9; Figure 12); it generally includes Lower Cretaceous strata, Upper Cretaceous calcareous  
508 sandstones (*i.e.*, Whangai Formation) and Uppermost Cretaceous to Paleocene glauconitic  
509 sandstones. The Lower Cretaceous lithoclasts mostly consist of (sub-)rounded granules and pebbles of  
510 greywackes (Figure 9), rarely of red cherts and lavas. At Pahaoa, a few scattered sub-angular boulders  
511 to oversized clasts of greywackes can also be found (Figure 12a). The Upper Cretaceous calcareous  
512 sandstone content is very scarce. Conversely, the Uppermost Cretaceous to Paleocene glauconitic  
513 sandstones are regularly present, either as sub-angular to sub-rounded pebble- to boulder-grade clasts  
514 or as contorted strata (Figure 12a). The syn-subduction content is rare; nevertheless, it typically occurs  
515 at the base of the conglomerate deposits as oversized clasts (decametric) of coherent to contorted thin-  
516 bedded turbidites of the Whakataki Formation.

517 At Pahaoa, this style of **Fa3n** is described by [Chanier and Ferrière \(1991\)](#). It can reach up to 40 meters  
518 in thickness and sporadically crops out over 900 meters along the coast (Table 2; Figure 5a), finishing  
519 its course under water. It conformably overlies (at least at the scale of the outcrop) the Paleocene to  
520 Eocene pelagic unit series (Figure 12a) and does not comprise one but a succession of coalescing (a  
521 few meters thick) conglomerates (**DF**) with a matrix greatly affected by complex syn-sedimentary folding  
522 ([Chanier and Ferrière 1991](#)) and mostly holding boulder-grade to oversized clasts. To the south, it is  
523 overlain by Whakataki Formation turbidites (**Fa1w?**) (Figure 5a) ([Chanier 1991](#)).

524 At Flat Point and Waimimi however, this style of **Fa3n** is only a few meters thick (up to three meters)  
525 and is interbedded with the **Fa1w** turbidites (see Section 4.1) (Table 2; Figure 9). Owing to the drone  
526 pictures, we were able to observe that the two **Fa3n** occurrences at Flat Point are not in the same  
527 stratigraphic position (Figure 9a) and as such do not correspond, as previously suggested by [Chanier  
528 and Ferrière \(1991\)](#), to a single and widespread conglomeratic episode but instead represent two  
529 distinctive episodes.

### 530 Interpretations

531 Owing to the extraformational lithoclasts that have lithological composition similar to that of the thrust  
532 tectonic units, we interpret this first style of **Fa3n** to mainly result from the dismantlement of an

533 advancing thrust sheet developed in the pelagic units of the Hikurangi margin pre-subduction series (-  
534 Figure 4B, pelagic unit) (Chanier and Ferrière 1989; Chanier and Ferrière 1991). Although  
535 discontinuous, the distribution of the resulting deposits suggests that these pelagic units were  
536 consistently exposed to submarine erosion along the southern Hikurangi margin at the time.

537 The analysis of the syn-sedimentary deformation recorded in the deposits (see Chanier and Ferrière  
538 1991) indicates that the failed material was transported downslope and subsequently deformed (e.g.,  
539 shearing structures, intrafolial folds) through mass-wasting processes (e.g. Festa et al. 2016) and also  
540 that the transport direction was to the E or NE. The rafted blocks of turbidites, recurrently found at the  
541 base of **Fa3n**, suggest basal interaction and substrate disruption from the overriding mass  
542 (Posamentier and Martinsen 2011; Sobiesiak et al. 2018).

543 The **Fa3n** deposits do not point toward an isolated catastrophic event but rather a series of semi-  
544 continuous mass-wasting events that were linked to the seaward emplacement of a thrust sheet  
545 (Chanier and Ferrière 1991), and which triggered successive debris flows (*sensu* Mulder and Cochonat  
546 1996).

547 The deposits at Pahaoa would represent a relatively proximal expression of the failures, being coarse-  
548 grained, thick and coalescing in front of the propagating thrust sheet; whereas the Flat Point and  
549 Waimimi deposits would represent thinner, more distal incursions, occasionally reaching the Castlepoint  
550 trench-slope basin floor several kilometers to the east, and interacting with the contemporaneously  
551 developing turbidite system (**Fa1w**). The contrasting styles and thicknesses could result from (1) MTDs  
552 that thin away from their source towards the trench-slope basin center, (2) different magnitudes of  
553 mass-wasting events (e.g., Watson et al. 2020), (3) similar sources but with contrasting catchment  
554 sizes (e.g., Naranjo-Vesga et al. 2020), or (4) a preferential routing of the MTDs interacting with the  
555 turbidite system (e.g., Pickering and Corregidor 2005; Ortiz-Karpf et al. 2017). A different timing of  
556 events could also be envisaged with a sustained period of mass-wasting (Pahaoa MTDs) occurring  
557 before the establishment of the turbidite system (Flat Point and Waimimi **Fa1w** turbidites), only then  
558 followed by some punctuated tectonic pulses that would episodically (but not necessarily always)  
559 produce MTDs locally seen to reach and interrupt the turbidite sedimentation taking place in the trench-  
560 slope basin (Flat Point and Waimimi MTDs). Detailed micropaleontological analyses are however  
561 required to ascertain such scenarios and along slope controls.

562 Although mass-wasting processes traditionally represent a continuum along slope, whereby one  
563 process can evolve into or trigger another (Stow 1986; Nemeč 1990), the comparisons of the proximal  
564 and distal expressions of similar slope failures here indicate that the mass-wasting process did not

565 change. This suggests very little to no flow transformation (Fisher 1983) that may be due to strongly  
566 coherent debris flows, typically extending back to their original failure (*sensu* Talling 2013).

567 Finally, at Pahaoa, the (sub-)rounded pebbles of Lower Cretaceous strata, constantly present in these  
568 **Fa3n** deposits, unlikely come from the underwater substratum and might instead result from direct  
569 erosion of the hinterland (*e.g.*, Bland et al. 2022) or reworking of the Upper Cretaceous conglomerates,  
570 comprising already fluviually-reworked greywackes (Chanier 1991; Chanier and Ferrière 1991).

#### 571 **4.2.1.2. Reworking of intermediary units**

##### 572 Observations

573 The second style of **Fa3n** is here described using the southern Orui locality as reference (Table 2;  
574 Figure 5c, the Orui-1 section (o-1); Figure 11).

575 The associated conglomerates are primarily distinguished by varying matrix content (Table 1; Figure  
576 11c;). They frequently present more than 95% (**MF**); yet, are often interspersed by intervals with lesser  
577 matrix (~50%, **DF**) laterally and or vertically evolving into **MF**. The matrix characteristically shows  
578 compositional foliations. Only one instance was observed to virtually hold no matrix (**CF**).

579 Contrary to the previously described **Fa3n** style (see Section 4.2.1.1), these conglomerates show an  
580 upward evolution in the nature of their clast content (Figure 11c). The lithoclasts however remain  
581 randomly distributed.

582 In stratigraphic order, the basal conglomeratic units (here, MTDs 01 to 04) mostly (>75 to 90%)  
583 comprise pebbles to outsized clasts (deci- to decametric) of Paleocene limestones (sub-micritic  
584 equivalent to the white Kaiwhata limestones), Paleocene siltstones (*i.e.*, Waipawa Formation) and light  
585 green, red or black Eocene calcareous smectitic mudstones (Figure 11c, d6, d7, d8, d9). Both the  
586 Paleocene limestones and Eocene lithoclasts present elongated shapes, recurrently asymmetrical (both  
587 sinistral and dextral geometries), similar to that of the previously described **Fa3n** style. In the clast-rich  
588 intervals (**DF**), the Eocene calcareous smectitic mudstones are often intricately interbedded with the  
589 lowermost Miocene matrix and aligned along a N-S direction, parallel to bedding. These basal units  
590 also occasionally (>5 to 25%) reworked cobbles and outsized clasts of Uppermost Cretaceous to  
591 Paleocene glauconitic sandstones, as well as sporadically (2 to 15%) incorporated rafts (several tens of  
592 meters, *e.g.*, olistoliths) of Paleocene rocks, and more regularly of Upper Cretaceous siliceous rocks  
593 (*i.e.*, Whangai Formation) (Figure 11b, c). Syn-subduction clasts are only present in the first  
594 conglomeratic unit (~25%) as rafts of turbidite strata (Figure 11c).

595 The following conglomeratic units (here, MTDs 05 to 08) mainly (~80%) consist of outsized clasts and  
596 rafts (several tens of meters) of Paleocene siltstones, Uppermost Cretaceous to Paleocene glauconitic  
597 sandstones and Upper Cretaceous limestones (sub-micritic equivalent to the Pithonellid-bearing  
598 limestones) (Figure 11c, d2, d4, d5; Appendix 4). They also generally incorporate Upper Cretaceous  
599 strata from the Whangai and more rarely Glenburn Formations, as well as interstratified very-thick  
600 intervals of Eocene calcareous smectitic mudstones.

601 The upper units (here, MTDs 09 and 10) are largely dominated by sub-angular pebbles to outsized  
602 clasts as well as rafts (several tens of meters) of Upper Cretaceous strata from both the Whangai (e.g.,  
603 siliceous mudstones with carbonate concretions) and Glenburn Formation (e.g., conglomerates and  
604 sandstones) (Figure 11c, d1, d2). They also sporadically include sub-angular pebbles to boulders of  
605 Lower Cretaceous greywackes as well as outsized clasts (deci- to decametric) of Paleocene siltstones  
606 and Miocene turbidite strata (Figure 11c, d3).

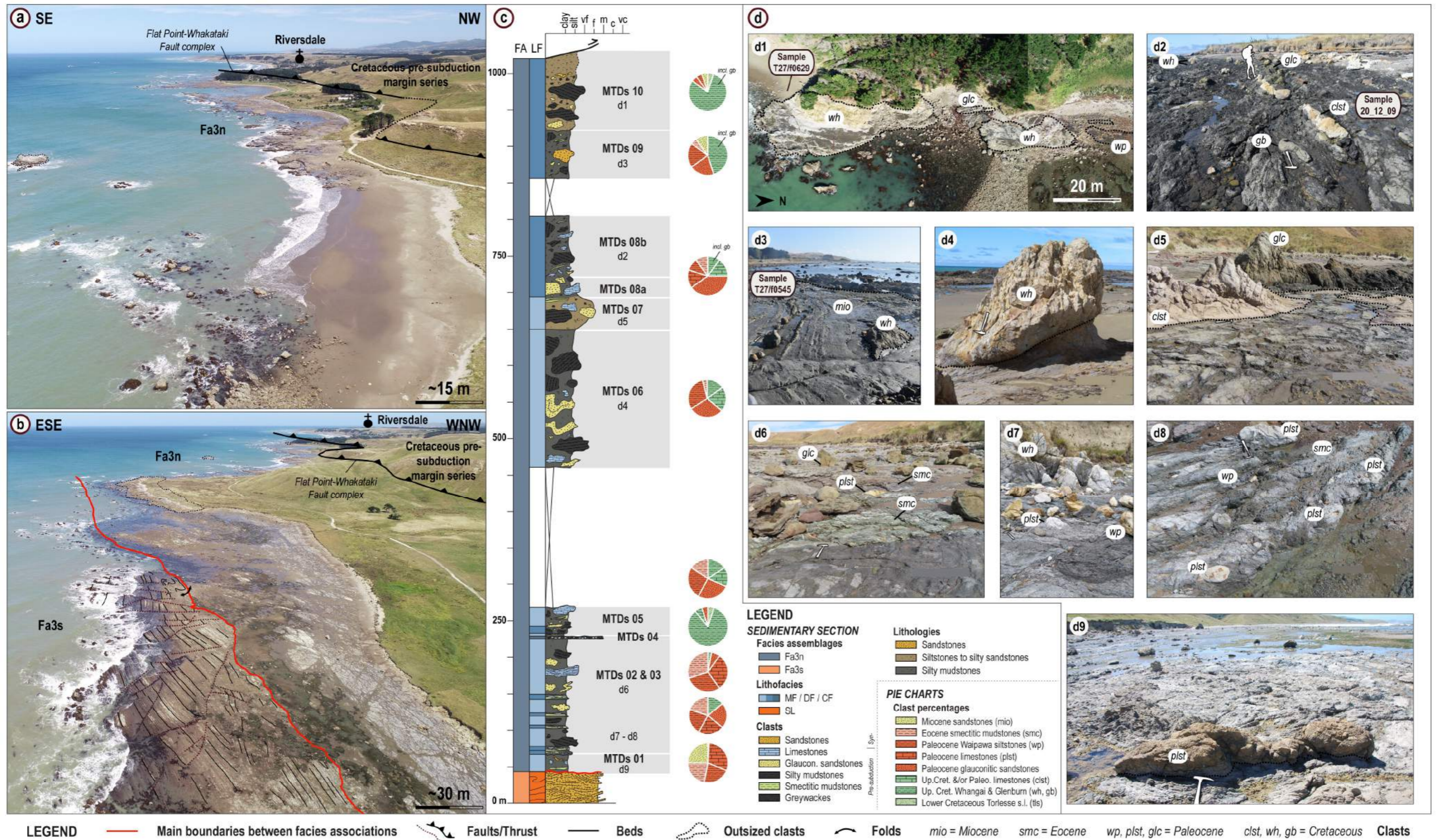
607 Ductile and brittle-ductile deformation fabrics, such as asymmetrical boudinage and pseudo-sigma  
608 structures as well as intrafolial and rootless folds (*sensu* Festa et al. 2016), were commonly observed in  
609 the deposits (Figure 11).

610 At Orui, this style of **Fa3n** represents between 400 to 900 meters (lateral cumulative thickness) of  
611 successive MTD inputs, cropping out along ~four kilometers of coastline (Table 2; Figure 5c; Figure  
612 11). Particularly, at the top of the series, the deposits are sometimes intercalated with pre-Miocene  
613 strata from the Coastal Block due to strike-slip faulting. The overall thickness estimate is therefore  
614 questionable; yet, remains particularly important (>400 meters). This style can be grouped into at least  
615 10 distinct coalescing conglomeratic events, themselves comprising a series of internal events  
616 reworking material of similar nature (Figure 11c). Its basal surface is sharp and highly erosive (>20  
617 meters) into the underlying **Fa3s** turbidites (see Section 4.2.2), and can be traced over one kilometer  
618 (Figure 11b). The outcrop conditions however hinder the exposure of its upper surface, which  
619 corresponds to the seaward-directed Flat Point-Whakataki Fault complex (Figure 2c; Figure 5c; Figure  
620 11a, b).

621 To the north of the study area, between Suicide Point and Mataikona river outlet, a similar style of **Fa3n**  
622 crops out, roughly representing ~800 meters (cumulative thickness) of deposits, along more than three  
623 kilometers of coastline, also at the front of the Flat Point-Whakataki Fault complex (Table 2; Figure 5e;  
624 Figure 12b). The deposits were previously described by Neef (1995), Delteil et al. (2006) and Down  
625 (2016). Down (2016) identified two main events of conglomerate deposition separated by an episode of  
626 turbidite deposition and or folding (**Fa3s?**). The first (basal) conglomeratic unit, located close to the

627 Mataikona river outlet (*i.e.*, Mataikona MTDs) (Figure 5e), would be monomict, either only reworking  
628 Upper Cretaceous material from the Whangai Formation (Neef 1995) or Upper Cretaceous to Eocene-  
629 Oligocene material from the Whangai, Kaiwhata, Wanstead and or Weber Formations (Down 2016).  
630 We here only focus on the second conglomeratic unit (~500 meters) (Figure 12b), located at and to the  
631 north of Suicide Point (*i.e.*, Suicide Point MTDs) (Figure 5e), characteristically holding similar deposits  
632 to those described in the Orui section (Figure 11).

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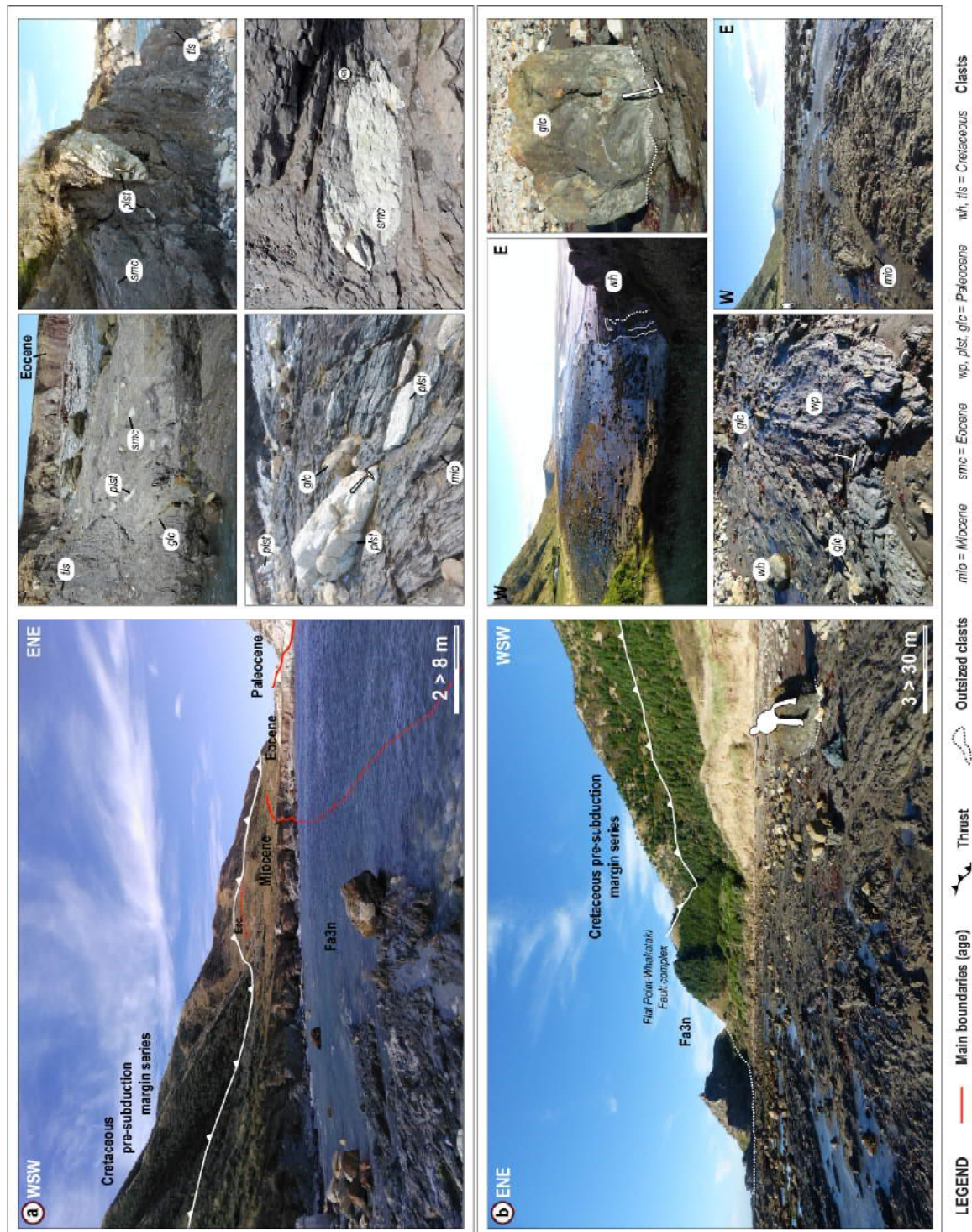
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Figure 11: Orui mass-transport deposits (MTDs) resulting from the emplacement (Fa3s) and subsequent frontal denudation (Fa3n) of the Glenburn thrust sheet developed in the intermediary units of the Hikurangi margin pre-subduction series. (a, b): Drone views. (c): Composite sedimentary section capturing the main MTD styles, themselves comprising a series of internal MTDs reworking material of similar nature. The pie charts provide insights as to the nature and associated proportions of each lithoclast style. (d): Detailed views of the MTDs and their lithoclast content. *mio* = alternating sandstones and mudstones (e.g., Fa1w); *smc* = smectitic mudstones; *wp* = organic-rich silty mudstones; *plst* = whitish sub-micritic limestones; *glc* = glauconitic sandstones; *clst* = pink-grey sub-micritic limestones; *wh* = calcareous or siliceous mudstones; *gb* = coarse detrital sedimentary rocks. See Table 2 for the description of the facies association codes.

638



639 Figure 12: (a) Pahaoa and (b) Suicide Point mass-transport deposits (MTDs), resulting from the frontal denudation of thrust  
 640 sheets (Fa3n) respectively developed in the pelagic units (first style of Fa3n) and intermediary units (second style of Fa3n)  
 641 of the Hikurangi margin pre-subduction series. At Pahaoa (a), the Eocene strata (Eoc.) acted as *décollement* level. Present  
 642 at the sole of the thrust sheet, these strata protected the underlying and overthrusted Pahaoa MTDs (see Section 5.1.1).  
 643 Detailed views of the MTDs and their lithoclast content. mio = alternating sandstones and mudstones; smc = smectitic  
 644 mudstones; wp = organic-rich silty mudstones; plst = whitish micritic limestones; glc = glauconitic sandstones; wh =  
 645 calcareous or siliceous mudstones; t/s = greywackes. See Table 2 for the description of the facies association codes.

647 In this second style of **Fa3n**, the nature of the extraformational lithoclasts gradually evolves upward,  
648 recording progressive submarine exhumation and erosion of an advancing thrust sheet developed in the  
649 intermediary units of the pre-subduction series (Figure 4B, detrital and intermediary units; Figure 11;  
650 Figure 12b). Although, the basal units (corresponding to MTDs 01 to 04 at Orui) comprise a series of  
651 debris flows closely resembling the previously described **Fa3n** (see Section 4.2.1.1), the coeval  
652 presence of (1) Paleocene limestones that are sub-micritic equivalent to those in the pelagic unit and of  
653 (2) Waipawa strata both indicate remobilization of the intermediary (and not pelagic) units (Figure 4B).  
654 In the southern coastal ranges, the Glenburn Nappe, transported on the back of the seaward-directed  
655 Flat Point-Whakataki Fault complex, is a prime source candidate. Up to 1,500 meters thick, it records  
656 lateral facies transition from the detrital to intermediary poles eastwards (Chanier 1991), and directly  
657 overthrusts the thinner (typically 200 to 500 meters thick each) and underlying pelagic units (Figure 4)  
658 (Chanier and Ferrière 1989).

659 We interpret this second style of **Fa3n** to represent deposition from a semi-continuous, uninterrupted  
660 period of slope failure and mass-wasting processes, leading to the large-scale (~400 to 900 meters  
661 thick, several kilometers wide) remobilization and transport of the intermediary pre-subduction margin  
662 series, starting with the Paleocene-Eocene down to the Cretaceous strata, through consecutive debris  
663 flows and mudflows (*sensu* Folk 1954; Moncrieff 1989; Mulder and Cochonat 1996; Mulder and  
664 Alexander 2001).

665 Large mass-wasting events ascribed to advancing nappes typically present outsized clasts and rafts  
666 (*e.g.* Ogata et al. 2019), such as the ones described here. The disorganized clast fabric, average clast  
667 size (*i.e.*, outsized clasts) and shape (*i.e.*, sub-angular) recorded throughout also suggest short travel  
668 distance from nearby source areas (Nemec and Steel 1984) and mobilization (*sensu* Iverson 1997).  
669 Notwithstanding succeeding advances of the nappe since then, making it even closer today (Figure 11),  
670 all the previously-stated elements strongly support MTDs that were already in close vicinity of the  
671 source, and at the front of the nappe (*sensu* Festa et al. 2010 and references therein).

672 Although also dating from the earliest Miocene (Appendix 3), these MTDs are not concurrent to the  
673 turbidite channel-levee complexes (**Fa1w**) documented at Flat Point as well as at Waimimi. Instead,  
674 they overlie it, thereby informing that this episode of erosion post-dates the one that affected the pelagic  
675 units and resulted in the emplacement of the first style of **Fa3n** (see Section 4.2.1.1).

676 The erosive character of the basal surface and the rafts of Miocene turbidites found at the base of the  
677 MTDs at Orui (*i.e.*, MTDs 01) both suggest basal ploughing and scouring leading to the incorporation of  
678 material from the overridden seafloor (*e.g.* Posamentier and Martinsen 2011; Sobiesiak et al. 2018).  
679 Conversely, lowermost Miocene clasts are next found in the upward part of the succession, and thus  
680 may indicate different processes, such as local ponding of contemporaneous turbidity currents (*e.g.*, Bull  
681 et al. 2009; Armitage et al. 2009), then subsequently remobilized during the next event of slope failure  
682 and mass wasting. Finally, the lithoclasts from the Lower Cretaceous strata only appear at the top of the  
683 series and may come from the direct erosion of the hinterland.

684 The foraminiferal analysis of sample T27/f02629, taken in the matrix content at the top of the series,  
685 informs that the Orui deposits date from the earliest Miocene and are restricted to the middle/late  
686 Waitakian to middle Otaian (Aquitanian, 23.2 – ca. 20.2 Ma) (Appendix 3). Between Suicide Point and  
687 Mataikona river outlet, although Delteil et al. (2006) proposed an Eocene age for the Mataikona MTDs,  
688 we here suggest, as highlighted by Neef (1995) and Down (2016), that owing to their stratigraphic  
689 relationships with the Whakataki Formation turbidites (**Fa1w** equivalent), both the Suicide Point and  
690 Mataikona MTDs were most likely earliest Miocene in age, and like the Orui deposits, linked to the  
691 nearby Flat Point-Whakataki Fault complex.

692 The absence of precise dating prevents us from providing a chronological order between the Orui and  
693 Suicide Point deposits. Yet, their characteristics inform that similar mass-wasting processes developed  
694 at the front of the Glenburn Nappe along the southern margin during that period. Among others, the  
695 'reduced' thickness encountered at Suicide Point could be explained from (1) mass-wasting events of  
696 smaller magnitude, (2) a thinner Glenburn Nappe to the north and or (3) a more distal record of the  
697 deposits.

#### 698 **4.2.2. Fa3s: Remobilized syn-subduction series**

##### 699 Observations

700 **Fa3s** essentially comprises strata from the previously documented facies association **Fa1w** that is  
701 completely disorganized and remobilized (**SL-a**, **SL-b**) over several hundreds of meters vertically (Table  
702 1; Table 2; Figure 7). Varying folding styles are observed including widely open upright folds, narrow  
703 recumbent folds as well as curvilinear and rootless folds (Figure 13). They are found across a large  
704 spectrum of scales, mostly displaying meters to tens of meters wavelength. The fold axis and hinge  
705 measurements reveal a rather scattered distribution; yet, they highlight a dominant N-S direction with

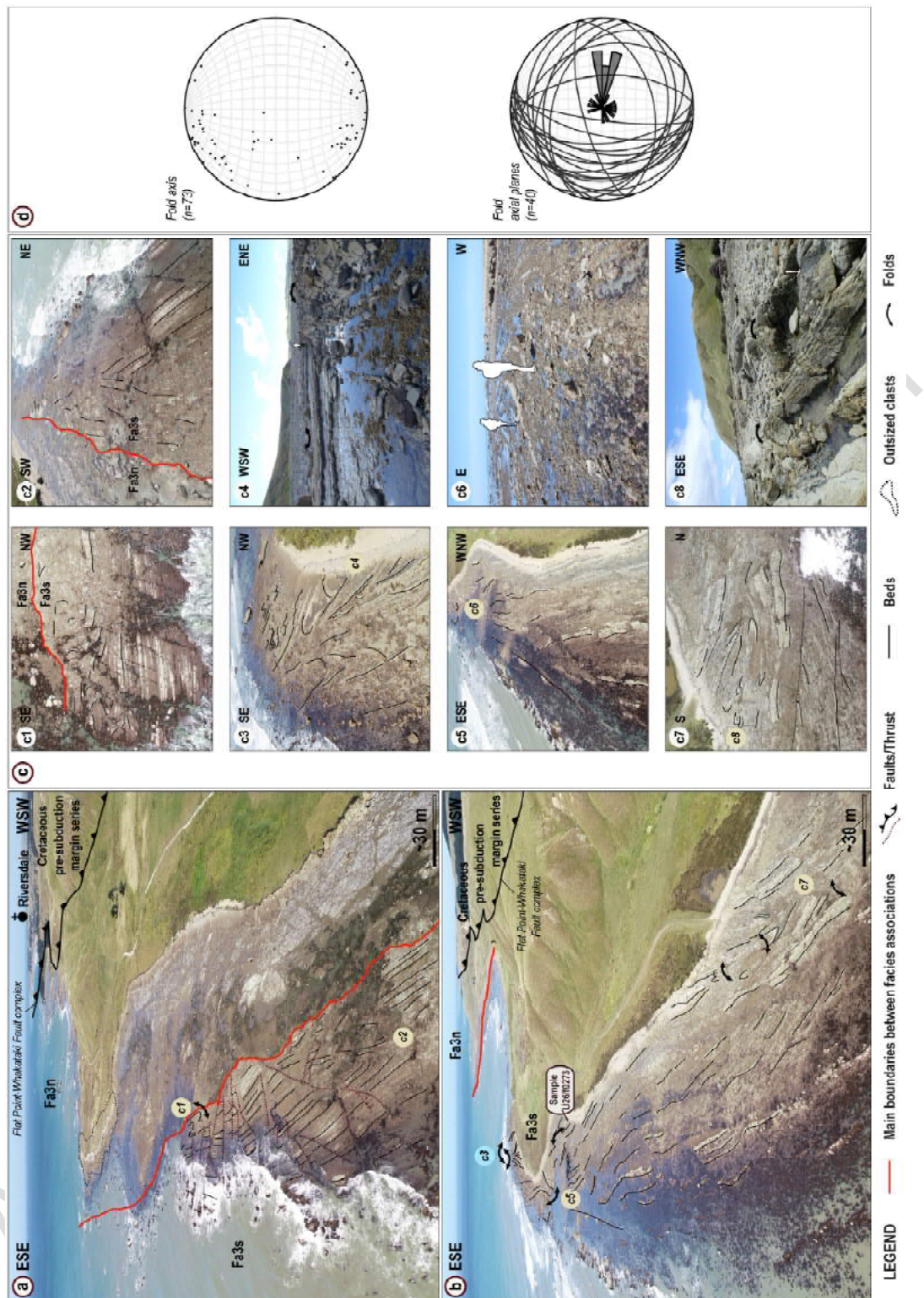
706 respect to present-day geography for the fold axis and a preferential eastward-verging plunge direction  
707 (Figure 13).

708 At Orui, **Fa3s** is about 300 meters thick and extends for several kilometers laterally. Its upper surface is  
709 erosive, NW-SE oriented (and so parallel to the dominant fold axis direction) and characterized by the  
710 following emplacement of **Fa3n** (see Section 4.2.1.2; Table 2; Figure 11b; Figure 13). At Orui, **Fa3s**  
711 ends with a contrasting style; although still locally including large-scale folding (**SL-a**) and sliding  
712 features (**SL-b**) (Figure 13c1, c2), the **Fa1w** strata seems largely undeformed in its upper ~65 meters  
713 (Figure 13a). **Fa3s** is also observed to the southernmost part of Waimimi (Figure 8a1). Between Suicide  
714 Point and Mataikona river outlet, **Fa3s** would correspond to the folded strata described in details by  
715 [Down \(2016\)](#), also typically overlain by **Fa3n**.

#### 716 Interpretations

717 We interpret **Fa3s** to represent the large-scale soft-sediment deformation (several hundreds of meters,  
718 several kilometers) of the previously deposited and poorly lithified turbidites (**Fa1w**) ([Maltman 1984](#)).  
719 Notwithstanding a tectonic overprint, the variabilities encountered in fold geometries and orientations  
720 are not particularly coherent with the regional paleodirection of the main tectonic structures (NE-SW)  
721 ([see Chanier and Ferrière 1991; Rait et al. 1991](#)).

722



723 Figure 13: (a, b, c): Drone and detailed views of Fa3s. It is relatively undeformed in its upper part and overlain by Fa3n (c1,  
 724 c2). Conversely, Fa3s is substantially deformed in its lower part (c3 to c8), whereby it is dominated by soft-sediment  
 725 slumping (*sensu* Nardin et al. 1979) of the previously deposited, poorly lithified sediments of the channel-levee system  
 726 (Fa1w). (d): Stereoplots (Schmidt, lower hemisphere) after back-tilting of bedding planes to initial horizontal position  
 727 highlighting the fold axis and axial planes of the related slump-related folds. See Table 2 for the description of the facies  
 728 association codes.

729 Such observation therefore makes it difficult to envisage the contemporaneous tectonic deformation as  
730 a main driving process for the structures described here. Instead, their preferential N-S azimuthal  
731 direction and dip towards the east, both similar to that of the overlying deposits (**Fa3n**), as well as their  
732 stratigraphic position (underlying the second style of **Fa3n**) rather suggest that these **Fa3s** deposits  
733 were intrinsically related to the overriding MTDs.

734 When the stress related to mass movements is wedded to a poorly lithified substrate (**Fa1w**), the  
735 dynamic/static overloading and rear push of the sliding mass (**Fa3n**) may, in turn, control soft-sediment  
736 deformation (e.g., Butler and McCaffrey 2010; Alves and Lourenço 2010; Ogata et al. 2014). Attenuating  
737 downwards, it generally results in the development of a thick continuous deformed zone between 11%  
738 to 15% of the total thickness of the overlying MTD (Alves and Lourenço 2010; Alves 2015; Sobiesiak et  
739 al. 2018; Sobiesiak et al. 2019). Here however, the thickness of the deformation zone is almost ten  
740 times thicker than the first MTD. Notwithstanding an overestimated thickness of the deformed zone  
741 (**Fa3s**) or coalescing debris flows (**Fa3n**), one could argue that these approximations were initially  
742 calculated for a single episode of MTD emplacement, generally less than 200 meters thick (Alves and  
743 Lourenço 2010; Sobiesiak et al. 2018), and therefore do not take into consideration the cumulative  
744 effect of several episodes of mass-wasting as the ones described here. Progressive overloading of  
745 more than 400 meters (up to 900 meters) of MTDs could thus have promoted further downward  
746 propagation of the deformation front, gradually increasing its distance from the overriding MTDs. Its  
747 overall size (33% of overall MTDs) remains however highly questionable. Also, the presence of a  
748 relatively 'undeformed' zone ~65 meters thick, which represents more than twice the size of the first  
749 MTD, here remains problematic (Figure 11; Figure 13). When an undeformed zone is sandwiched  
750 between the MTD and the deformed basal shear zone, it usually only represents a few meters of  
751 thickness, even for MTDs up to 200 meters thick (Sobiesiak et al. 2018).

752 Conversely, thrust propagation typically alters initial topographies and leads to the generation of a rising,  
753 laterally extensive and downward-facing slope at its front (i.e., forelimb). The second episode of nappe  
754 emplacement (Glenburn Nappe) could have therefore (1) generated such a gradient leading to the  
755 downslope mass movement (e.g., sliding) and deformation (e.g., slumping) of the poorly lithified  
756 sediments previously deposited at its front under the action of gravity (**Fa1w** becoming **Fa3s**) (*sensu*  
757 Nardin et al. 1979), and only then, (2) triggered, through continued nappe motion and oversteepening of  
758 the forelimb gradient, the repeated failures and collapses of the front (and related pre-subduction  
759 strata), eventually resulting in the overriding mass flows (**Fa3n**) (Figure 14).

760 Slump-related folds are perhaps one of the most widely used indicators of the general paleoslope and  
761 transport directions (Woodcock 1979; Alsop and Marco 2011; Alsop and Weinberger 2020) and would  
762 here indicate a N-S oriented (with respect to present-day geography) paleoslope that dipped to the east  
763 (Figure 13). Such paleoslope would be consistent with being at the front (forelimb) of the seaward-  
764 moving and -verging Glenburn Nappe. Whether **Fa3s** would result, in such a scenario, from more than  
765 one slump event is difficult to ascertain. The absence of clear undeformed, horizontal horizons  
766 separating the over 300-meter-thick unit as well as the broad preferential orientation of slumping (Figure  
767 13) rather suggests one main slide/slump event triggering a progressive soft-sediment deformation  
768 sequence (Alsop and Marco 2011). The induced continuous reworking of the early structures would, in  
769 part, explain the distribution dispersal, whereby the fold hinges gradually detach and rotate (Alsop and  
770 Marco 2011). The lateral extent of the deposits also suggests an extensive, most likely uneven slope  
771 topography, which can locally deflect the main direction of mass movement and thus, disturb the  
772 resulting slump folding patterns.

773 Therefore, although some substrate deformation may have locally occurred (Alves and Lourenço 2010;  
774 Alves 2015; Sobiesiak et al. 2018; Sobiesiak et al. 2019), we here interpret **Fa3s** to mainly result from  
775 mass-wasting processes that were linked to the emplacement of the Glenburn Nappe. This event not  
776 only interrupted the sustained development of the axial channel-levee system (**Fa1w**) present in the  
777 area at the time but also promoted the large-scale failure and subsequent downslope mass movements  
778 of the associated poorly lithified sedimentary cover (**Fa1w** becoming **Fa3s**) (Figure 14).

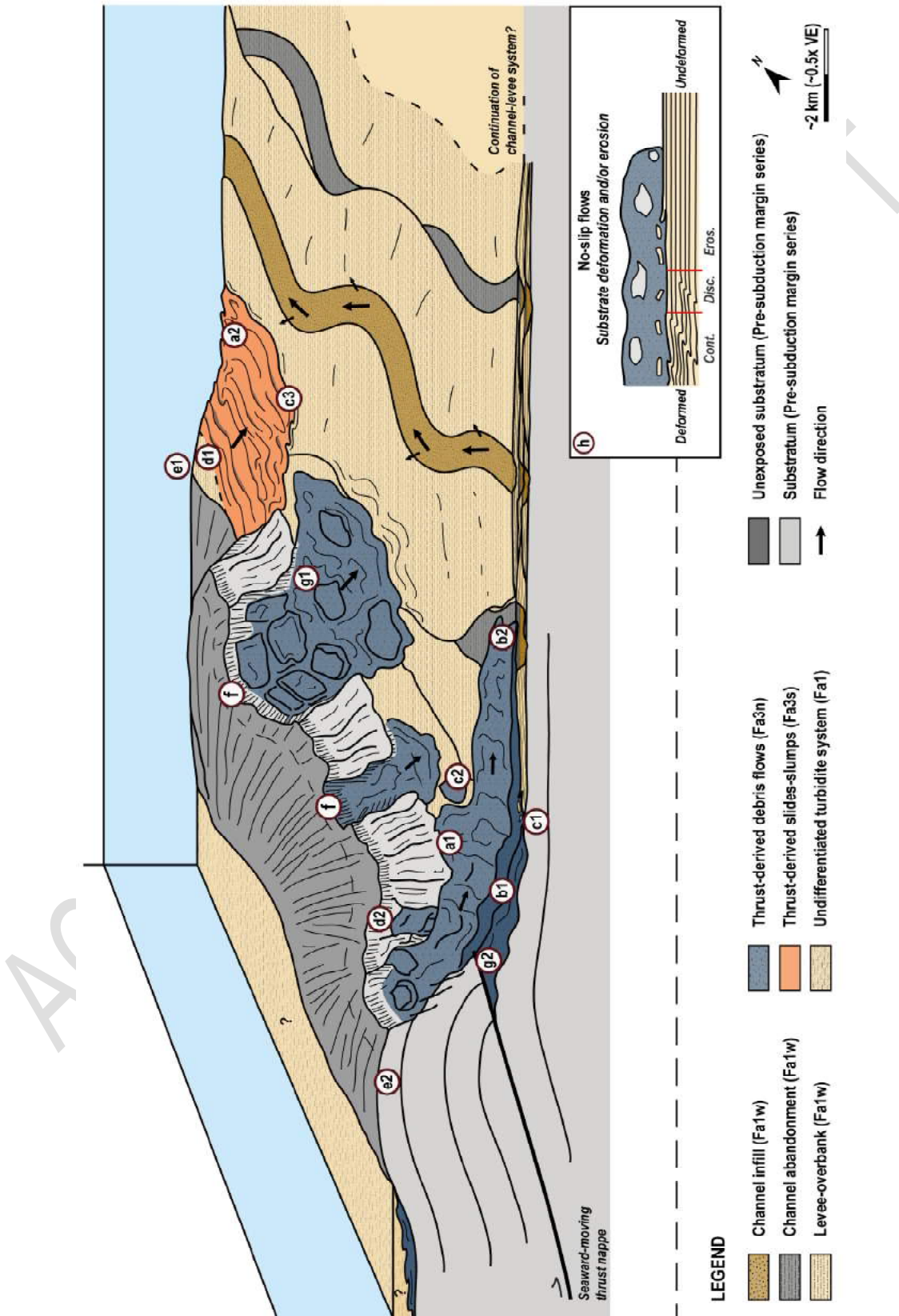
## 779 5. DISCUSSION

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### 780 5.1. Insights from thrust-front mass-transport deposits

781 The widespread distribution (*i.e.*, along 80 kilometers of coastline and up to two kilometers wide; Figure  
782 2; Figure 5) of the lowermost Miocene MTDs described in this study indicates that the regional tectonic  
783 settings played a significant role in triggering submarine slope failures and mass-wasting processes  
784 whereas their nature (see Section 0) and consistent location (*i.e.*, forelimb of the seaward-verging thrust  
785 sheets) suggests that they were derived from the emplacement, oversteepening and subsequent  
786 degradation of advancing thrust fronts (see also (Festa et al. 2010 and references therein) for worldwide  
787 examples and (Watson et al. 2020) for present-day examples along the Hikurangi Margin). Their  
788 extensive lateral continuity (hundreds of meters to kilometers) can be attributed to the typical sublinear  
789 morphology of the nappe front, hereby controlled by underlying thrusts.

790 The different styles of MTDs and their interactions with the coeval turbidite systems however provide  
 791 additional insights to the processes and controls involved (Figure 14) and can also be used to detail the  
 792 overall geodynamic context in which their emplacement occurred (Figure 15).



793

794 Figure 14: [previous page] Schematic representation of the processes and controls influencing the generation of mass-  
795 transport deposits at the front of thrusts in an intra-slope basin setting. (a): Styles of deposits = (a1) debrites, (a2) slides and  
796 or slumps; (b): Deposition styles = (b1) stacked, coalescing in the vicinity of the thrust, (b2) standalone, interbedded with  
797 coeval turbidite system; (c): Different interactions with the coeval turbidites = (c1) erosion, (c2) rerouting due to local  
798 irregularity of the seafloor, (c3) deformation; (d): Nature of the source = (d1) poorly-lithified sediments, (d2) lithified thrust  
799 sheet strata; (e): geometry of the source = (e1) initial rise and (e2) propagation of sublinear thrust-related fold; (f): size of the  
800 source (catchment) and its impact on the resulting deposits; (g): relation to thrust = (g1) frontal deposition, (g2) olistostromal  
801 carpet position which may be preserved from tectonic reworking due to extreme pore pressures; (h): possible styles of basal  
802 interactions from Sobiesiak et al. (2018), which could be found under the flows observed in this study. Note that there is no  
803 demonstrated relationship existing between them. Cont./Disc.: continuous or discontinuous substrate deformation.  
804 Discontinuous deformation occurs when an undeformed zone is sandwiched between the MTD and the deformed basal  
805 shear zone. Eros.: substrate erosion. VE, Vertical exaggeration.

### 806 5.1.1. Preservation at the sole of thrust sheet

807 Along exhumed subduction complexes, MTDs produced from sedimentary origin (*i.e.*, mass-transport  
808 processes) are commonly significantly overprinted by tectonic deformation processes and can therefore  
809 be mistaken as resulting from tectonic mechanisms (*e.g.*, offscraping, tectonic slicing) (*e.g.*, Raymond  
810 1984; Cowan 1985; Festa et al. 2019). This long-lasting debate is particularly true for MTDs involved in  
811 thrust faulting and or found at the sole of advancing thrust sheets (*e.g.*, Fa3n, Table 2) (*e.g.*, Festa et al.  
812 2016; Ogata et al. 2019).

813 In this study however, despite tectonic overlap, the compositional attributes of the matrix and  
814 extraformational lithoclasts (*sensu* Flores 1955; Raymond 1984) as well as the recurrent brittle-ductile  
815 syn-sedimentary deformation features (*e.g.*, Festa et al. 2016) confirmed both the sedimentary origin  
816 and mechanisms of emplacement (*i.e.*, denudation of oversteepened moving nappes) of the Fa3n  
817 MTDs (see Section 4.2.1; Table 2) (Chanier and Ferrière 1991). Interestingly, the Pahaoa MTDs are  
818 interpreted to be in an 'olistostromal carpet' position (*sensu* Pini et al. 2004) under the Flat Point-  
819 Whakataki Fault complex (*i.e.*, thrust) (Figure 12a) (Chanier and Ferrière 1991); yet, they do not record  
820 the traditional 'structurally ordered' and scaly-matrix fabric developing with tectonic reworking (Festa et  
821 al. 2019). Similarly, at the scale of the Flat Point outcrop, the associated MTDs and turbidites only  
822 present minor tectonic overprint even though they are located underneath the Flat Point-Whakataki  
823 Fault complex (Figure 15).

824 The Ocean Drilling Program (ODP) Leg 131 through the Nankai accretionary prism, offshore Japan,  
825 revealed that underthrust sediments can remain generally undeformed, possibly preserved by excess  
826 pore pressure in the *décollement* zone (Taira et al. 1992). Among others, tectonic compression and clay

827 diagenesis (especially the smectite-illite transformation) have been widely recognized mechanisms  
828 causing extreme pore pressures (Mourgues and Cobbold 2006).

829 Overpressures at the sole of the Glenburn Nappe may therefore explain the preservation and relatively  
830 insignificant tectonic overprint seen in both the Pahaoa and Flat Point deposits. Instead, stress focused  
831 onto the overlying fault zone (Flat Point-Whakataki Fault complex) and resulted in several tens of  
832 meters of highly tectonized Eocene smectitic mudstones with pervasive scaly fabrics and bearing  
833 dislocated blocks of intraformational beds of glauconitic sandstones ('tectonic mélange' (*sensu*  
834 Raymond 1984; see also Pini et al. 2004; Festa et al. 2019)) (Chanier 1991; Burgreen-Chan et al. 2016;  
835 Maison et al. 2018). The scaly fabrics are strictly restricted to the thick nappe soles and do not affect the  
836 underlying overthrust sediments, whether they are turbidites (at Flat Point) or olistostromes (at  
837 Pahaoa). As such, these examples inform that not all "olistostromal carpet" positions will result in high  
838 tectonic reworking of underlying sedimentary rocks.

### 839 5.1.2. Spatial-temporal markers of moving thrust sheets

840 The temporal distribution of the MTDs (**Fa3n**, **Fa3s**) and their interactions with the turbidite systems  
841 (**Fa1w**) allows a subdivision of the earliest Miocene in this part of the Hikurangi Margin into several  
842 tectonic periods (Figure 15), two of which are characterized by the coeval motion, oversteepening and  
843 frontal erosion of thrust sheets.

844 Through the failed material, the MTDs mostly recorded the erosion of the associated pre-subduction  
845 margin series and were used to (1) discriminate the nature of the nappe involved in a MTD, (2) specify  
846 the timing of nappe emplacement along this part of the margin and (3) better characterize the events of  
847 (submarine) exhumation and erosion.

848 As described by Chanier and Ferrière (1991), in the study area, the first nappe developed in the pre-  
849 subduction pelagic series, while the detrital series were still farther away to the west (Figure 4; Figure  
850 15a). This nappe formed the landward-bounding structure of the Castlepoint trench-slope basin at the  
851 time and its dismantlement triggered both the formation of the Pahaoa MTDs, close to the thrust front  
852 and of the Flat Point and Waimimi MTDs, farther into the trench-slope basin to the east (Figure 15a).

853 During the same period (earliest Miocene; Figure 15c), the Castlepoint trench-slope basin was the  
854 location of a second episode of nappe emplacement, here developed in the pre-subduction intermediary  
855 to detrital series. This nappe, known as the Glenburn Nappe, was transported on the back of the  
856 seaward-verging Flat Point-Whakataki Fault complex using the Eocene smectitic mudstones as

857 shallower décollement level (Figure 12a; Figure 15c) (Chanier and Ferrière 1991). The Glenburn Nappe  
858 still forms the landward bounding structure of the Castlepoint trench-slope basin today (Figure 2). Its  
859 motion led to overthrusting of the previously deposited Pahaoa and Flat Point series to the south,  
860 placing them in an 'olistostromal carpet' position (*sensu* Pini et al. 2004) and participating to the overall  
861 shortening of the area as a consequence (Figure 12a; Figure 14; Figure 15).

862 This rapid seaward nappe motion undoubtedly played a significant role in the dramatic emplacement of  
863 the Orui and Suicide Point MTDs, largely bigger than the Pahaoa MTDs (Appendix 5) and could, in part,  
864 be explained by the rapid development of thrust-controlled ridges during the onset of subduction.  
865 Contrary to the previous event of nappe denudation (*e.g.* Pahaoa MTDs), the analysis of the Orui and  
866 Suicide Point MTDs suggests progressive denudation of the up to 1,500 meter-thick Glenburn Nappe  
867 resulting in erosion of most (if not all) the Paleocene to Eocene strata and reaching some of its Upper  
868 Cretaceous strata (Figure 14; Figure 15c). The subsequent MTDs hold incredible thicknesses (>400  
869 meters), considerably greater than the commonly reported thrust sheet-derived destabilization and  
870 failures (*i.e.*, *detached* systems) (*sensu* Moscardelli and Wood 2015).

871 Interestingly, the emplacement of the second thrust sheet also resulted in a vertical partitioning of the  
872 mass-wasting processes at its front, to the north of the study area, as similarly observed elsewhere  
873 along the Nankai accretionary prism in Japan (*e.g.*, Strasser et al. 2011; Lackey et al. 2020).. The initial  
874 growth and steepening of the thrust forelimb promoted the failures and mass movements of the poorly  
875 lithified sediments deposited at its front (**Fa3s** at Orui), whereas the continued motion and propagation  
876 of the thrust eventually led to slope oversteepening, subsequently triggering the recurrent failures and  
877 gradual dismantlement of its forelimb (and related strata) through the emplacement of successive debris  
878 flows (**Fa3n** at Orui) (Figure 14) while also recording the progressive incorporation through time of the  
879 associated clasts in reverse stratigraphic order (Figure 11). Conversely, the nature of the substrate  
880 affected by the first thrust sheet differs to that of the second and as such, the older (*i.e.*, non-coeval)  
881 semi-lithified pre-subduction strata might instead explain the absence of vertical partitioning at the front  
882 of the first thrust sheet (Figure 12a). At Pahaoa, the mass-flow deposits (**Fa3n**) directly overlie the  
883 (undeformed) pre-subduction strata, depositing above a geological contact with pyrite concretions (hard  
884 ground), witness of an Oligocene sedimentary hiatus in this area (Chanier and Ferrière 1991; Morgans  
885 and Hollis 2000).

886 Overall, the variations encountered in the nature and size of the MTDs indicate that (1) the outboard  
887 migration of deformation was uneven during the earliest Miocene and punctuated by the emplacement  
888 and motions of two distinct thrust sheets, displaying longitudinal and lateral variations along the margin,

889 and that (2) the frontal denudation of a nappe generally resulted from a series of destabilizations, rather  
890 than only one event, and thus promoted the gradual (submarine) exhumation and erosion of its  
891 substratum.

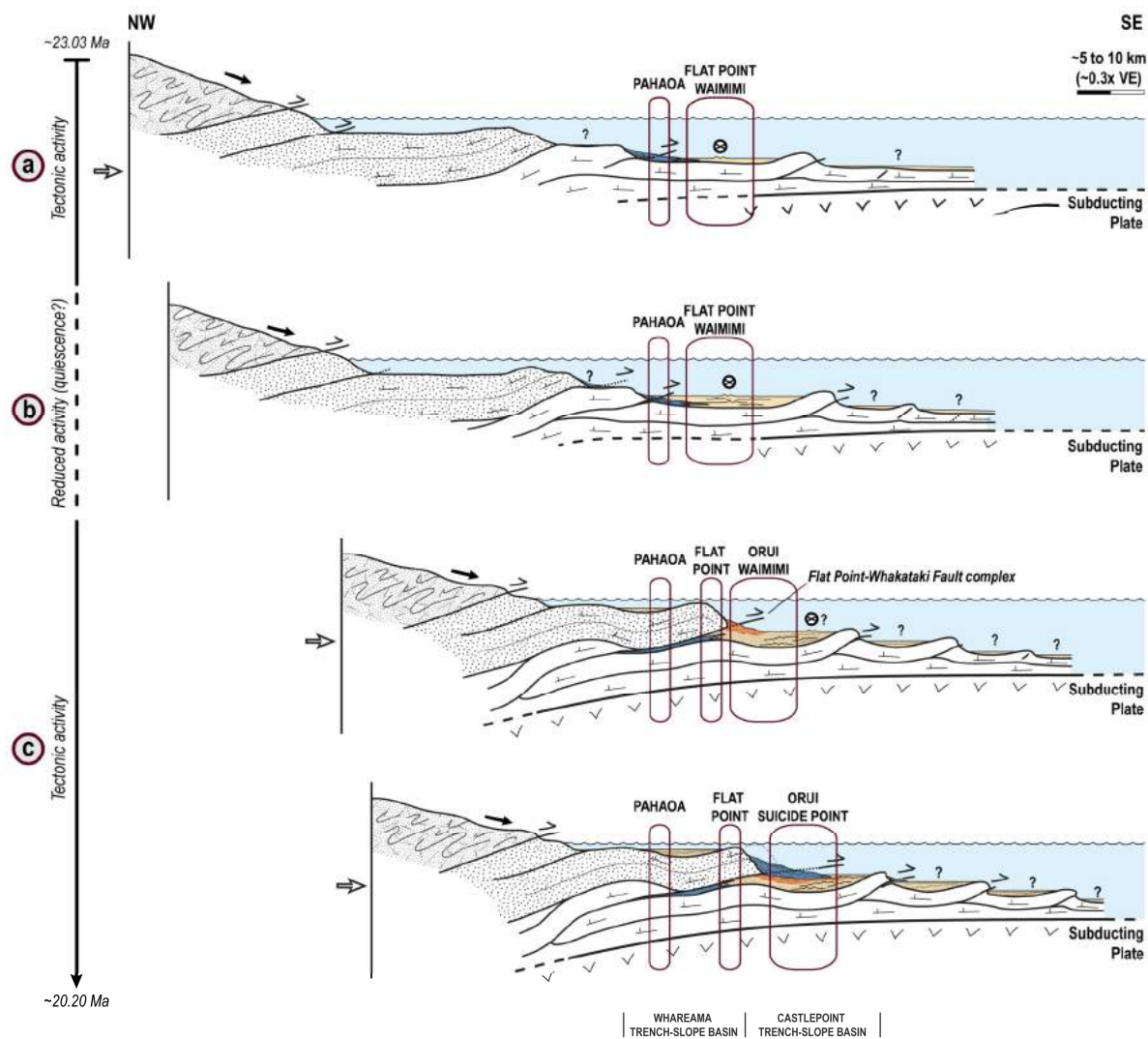
892 Notwithstanding the nature and topography of the overridden substratum as another contributor (*e.g.*,  
893 [Ortiz-Karpf et al. 2017](#)), the source areas here appear to have chiefly controlled the lateral and vertical  
894 variations encountered in both the morphometric parameters (*e.g.*, lateral extent, overall thickness) and  
895 nature of lithoclasts of the MTDs (**Fa3n**, Table 2). The thrust sheet involved not only generated a  
896 specific type of failed material related to the nature of its substrate, but also provided different catchment  
897 sizes from the nappe thickness (Pahaoa vs Orui MTDs) (Figure 14). Contrasting magnitude of mass-  
898 wasting events linked to both regional and local tectonics (*e.g.*, variation in thrust angle, convergent  
899 deformation rate, seismicity) can also be considered to explain the locally varying recurrence, erosive  
900 magnitude and size of the resulting MTDs.

## 901 **5.2. Early stages of trench-slope basin development**

902 At their early stages of development, trench-slope basins are typically narrow (five to 10 kilometers  
903 wide) ([Bailleul et al. 2013](#)). Often located downslope (*i.e.*, towards the base of the lower trench-slope) at  
904 that time, they are supposed to be sedimentologically 'immature' (*sensu* [Underwood and Bachman  
905 1982](#)), being disconnected from the main sediment pathways that cross the margin. The  
906 tectonostratigraphic development of the Castlepoint trench-slope basin, contemporaneous with the  
907 beginning of the subduction, deviates from this model.

908 As previously suggested by [Turnbull \(1988\)](#), [Field \(2005\)](#) and [Sloss et al. \(2021\)](#), the consistent axial  
909 routing of the turbidite paleoflows within the channel-levee system (**Fa1w**, Table 2) outlines the  
910 presence of a sublinear bathymetry to the east, which was likely controlled by an underlying thrust. This  
911 bathymetry formed an outboard basin-bounding structure at the time (earliest Miocene), and thus  
912 provided an elongate shape to the Castlepoint trench-slope basin. The basin likely formed a wide  
913 structural depression in its early stages recording the coeval development of gravity-driven systems at  
914 least ~12 to 15 kilometers apart (minimum orthogonal distance between Pahaoa and Flat Point deposits  
915 nowadays) (Figure 15). The emplacement of the inboard second thrust sheet (*i.e.*, Glenburn Nappe)  
916 produced a shortening with overthrusting of its western part (Figure 15). Such structural control is  
917 intrinsically linked to the initial stages of development of the Hikurangi Margin ([Chanier and Ferrière  
918 1989](#); [Chanier and Ferrière 1991](#); [Rait et al. 1991](#); [Nicol et al. 2007](#); [Bailleul et al. 2013](#); [Bland et al.  
919 2022](#)), characterized by initial deformation of the previous margin and seaward nappe emplacement. It

920 therefore informs that several thrusts can control the development of the tectonically active, sublinear  
 921 bathymetric highs that delineate a trench-slope basin, as also observed elsewhere from offshore  
 922 seismic reflection data (e.g., Nankai: (Gulick et al. 2004) and Hikurangi Margins: (Barnes et al. 2010;  
 923 Bland et al. 2015; McArthur et al. 2019; Griffin et al. 2022)).



**LEGEND**

<b>Pre-subduction - Lower Cretaceous to Uppermost Oligocene</b>	<b>Syn-subduction - Lowermost Miocene</b>	<b>Miscellaneous</b>
Upper Cretaceous to Oligocene detrital unit series	Turbidite systems (Fa1w, otherwise Fa1 s.l.)	Longitudinal siliciclastic input
Upper Cretaceous to Oligocene intermediary to detrital unit series	Debrite-dominated MTDs (Fa3n)	Axial siliciclastic input
Upper Cretaceous to Oligocene pelagic unit series	Slide- to slump-dominated MTDs (Fa3s)	Thrust sheet
Lower Cretaceous Torlesse Supergroup		Compression

924  
 925 Figure 15: Schematic NW-SE cross-sections reconstructing the tectonostratigraphic development of the southern Hikurangi  
 926 subduction wedge during the Early Miocene. These cross-sections specifically focus on the Castlepoint trench-slope basin,  
 927 and highlight the evolution in depositional settings through time, encountered at the Pahaoa, Flat Point, Orui, Waimimi and  
 928 Suicide Point localities described in the text. VE, Vertical exaggeration. Inspired from Chanier (1991).

930 Contemporaneously, mixed gravity-driven sedimentation prevailed during the early fill of the Castlepoint  
931 trench-slope basin, featuring both the emplacement of (1) locally-derived MTDs (**Fa3s**, **Fa3n**) and (2)  
932 hinterland-derived turbidite systems (**Fa1w**) (Table 2; Figure 15). These two contrasting sources of  
933 sediment supply are not only local and from bathyal water depths, but also connected to a perennial  
934 nearshore system, and thus indicate that the trench-slope basin was sedimentologically 'mature' (*sensu*  
935 [Underwood and Bachman 1982](#)) as soon as its initial fill started.

936 This contrasts with the interpretation of [Sloss et al. \(2021\)](#) inferring that the Castlepoint trench-slope  
937 basin was 'immature' (*sensu* [Underwood and Bachman 1982](#)) and instead suggests that the basin floor  
938 of the Castlepoint trench-slope basin was reached by submarine canyons, maintaining their channels  
939 downslope, very early in the history of the convergent Hikurangi margin. Such phenomena may have  
940 been favored by a young, narrow subduction wedge, where the distance down the lower trench-slope  
941 was reduced and with it, the number of active thrust ridges. This would have, in turn, increased the  
942 chances for canyon and or slope channel systems to connect and remain connected with the trench-  
943 slope basins downslope. The coeval episodes of submarine destabilization and collapses, essentially  
944 recorded at the front (*i.e.*, forelimb) of the landward basin-bounding structure however indicates that the  
945 associated thrust ridge(s) remained active, probably still in close proximity with the deformation front.

946 Interestingly, the associated turbidite deposits (**Fa1w**) do not appear strongly influenced by syn-  
947 depositional tectonics, recording the development of a several hundreds of meters thick aggradational  
948 channel-levee system along the Castlepoint trench-slope basin (>50 kilometers long) (Figure 8; Figure  
949 9; Figure 14; Figure 15a, b). This depositional architecture not only contrasts with previous  
950 interpretations inferred for the area now occupied by the southern coastal ranges ([Chanier and Ferrière](#)  
951 [1991](#); [Neef 1992](#); [Bailleul et al. 2007](#); [Sloss et al. 2021](#)) and lower trench-slope basins in general  
952 ([Underwood and Bachman 1982](#); [Underwood and Moore 1995](#)), but also suggests that (1) the  
953 destructive compressional deformation affecting the margin at the time was uneven along the margin  
954 and or that (2) a balance between the controlling parameters (*e.g.*, sea-level changes, tectonics,  
955 sediment fluxes) was locally maintained as demonstrated elsewhere by [McArthur et al. \(2021\)](#) (lobe  
956 deposits of the onshore Akitio and offshore Porangahau trench-slope basins, Hikurangi Margin).

957 Much work has been done on basin floor aggradational channel-levee complexes (*e.g.*, [Kolla et al.](#)  
958 [2007](#); [Armitage et al. 2012](#); [Jobe et al. 2020](#)); and notwithstanding their impact on the sediment supply  
959 or hinterland conditions, sea-level changes are often considered to have limited effects on the vertical  
960 organization of deep-marine channels ([Kolla et al. 2007](#)). Conversely, the feedback mechanism coupling  
961 structure growth and sediment loading proposed by [McArthur et al. \(2021\)](#) can explain the prolonged

962 generation of accommodation in a trench-slope basin and allow continued sediment deposition forming  
963 large-scale aggradational systems.

964 Such a model implies a balanced interaction between load-driven subsidence in the basin and tectonic  
965 activity focused at the bounding structures, whilst providing a relatively stable depocenter within the  
966 basin. This focused tectonic activity (*e.g.*, vertical and or horizontal motion) chiefly controlled the  
967 sediment distribution and architecture in the trench-slope basin (*e.g.*, Vinnels et al. 2010), alternatively  
968 maintaining direct input from the upper slope settings and or promoting remobilization from the  
969 downslope bathymetric highs (Figure 15a, b). Such feedback mechanism therefore suggests that even  
970 during the early stages of structural development of a subduction margin, some 'mature' trench-slope  
971 basin fills can reach a balance between active tectonics and sedimentation.

972 External forcing factors, such as the second event of moving thrust sheets (*i.e.*, Glenburn Nappe),  
973 eventually disrupted the sedimentation-deformation equilibrium and drastically transformed the  
974 sedimentation style recorded within the Castlepoint trench-slope basin (*e.g.*, from a long-lasting  
975 channel-levee system (**Fa1w**) to large-scale MTDs (**Fa3n**)) (Figure 15c).

977 New observations are drawn from this outcrop-based study on the initial development of the Hikurangi  
978 subduction wedge (eastern North Island of New Zealand). The high-resolution analysis of the different  
979 styles of mass-transport deposits (MTDs) and their interactions with a coeval turbidite system permits  
980 fresh insights on the structural evolution and stratigraphic infill of one of the oldest trench-slope basins  
981 (the Castlepoint trench-slope basin) of the Hikurangi subduction zone.

982 MTDs are powerful spatial-temporal markers of geologic events. They have allowed us to discriminate  
983 the nature of the nappes responsible for shedding each MTD, to specify the timing of nappe  
984 emplacement along this part of the margin, and to provide significant clues for understanding the  
985 tectonostratigraphic evolution of both the intra-slope basin and the Hikurangi Margin.

986 (1) The matrix-supported pebbly conglomerates described in this study were produced from  
987 sedimentary processes (*i.e.*, MTDs). Although some were found at the sole of the thrust sheets,  
988 they were not always significantly overprinted by tectonic deformation processes (*i.e.*, tectonic  
989 mélanges). Tectonic reworking of underthrust deposits (*e.g.*, MTDs) should therefore not always  
990 be expected from olistostromal carpet positions, since overpressures at the sole of the overlying  
991 thrust sheet may instead favor their preservation and only result in minor tectonic deformation.

992  
993 (2) Oversteepened slopes at the front of advancing thrust sheets were the main causal mechanism  
994 for the mass-wasting processes described here and resulted in a series of (rather than one)  
995 destabilization events, dominated by mass flows. The thrust sheet involved not only generated  
996 a specific type of failed material related to the nature of its substrate but also provided different  
997 catchment (and resulting deposit) sizes from the nappe thickness. When affecting poorly lithified  
998 sediments however, the thrust faults were seen to control the generation of different styles of  
999 MTDs at their front, showing a vertical partitioning of the mass-wasting processes, (1) first  
1000 dominated by mass movements (*e.g.*, sliding, slumping) and (2) then by mass flows (*e.g.*,  
1001 debris flows). The initial growth and steepening of the thrust forelimb flank promoted the failures  
1002 and mass movements of the poorly lithified sediments deposited at its front, whereas continued  
1003 thrust propagation eventually led to oversteepening, subsequently triggering the recurrent  
1004 failures and gradual dismantlement of its forelimb (and associated core strata) through the  
1005 emplacement of successive mass flows.

1006

- 1007 (3) The associated deposits are essentially captured in close vicinity to the thrust sheet front where  
1008 they form a series of stacked MTDs. Commonly referred to as *detached* systems, they here  
1009 characteristically comprise less than three square kilometers in area and a few kilometers in  
1010 width and length. The Orui and Suicide Point MTDs however show remarkable thicknesses  
1011 (greater than 400 meters). Interestingly, the mass flow deposits record the denudation of their  
1012 source (*i.e.*, thrust sheets) with progressive incorporation through time of clasts in reverse  
1013 stratigraphic order.  
1014
- 1015 (4) Surprisingly for trench-slope basins coeval with the birth of a subduction margin, the early  
1016 stages of their fill development can deviate from the classical models either showing (1) a direct  
1017 connection of the basin with sustainable sediment sources making them 'mature' (*sensu*  
1018 [Underwood and Bachman 1982](#)) very early in the history of the convergent margin, and (2) the  
1019 occurrence of sedimentation-deformation feedback mechanism(s) resulting in the development  
1020 of a several hundreds of meters thick aggradational turbidite system sourced from shallow  
1021 waters and maintained downslope.  
1022
- 1023 (5) The outboard migration of deformation during the Early Miocene period of compressional  
1024 deformation was discontinuous and uneven along the Hikurangi Margin. In the study area, two  
1025 major tectonic events were recorded at one of the trench-slope basin edges, separated by a  
1026 period of reduced tectonic activity. Each tectonic event or pulse lasted approximately of 1 to 2  
1027 Myrs in duration and resulted in seaward motion, oversteepening and frontal denudation of a  
1028 thrust sheet. The second nappe overthrust the preceding, thereby forming a succession of  
1029 two superposed nappes and participating to the overall shortening of the area. As a result, not  
1030 only one but several stacked seaward-verging thrust sheets were observed to control the  
1031 tectonically active sublinear bathymetric high that delineated the landward margin of the  
1032 Castlepoint trench-slope basin at the time.  
1033
- 1034 (6) Finally, important thrust ridges existed since the earliest Miocene, late Waitakian-Otaian. One of  
1035 them, controlled by the underlying Flat Point-Whakataki Fault complex, formed and still forms  
1036 the basin-bounding structure separating the 'Whareama trench-slope basin' (since the earliest  
1037 Miocene, late Waitakian-Otaian) and the 'Akitio trench-slope basin' (since at least the Middle  
1038 Miocene, Altonian) from the 'Castlepoint trench-slope basin', a newly identified sub-basin to the  
1039 East Coast Basin domain, which started to develop contemporaneously with the onset of  
1040 subduction.

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## 9. TABLES

Deposit	Dominant lithology	Lithofacies code	Thickness (cm)	Lithofacies description	Classification and process interpretation
Turbidite	Sandstone to Mudstone	<b>LDTc</b> Tabular, very thin-to medium-bedded sandstone with mudstone cap	1 to 25 (sand) 2 to 100 (mud)	Fine- to medium-grained. Parallel laminations, passing into climbing ripples with sometimes dewatering or soft sedimentation deformation structures installed above. Sometimes only developing the parallel laminations or sometimes directly developing the climbing ripples. Laminations can be highlighted by organic-rich, carbonaceous debris. Sometimes displaying sole marks such as flute casts. Rare bioturbation in the mud cap.	Tb-e Tb-Te Tc-Te Tbc-Te Low-density turbidity currents and hemipelagites
		<b>HDTC</b> Lenticular, medium to very thick-bedded sandstone with mudstone cap	50 to 1,500 (sand) 80 to 2,000 (mud)	Fine- to coarse-grained. Broadly lenticular, slightly to highly erosive, coarse- to very-coarse-grained base, commonly massive and structureless, with sand- to granule-grade clasts (lithoclasts and (elongated) rip-up mudstone clasts), overlain by well-developed parallel and or cross-laminations in the same material, overall normally grading. Followed by commonly very-thick, fine- to medium-grained intervals with well-developed parallel laminations, climbing ripples with frequent dewatering or soft sedimentation deformation structures (convolutes) installed above. Ending with thin regular, wispy and or convolute laminations in silty to very-fine grained material, overlain by normally graded, frequently including patchy silt pseudonodules, to ungraded mudstone cap. Rare bioturbation. Very calcareous, white to pale yellow sandstones. Very frequent amalgamation, commonly arising in the fine- to medium-grained and muddy intervals.	Ta-e High to low-density turbidity currents and hemipelagites
Debrite	Conglomerate	<b>CF</b> Disorganized clast-supported	300 to 600 (2)	Clast-supported, siltstone to silty mudstone with $\leq 90\%$ of granule- to boulder-grade extra- and intraformational clasts. Ungraded, disorganized. Common load structures.	/ Cohesionless debris flow
		<b>DF</b> Disorganized matrix-supported	200 to 300 (1) 150 to > 20,000 (2)	Matrix-supported, siltstone to silty mudstone with varying quantity of granule- to boulder-grade extra- and intraformational clasts. Ungraded, disorganized. Common recumbent folds, shear and load structures. Traction carpet possible.	/ Cohesive debris flow

		<b>MF</b> Disorganized matrix-supported	150 to > 20,000 (2) Matrix-supported, dominated by $\leq 95\%$ of silty mudstone to mudstone, otherwise including granule- to boulder-grade extra- and intraformational clasts. Ungraded, disorganized. Common recumbent folds, shear and load structures. Traction carpet possible.	/ Cohesive mudflow
Displaced or contorted strata	Alternating sandstone and mudstone	<b>SL-a</b> Deformed mass of sediments	100 to > 10,000 Contorted, remobilized facies characterized by recumbent folds. When present, sandy to silty mudstone background facies.	/ Soft-sediment deformation: (1) gravity-driven = coherent mass of sediment that moves along a glide plane, resulting in significant internal deformation, <i>i.e.</i> , slump; or (2) tectonic-driven = folding
		<b>SL-b</b> Undeformed mass of sediments	1,000 to > 10,000 Coherent, remobilized facies displaying sharp truncations, slightly concave-up geometries with downlap.	/ Soft-sediment deformation: (1) gravity-driven, initiation of movement of a coherent mass of sediment along a glide plane, no to very little internal deformation, <i>i.e.</i> , slide; or (2) tectonic-driven

Table 1: Lithofacies encountered at the Pahaoa, Flat Point, Orui, Waimimi and Suicide Point-Mataikona coastal outcrops. See Figure 7 for representative photographs of each lithofacies. (1) Conglomerates observed at Pahaoa, Flat Point and Waimimi, (2) conglomerates observed at Orui and Suicide Point. 'Classification' column refers to Bouma (1962), Stow and Shanmugam (1980) and Lowe (1982).

Depositional system	Facies association code	Facies association sub-code	Facies assemblage description	Thickness (m)	Interpretation
Turbidite system	Fa1	Fa1w	HDTC interbedded with LDTC. HDTC frequently amalgamated, with thick mud caps, and truncating underlying LDTC. LDTC frequently displaying wedging geometries with low-angle downlap terminations within interval or onto HDTC mud caps. Occasionally interrupted by standalone DF from coevally developing mass-wasting system (Fa3n). Common shear zones.	400 (Waimimi-2) 270 (Waimimi-1) 100 (Flat Point)	Channel-levee system
Mass-wasting system	Fa3	Fa3n	Intertwined, coalescing DF and MF, reworking extraformational lithoclasts derived from the pre-subduction margin series and intraformational lithoclasts from the contemporaneously developing syn-subduction strata. Rare CF. Common ductile and brittle-ductile deformation fabrics.  <i>First style:</i> mostly (>80%) Paleocene and Eocene extraformational clasts from pelagic units. Coeval to Fa1w.  <i>Second style:</i> Cretaceous to Eocene extraformational clasts from intermediary units, overall being incorporated progressively in a reverse stratigraphic order. Overlying Fa1w.	<i>First style</i> up to 3 (Waimimi, Flat Point) 40 (Pahaoa)  <i>Second style</i> ~500 (Suicide Point) 400 to 900 (Orui)	Dismantlement of advancing thrust sheet  <i>First style:</i> from thrust sheet developed in the pelagic units of the pre-subduction margin series  <i>Second style:</i> from thrust sheet developed in the intermediary units of the pre-subduction margin series
		Fa3s	Intertwined SL-a and or SL-b. Varying folding styles including widely open upright folds, narrow recumbent folds as well as curvilinear and rootless folds. Preferential general direction of fold axis and hinge. Underlying Fa3n.	300 (Orui)	Large-scale soft-sediment deformation of the previously deposited and poorly lithified sediments linked to advancing thrust nappe

Table 2 : Facies associations encountered at the Pahaoa, Flat Point, Orui, Waimimi and Suicide Point-Mataikona coastal outcrops. See Figure 8, Figure 9, Figure 11, Figure 12 and Figure 13 for representative photographs of each facies assemblage. The nomenclature leverages and complements the one that was defined by Bailleul et al. (2007) and Bailleul et al. (2013), and where **Fa1** are associated to turbidite systems and **Fa3** to mass-wasting deposits.

## 10. SUPPLEMENTARY MATERIAL

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Supplementary data, namely Appendix 1 to 5, to this article can be found online at <https://doi.org/10.1016/j.marpetgeo.2023.106191>.

Appendix 1: Enlarged view of the southern part (w-1) of the Waimimi outcrop model, annotated with detailed paleocurrent analysis for each of the channel and levee-overbank settings (see Figure 5 for exact location of w-1 section).

Appendix 2: Enlarged view of the northern part (w-2) of the Waimimi outcrop model, annotated with detailed paleocurrent analysis for each of the channel and levee-overbank settings (see Figure 5 for exact location of w-2 section).

Appendix 3: Sample list for the Castlepoint trench-slope basin outcrops. The Fossil Record numbers including "T27" and "U26" respectively relate to the T27 and U26 New Zealand Map Grid 1:50,000 series and are captured in the Fossil Record Electronic Database FRED (<https://fred.org.nz/>) (Clowes et al. 2021). The Fossil Record numbers including "CZ" come from Chanier (1991) and are unpublished in FRED. See the respective Table 1 for the description of the lithofacies codes. The age of the sedimentary units and the paleobathymetries were defined using micro and macropaleontological analyses conducted by GNS Science New Zealand. (Jenkins 1971; Hornibrook et al. 1989; Scott et al. 1990; Cooper 2004; Pearson et al. 2006) and GNS file were used for the foraminiferal age determinations, and (Hayward and New Zealand Geological Survey Paleontology Group 1986; van Morkhoven et al. 1986; Crundwell et al. 1994; Hayward et al. 2012) and GNS file for the paleodepth interpretations. The general margin of error for the paleodepth interpretations is 30 meters error for 0 to 200 meters, 50 meters error for 200 to 600 meters, 100 meters error for 600 to 1000 meters and 200 meters error above 1000 meters.

Appendix 4: Thin section photographs from sample 20\_12\_09 corresponding to a limestone clast taken in the Orui mass-transport deposits, and more particularly in the mass-transport deposits d2 (see Figure 11, d2; Appendix 3). The identification of pithonellids (p) allows to discard an origin from the Paleocene limestones and instead suggests reworking of the Upper Cretaceous pithonellid-bearing limestones previously identified along the coastal ranges by (Chanier et al. 1990).

Appendix 5: Morphometric parameter calculations for the Pahaoa, Flat Point, Orui and Suicide Point mass-transport deposits using the equations from (Moscardelli and Wood 2015), where V = volume, A = area, L = length, T = thickness. (d) indicates that these equations were specifically created for *detached* mass-transport deposits.