Supplement

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A1 Description of section localities, with notes on sources of data and paleobathymetry

The onshore stratigraphic sections included in this study extend from the allochthonous remnants of North Slope Basin sediments outcropping in Black's Quarry in northernmost New Zealand to the southernmost onshore record of Waipawa organofacies within the Waipara Greensand in the mid-Waipara section in the northern Canterbury Basin (Fig. S1). An onshore drillhole in southeastern North Island (Orui-1A) is also included. Offshore records of Waipawa organofacies incorporated into this study include exploration drillholes in Canterbury and Great South basins and ODP Site 1172. As discussed by Hollis et al. (2014), Waipawa organofacies has been identified in several formal lithostratigraphic units, including the Waipawa Formation, the Te Uri Member of the Whangai Formation, the Waipara Greensand, the Tartan Formation (Fig. S2).

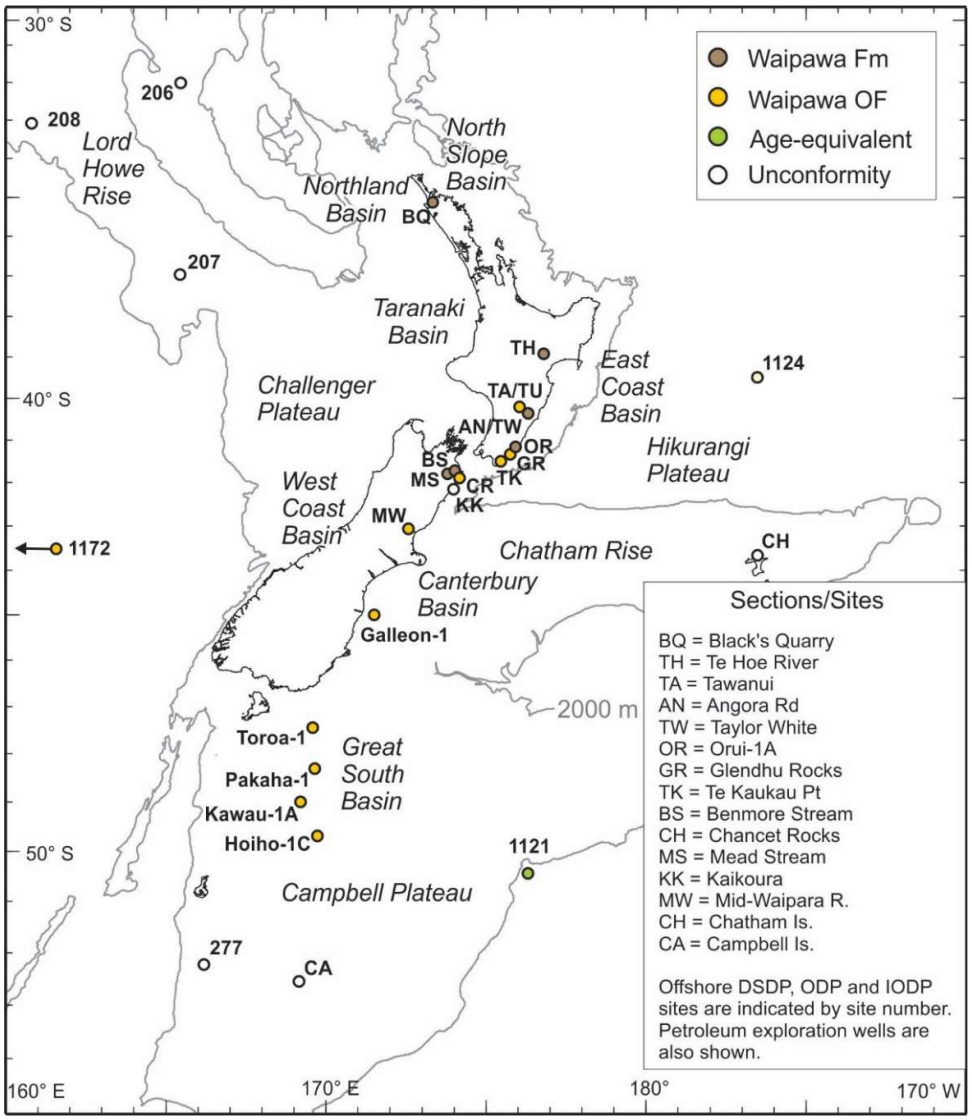

Figure S1. Localities of study section and drillhole sites on present-day map of New Zealand and Tasman Sea region. Sites in which Waipawa organofacies occurs within the Waipawa Formation (brown circles) are differentiated from sites where the organofacies occurs within other formations or formal formation names have not been used (yellow circles). Age-equivalent sedimentary records that do not include Waipawa organofacies (green circles) and sites with unconformities that span Waipawa deposition are also shown (white circles).

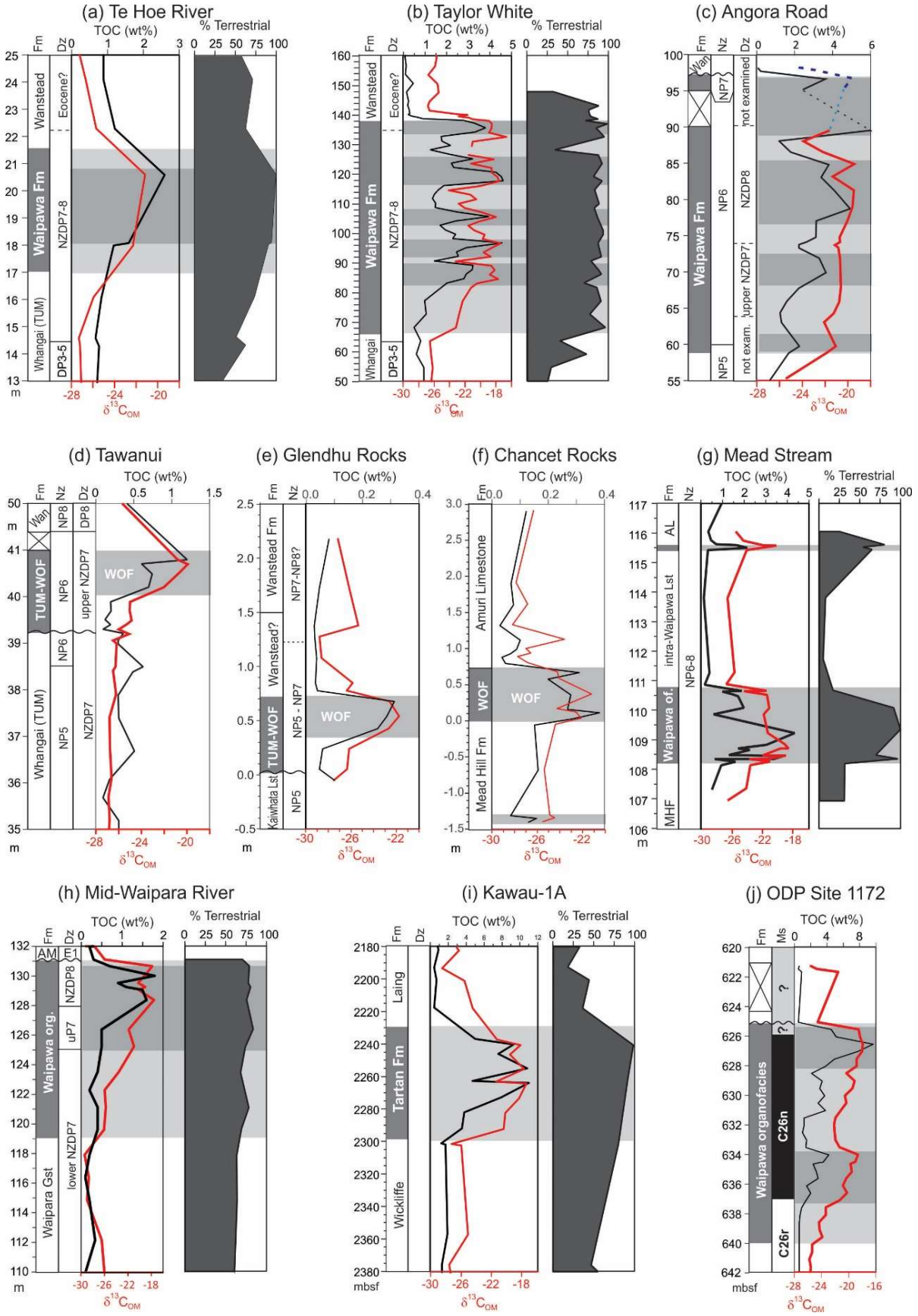

Figure S2. Stratigraphic summary and variation in TOC, $\delta^{13}C_{OM}$ and the percentage of terrestrial palynodebris for representative sections containing Waipawa organofacies. Palynofacies data available only for selected sites. Note differences in scale between sections.

The information described below is summarised in Table S1.

a. **Black's Quarry**. At this locality in Doubtless Bay, Northland (34°59'17'' S, 173°23' E), Waipawa Formation has been quarried for roading. The lithology is massive silty mudstone with sulfur efflorescence. Bedding has not been identified with confidence. Eleven samples were collected as representing the range of lithologies (Hollis et al., 2006). The formation is part of the Northland Allochthon (Isaac et al., 1994). Although contacts with bounding units were not observed, elsewhere in Northland the formation overlies Whangai Formation (Isaac et al., 1994). In Northland, Whangai Formation is a relatively uniform siliceous mudstone inferred to have been deposited in upper to mid-bathyal depths (Isaac et al., 1994). In the present study, palynofacies analysis was carried out on five samples, carbon stable isotope analysis was carried out on 11 samples and bulk pyrolysis was carried out on two representative organic-rich samples (Table S2).

b. **Te Hoe River**. Stratigraphic description and geochemical data (Table S2) from Hollis and Manzano-Kareah (2005). Palynofacies data from Schiøler et al. (2010). In the nomenclature of Moore (1988), this section lies in the western (proximal) facies of the Whangai Formation and is inferred to have been deposited at shelf depths, possibly mid-shelf in the Paleocene (Wilson and Moore, 1988).

c. **Tawanui**. Stratigraphic description and geochemical data (Table S2) from Hollis et al. (2014). Upper Cretaceous and Paleocene foraminiferal assemblages indicate deposition at upper to mid-bathyal water depths (500–1000 m) (Kaiho et al., 1996).

d. **Taylor White**. Stratigraphic description and primary geochemical and palynofacies data (Table S2) from Naeher et al. (2019). The present study includes additional analysis of selected samples, namely palynofacies analysis and carbon stable isotope geochemistry of density fractions (Table S3), compound specific isotope analysis of aromatic and saturated hydrocarbons, including pristane, phytane and *n*-alkanes (Table S4). Foraminiferal assemblages indicate progressive deepening during deposition of the Waipawa Formation, from upper to middle or lower bathyal depths (Naeher et al., 2019). An outermost shelf–upper bathyal setting for the underlying Whangai Formation is extrapolated from the nearby Angora Road section (Leckie et al., 1995).

e. **Angora Road**. Stratigraphic description and geochemical data (Table S2) from Hollis et al. (2014). Foraminiferal assemblages indicate the underlying Paleocene Whangai Formation was deposited at outer shelf to upper bathyal water depths (Leckie et al., 1995).

f. **Orui-1A drillhole**. Stratigraphy and geochemical data (Table S2) from Field et al. (2018). The drillhole recovered lowermost Wanstead Formation and a ~90 m-thick interval of Waipawa Formation. The base of the formation and underlying formation were not sampled. Foraminiferal assemblage studies have not been undertaken. The location of the section in the eastern margin of the East Coast Basin (Fig. S1) suggests a distal depositional setting, probably upper to middle bathyal (Moore, 1989; Field et al., 1997).

g. **Glendhu Rocks (Pahaoa River mouth)**. This is a new record of Waipawa Formation (Fig. S3a, b), which was identified and described by Tayler (2017). The section outcrops on the coast of southern Wairarapa (41°23'22'' S, 175°44'50" E). Waipawa Formation forms a thin mudstone interval within the micritic Kaiwhata Limestone (van den Heuvel, 1960), a correlative unit to the Mungaroa Limestone to the south (Hines et al., 2013). Both units are inferred to have been deposited at middle to lower bathyal water depths (Field et al., 1997). Geochemical analysis (bulk carbon isotope and source rock analysis) was carried out on 14 samples (Table S2).

h. **Chancet Rocks**. This is a new exposure of Waipawa organofacies (Fig. S3c), adjacent to the Chancet Rocks scientific reserve, coastal Kaikoura District (41°49' 57'' S, 174°11'45" E). The shore platform exposure is the result of uplift during the 2014 Kaikoura earthquake. The exposure lies seaward of the Paleocene pink limestone, containing paramoudra, described by Strong (1984; see also Hollis, 1997). Waipawa organofacies here is a 0.7 m-thick interval of dark grey, thin-bedded calcareous porcellanite. Contacts are sharp with underlying and overlying units, both of which comprise light grey micritic limestone. Based on stratigraphic relations at Mead Stream (Hollis et al., 2005), the

underlying unit is correlated with the uppermost Mead Hill Formation and the overlying unit is correlated with the basal Amuri Limestone. A biostratigraphic study has not been undertaken of this newly exposed upper part of the Chancet Rocks section. Previous studies indicate that the underlying pink limestone is of late early Paleocene age (Hollis, 1993). Geochemical analysis (carbon isotope and source rock analysis) was carried out on 20 samples. This section is in the distal part of the Muzzle Group shelf-to-basin profile described by Reay (1994) and, therefore, is presumed to represent a similar depositional setting to the Ben More Stream section, i.e., middle to lower bathyal depths.

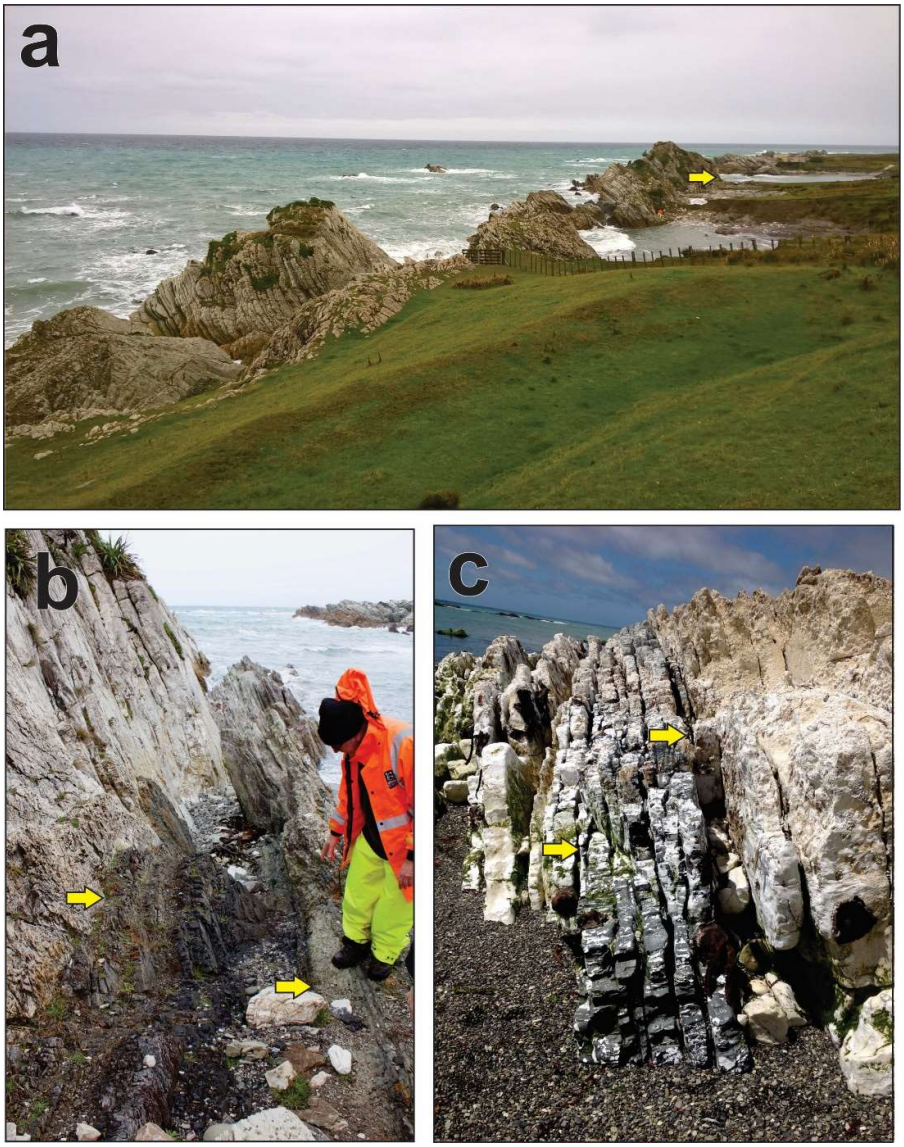

Figure S3. Waipawa organofacies at Glendhu and Chancet Rocks, showing (a) location of Glendhu Rocks section (yellow arrow), north of Pahaoa River mouth, eastern Wairarapa, (b) exposure of Waipawa organofacies within Kaiwhata Limestone, Glendhu Rocks, and (c) exposure of Waipawa organofacies between Mead Hill Formation and Amuri Limestone, Chancet Rocks, eastern Marlborough. Yellow arrows indicate base and top of unit in (b) and (c). Photos: E. Dallanave (a), C. Boulton (b) and H. Thompson (c).

i. **Ben More Stream**. This is a new record of Waipawa Formation discovered by Naeher and Strong (2017) in deeply dipping Muzzle Group strata in Ben More Stream, Kekerengu River valley, Kaikoura District (Fig. S4; 41°58’23” S, 174°00’39” E). Waipawa Formation is exposed as a 1.2 m thick dark grey mudstone bounded by micritic limestone similar to the occurrence of Waipawa Formation at Mead Stream (Hollis et al., 2005, 2014), where the underlying

limestone is correlated with the Mead Hill Formation. A significant difference from Mead Stream, however, is that the unit does not appear to be siliceous and chert nodules were not noted in the underlying or overlying limestone. At Mead Stream the overlying limestone is correlated with the Amuri Limestone. A second, 20 cm-thick, dark grey mudstone layer located 1 m above the base of the Amuri Limestone is reminiscent of a similar layer at Mead Stream. However, a sample collected from the unit lost its dark colour once it dried and appeared more similar to the surrounding limestone. Geochemical analysis (carbon isotope and source rock analysis) was carried out on 10 samples. This section is in the distal part of the Muzzle Group shelf-to-basin profile described by Reay (1994) and, therefore, is presumed to represent a deeper depositional setting than Mead Stream is likely, i.e., middle to lower bathyal depths.

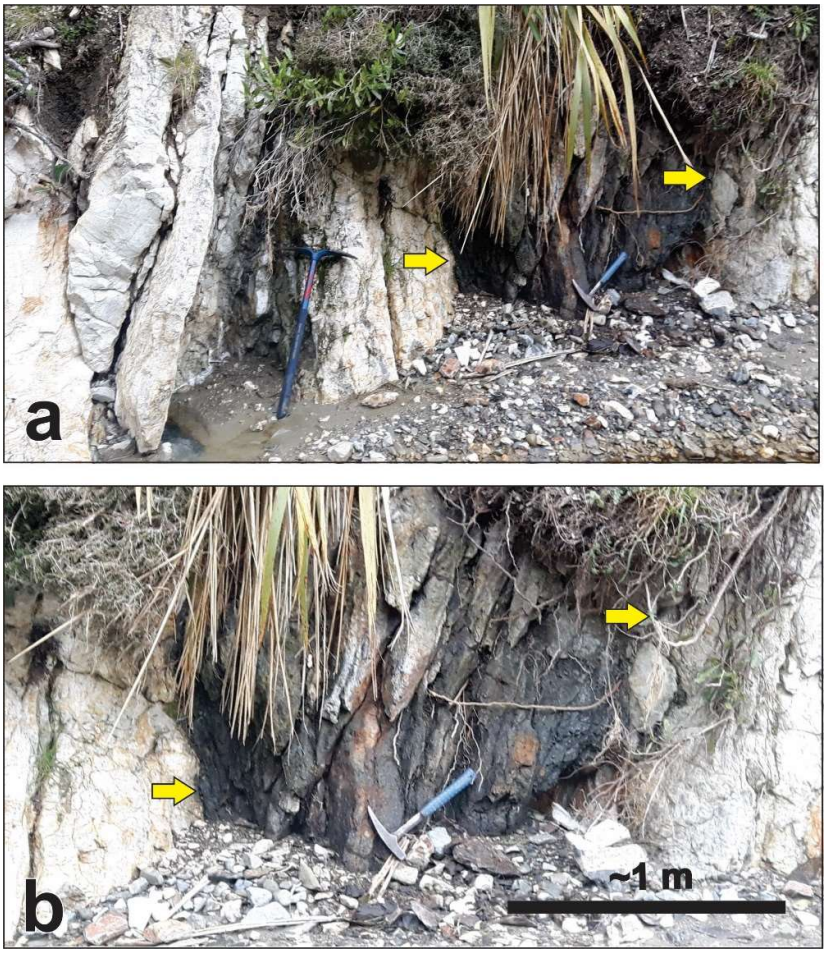

Figure S4. Waipawa Formation at Ben More Stream, showing (a) relationship with underlying and overlying units and (b) close-up of Waipawa Formation. Base and top of formation are indicated by yellow arrows. Section youngs from right to left. Photos: S. Naeher.

j. **Mead Stream**. Waipawa Formation is well exposed at Mead Stream, where it overlies the Mead Hill Formation and is succeeded by the Amuri Limestone (Hollis et al., 2005). Preliminary stratigraphy and geochemistry from Hollis et al. (2014). In this study, we have revised the stratigraphy based on new stable isotope data and carried out additional geochemical and palynofacies analysis. Foraminifera indicate that the upper Mead Hill Formation, which underlies Waipawa Formation, was deposited in upper to middle bathyal depths (Strong et al., 1995; Hollis et al., 2005).

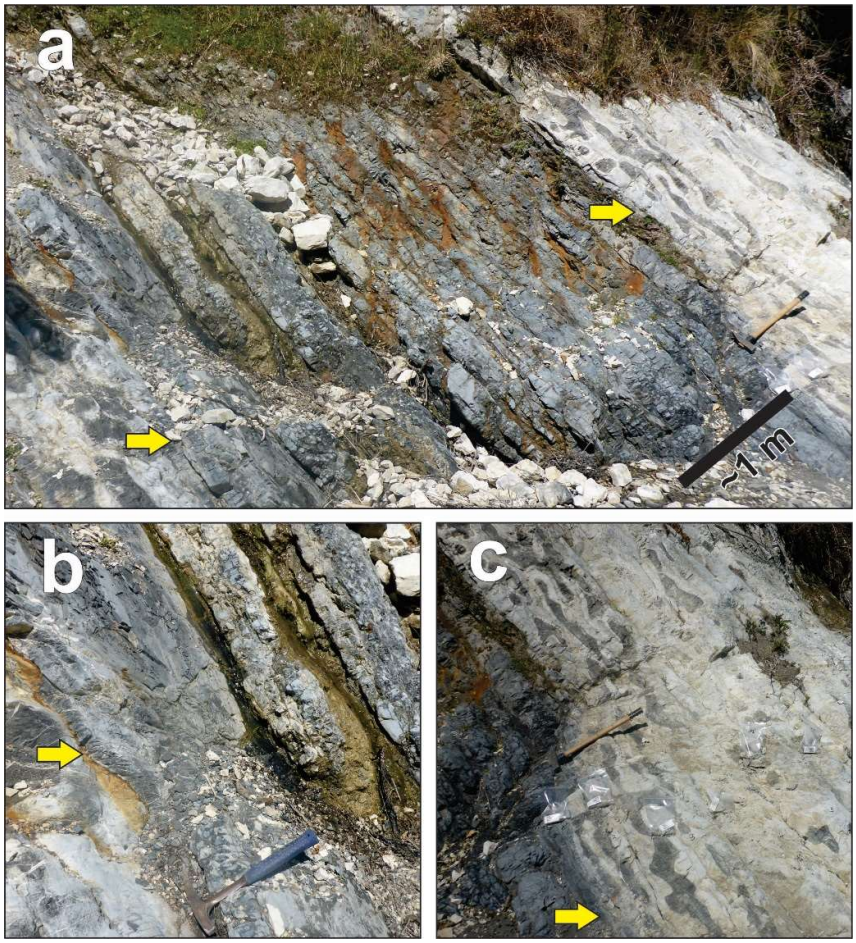

Figure S5. Waipawa Formation at Mead Stream, showing (a) complete unit (60 cm hammer handle for scale), (b) basal contact with Mead Hill Formation (at hammer head), and (c) upper contact with Amuri Limestone Formation (at hammer head). Base and top of Waipawa Formation indicated by yellow arrows. Section youngs from left to right. Photos: C. Hollis

k. **Mid-Waipara River**. The stratigraphy of this section and bulk sediment geochemistry was outlined by Hollis et al. (2014). In this study we have carried out palynofacies analysis on 23 samples and include results from compound specific isotope analysis of fatty acids undertaken by Taylor (2011). The Paleocene Waipara Greensand is inferred to have been deposited at outer shelf depths (Field et al., 1989).

l. **Galleon-1 drillhole.** Palynofacies data are from Schiøler et al. (2010). Foraminiferal assemblages indicate an inner to mid-shelf setting for units underlying and overlying Tartan Formation (Schiøler, 2011).

m. **Toroa-1 drillhole**. The stratigraphy of this drillhole was reviewed by Raine et al. (1993). Geochemical and palynofacies data used in this study are derived from Schiøler et al. (2010). Foraminiferal assemblages (Raine et al., 1993) indicate that the depositional setting shallowed from middle shelf to inner shelf or nearshore during Tartan Formation deposition (disappearance of *Bathysiphon*, persistence of *Cyclammina* and *Budashaevalla*) and then deepened to outer shelf (return of *Bathysiphon*, together with *Bolivinopsis spectabilis*). Depth assignments for all four Great South Basin drillholes in this study are from Hayward (1986).

n. **Pakaha-1 drillhole**. The stratigraphy of this drillhole was reviewed by Raine et al. (1993). Geochemical and palynofacies data used in this study are derived from Schiøler et al. (2010). Foraminiferal assemblages (Raine et al., 1993) are indicative of a middle shelf setting prior to, during and following Waipawa deposition (presence of *Bolivinopsis spectabilis and Alabamina creta* in addition to *Cyclammina* and *Budashaevella*). There is no evidence for shallowing during Waipawa deposition.

o. **Kawau-1A drillhole**. The stratigraphy of this drillhole was reviewed by Raine et al. (1993). Geochemical and palynofacies data used in this study are from Schiøler et al. (2010). Sparse foraminiferal assemblages comprising *Cyclammina* and *Budashaevella* (Raine et al. 1986) indicate a nearshore-inner shelf setting prior to, during and following Waipawa deposition. There is no evidence for shallowing during Waipawa deposition.

p. **Hoiho-1C drillhole**. The stratigraphy of this drillhole was reviewed by Raine et al. (1993). Geochemical and palynofacies data used in this study are from Schiøler et al. (2010). Foraminiferal assemblages comprising *Cyclammina*, *Budashaevella* and *Bolivinopsis spectabilis* (Raine et al. 1986) indicate an inner to middle shelf setting prior to, during and following Waipawa deposition. There is no evidence for shallowing during Waipawa deposition.

q. **ODP Site 1172**. Stratigraphy and geochemical data are from Hollis et al. (2014). In the present study, palynofacies analysis was carried out on selected samples for which source rock analysis was previously undertaken. A shelf setting is inferred.

A2 Correlation and age of Waipawa organofacies

The onset of Waipawa organofacies deposition is identified by a positive shift in $\delta^{13}C_{OM}$, which tends to coincide or to be followed by a gradual increase in TOC (Fig. S2). The onset was found to occur within calcareous nannofossil zone NP6 and near the base of magnetochron C26n (Hollis et al., 2014; Kulhanek et al., 2014). These constraints indicate an age for the onset of Waipawa organofacies of ~59.3 Ma. This is also the age of the early late Paleocene event (ELPE) and the base of the Paleocene carbon isotope maximum (PCIM) (Barnet et al., 2019). The termination of Waipawa deposition is harder to pinpoint because in all records examined it coincides with an obvious unconformity or a sharp shift in geochemical tracers suggesting a hiatus. Nannofossil age control indicates that the termination lies within zones NP7–NP8, i.e. between 58.97–57.22 Ma.

The Mead Stream section contains the most complete known record of Waipawa organofacies in a distal setting (Fig. S5a), with a gradational base (Fig. S5b) and sharp but potentially conformable top (Fig. S5c). It has the added advantage of a having bulk carbonate $\delta^{13}C$ record that is known to parallel benthic and bulk carbonate records in deep sea sediment cores (Hollis et al., 2005; Nicolo et al., 2007; Slotnick et al., 2012). We have identified five carbon isotope excursions (CIEs) in the bulk carbonate $\delta^{13}C$ record at Mead Stream that allow us to develop an age model for the Paleocene interval spanning Waipawa organofacies (Fig. S6): ELPE, 59.3 Ma; the unnamed "asterisk" event of Littler et al. (2014; Barnet et al., 2019), 58.15 Ma; the B2 CIE, 57.25 Ma; the C1 CIE, 56.9 Ma and the PETM, 55.93 Ma. Alternative correlations are possible, but the age model selected is in best agreement with biostratigraphy for the section (Hollis et al., 2005), age control from other sections (i.e., Hollis et al., 2014), does not require major changes in sediment accumulation rate within uniform lithofacies, and retains a consistent relationship with the record from ODP Site 1262 in which Mead Stream $\delta^{13}C$ values tend to be slightly more depleted. The resulting age model provides a precise age estimate for Waipawa organofacies of 59.2–58.4 Ma, which is similar in duration but slightly younger than previous estimates (Hollis et al., 2014).

In contrast to many other sections (Fig. S2), we find no sedimentary evidence for an unconformity at the top of the Waipawa Formation at Mead Stream (Fig. S5c). The extreme negative CIEs associated with the Waipawa interval and the "asterisk" event are artefacts of contamination in low carbonate/high organic facies and should not be interpreted as hyperthermals (Fig. S7). Nevertheless, the carbonate-rich samples within the latter event represent a modest negative CIE that is equivalent in scale to the CIE at ODP site 1262. It is uncertain if the Waipawa Formation within this CIE is a second expression of a short-lived "Waipawa" event or redeposition of sediments from the main "Waipawa" event. With further high-resolution sampling and analysis, it may be possible to correlate variation in bulk organic and compound-specific $\delta^{13}C$ within Waipawa

Formation with the deep-sea carbonate isotope record. In this study, however, we only correlate the base and top of the unit here (Fig. S7).

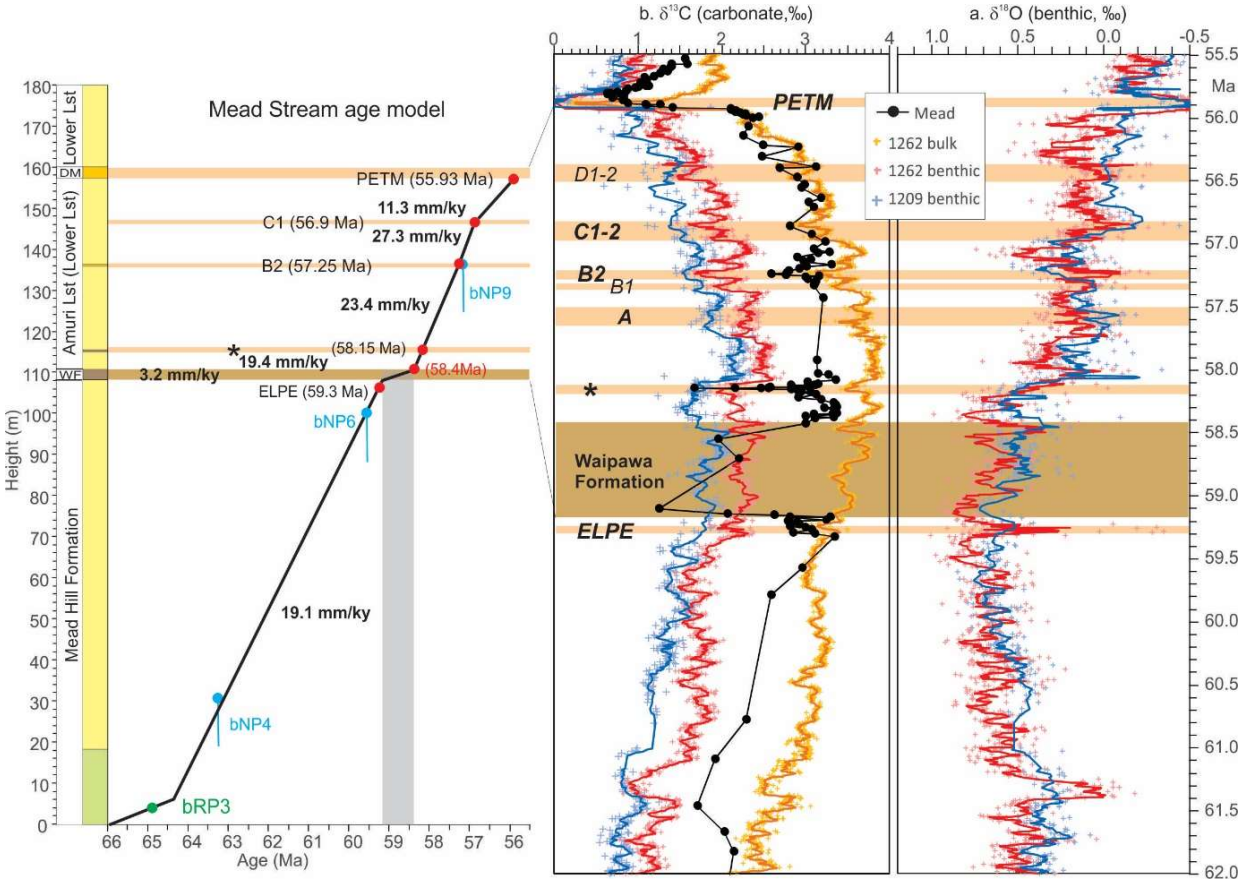

Figure S6. Age model for the Paleocene Mead Stream section (left panel) and correlation of bulk carbonate $\delta^{13}C$ record with bulk carbonate and benthic foraminiferal $\delta^{13}C$ records at ODP sites 1262 and 1208 (middle panel) and benthic foraminiferal $\delta^{18}O$ record from ODP sites 1262 and 1209. Paleocene carbon isotope excursions (CIEs) *, A, B1, B2, C1-2, D1-2 are identified in addition to the early late Paleocene event (ELPE) and the Paleocene-Eocene thermal maximum (PETM).

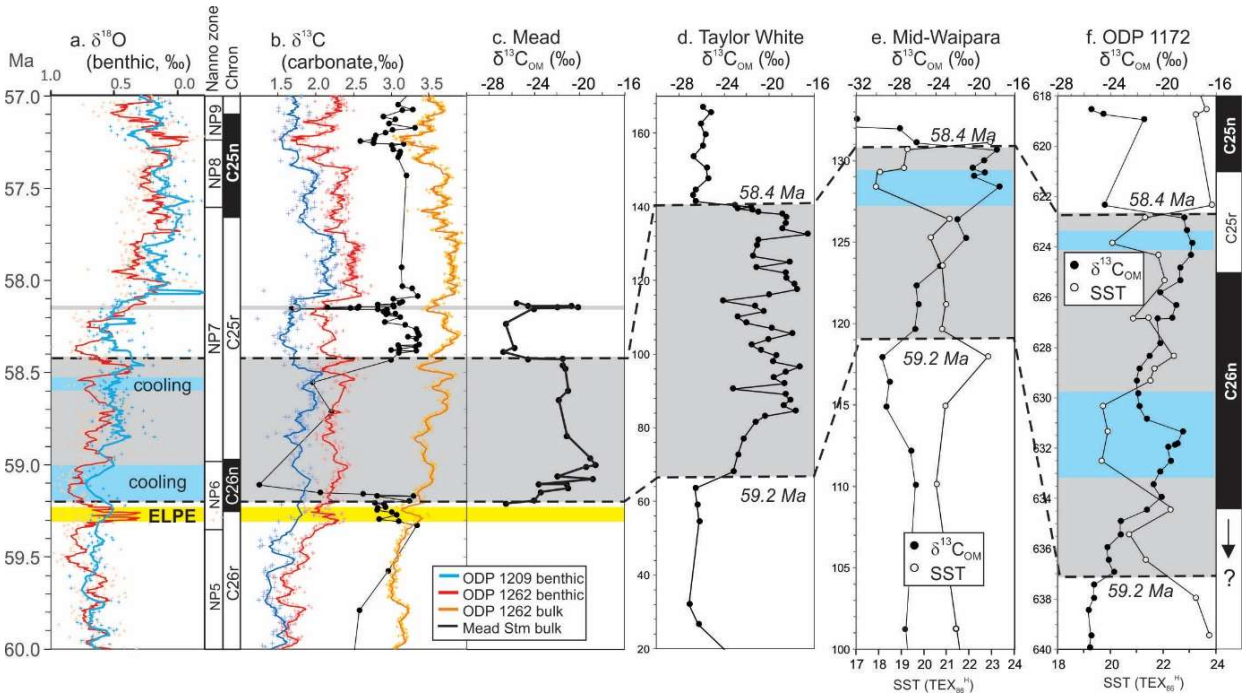

Figure S7. Correlation of deep-sea benthic foraminiferal oxygen and bulk carbonate carbon stable isotope records with Waipawa organofacies and $\delta^{13}C_{OM}$ and TEX_{86}-SST records at selected study sites.

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A3 Correlation between $\delta^{13}C_{OM}$ and TEX_{86}

The correlation between $\delta^{13}C_{OM}$ and the TEX_{86} proxy for sea surface temperature (SST) in the mid-Waipara section and ODP Site 1172 was noted by Hollis et al. (2014). Here we show that there is a stronger correlation between TEX_{86} and higher plant biomarkers at mid-Waipara (i.e., $C_{28–30}$ *n*-alkanoic or fatty acids).

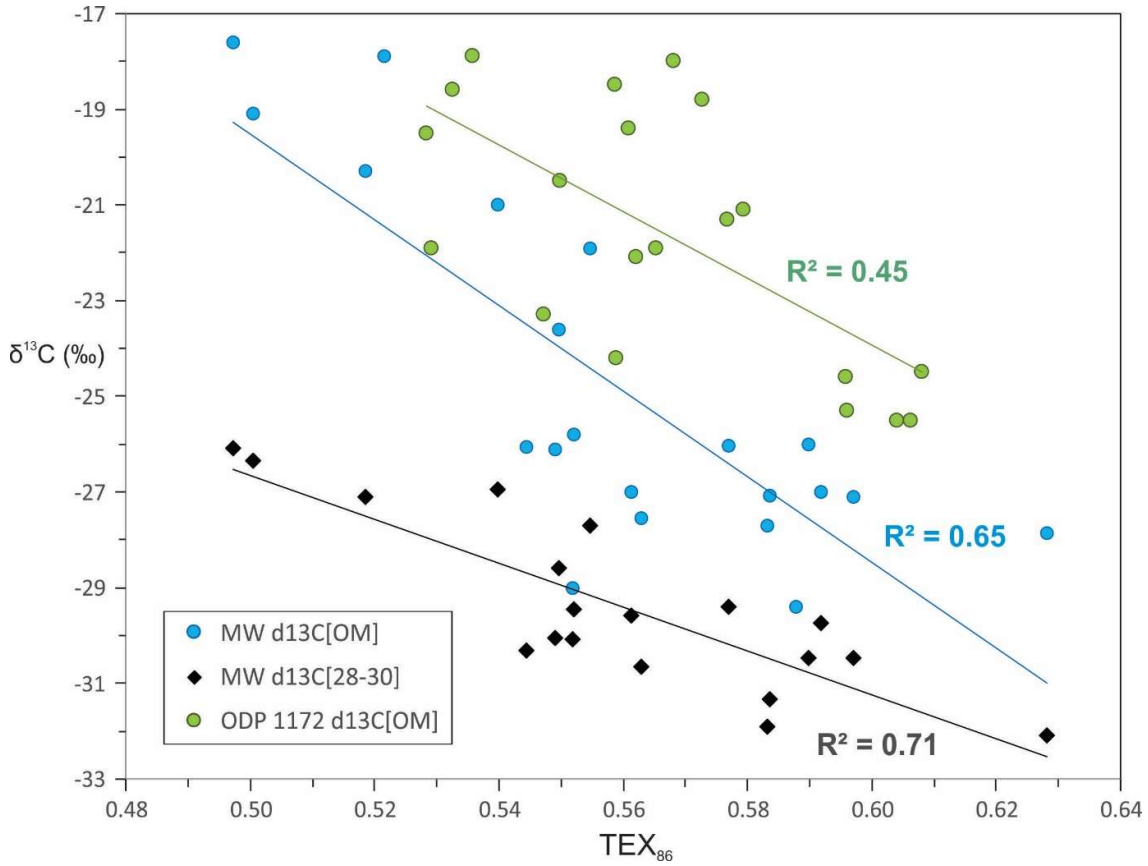

Figure S8. Cross-plot of TEX_{86}-SST proxy and $\delta^{13}C$ (bulk organic matter and $C_{28–30}$ fatty acids) at mid-Waipara and ODP Site 1172. TEX_{86} data from Hollis et al. (2014).

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