Age and depositional environment of the Tartan Formation, a potential source rock in the Great South Basin

P. Schioler, L. Roncaglia

GNS Science, 1 Fairway Drive, Avalon, P.O. Box 30368, Lower Hutt 5040, N.Z. Email: p.schioler@gns.cri.nz, l.roncaglia@gns.cri.nz

Abstract

A detailed palynological analysis of sidewall core samples taken from below, within and above the Tartan Formation in the four Great South Basin wells Hoiho-1C, Kawau-1A, Pakaha-1 and Toroa-1 shows that the Tartan Formation is positioned in the Thanetian (Upper Paleocene) NZP5 dinoflagellate zone, corresponding to the international nannofossil zones NP7–9a, somewhat below the Paleocene-Eocene boundary and at the same stratigraphic level as the Waipawa Formation of the East Coast Basin.

Palynofacies analysis of samples from the upper part of the underlying Wickliffe Formation shows that they contain a mixed assemblage of marine algae and terrestrially derived plant material and indicates deposition in a proximal, probably shallow-water, oxic to suboxic marine environment. The Tartan Formation itself is characterised by very high percentages of degraded brown phytoclasts and rare marine algae and was deposited in a marginal marine, proximal, oxic to dysoxic environment. The lower part of the overlying Laing Formation is dominated by marine algae and amorphous organic matter and is relatively poor in terrestrially derived kerogen, and was deposited in an open marine, oxic to suboxic setting, relatively far from the shoreline.

The palynofacies changes observed may be best explained as a result of base-level changes in a shallow-water epeiric sea. The Tartan Formation was deposited in the central, southern and eastern parts of the basin during a peak regression in the Thanetian that terminated an overall Paleocene agradational to regressive trend and gave way to a latest Paleocene–Eocene transgression. The apparent absence of the Tartan Formation from coastal Otago and the proximal offshore wells Rakiura-1, Tara-1 and Takapu-1A is most likely due to sediment bypass and/or erosion.

Implications for hydrocarbon exploration potential are that the Tartan Formation may have a larger offshore distribution area than previously thought, and that its kerogen is likely to be gas prone rather than oil prone.

Keywords: *Tartan Formation, Great South Basin, Upper Paleocene, petroleum source rock, biostratigraphy, palynofacies, sequence stratigraphy.*

Introduction

The Tartan Formation is a 30–57 m thick, dark brown-coloured mudstone occurring in five of the eight Great South Basin (GSB, Fig. 1) wells: Hoiho-1C, Kawau-1A, Pakaha-1, Pukaki-1 and Toroa-1 (Table 1), sandwiched between the Wickliffe and Laing Formations (Fig. 2). On petrophysical logs, the Tartan Formation has a characteristic tripartite gamma ray (GR) log pattern with GR highs in its basal, middle and uppermost part (Fig. 3). The middle GR high is typically thickest and associated with velocity and density minimums. GR highs in Paleocene well section underlying the Tartan

Formation have a much lower response level and are generally associated with high velocity and density readings (Fig. 3). With TOC values commonly in the range 4–8 %, it is an excellent potential source rock for hydrocarbons. Although considered immature over most of the basin, it has probably been expelling oil since the Oligocene in the deepest part of the basin (Sutherland et al., 2002).

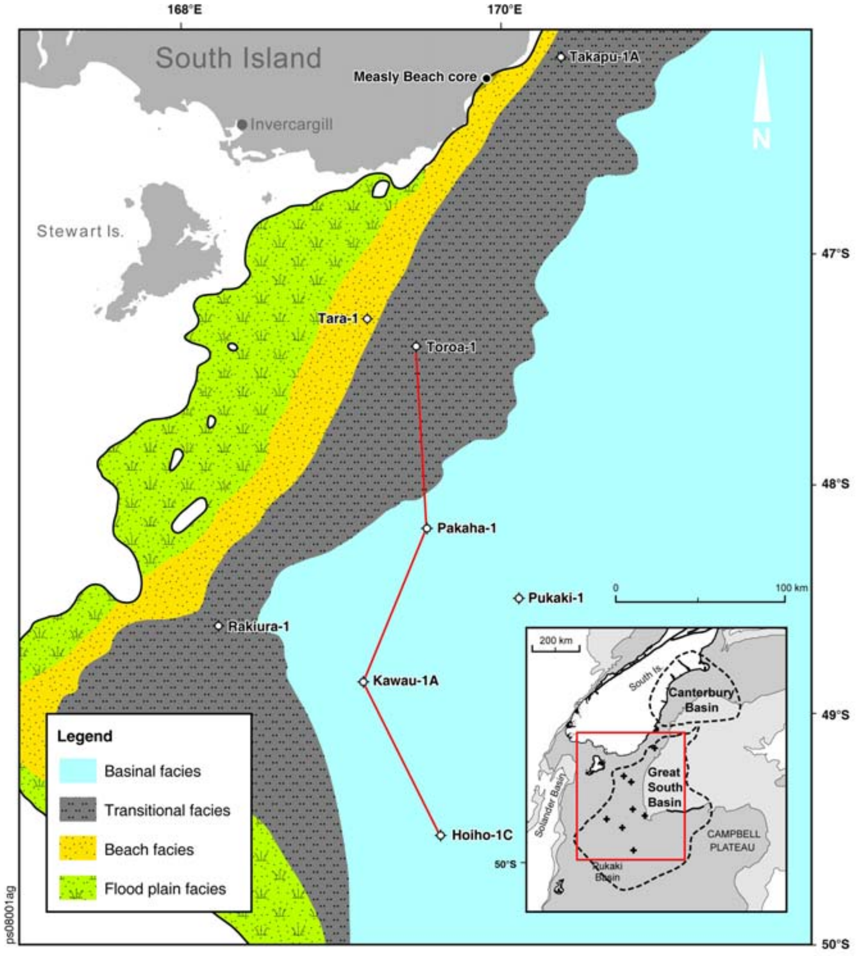

Figure 1. Map of the Great South Basin showing Late Paleocene paleogeography and well location. The basin was bounded to the north and northwest by a landmass which supplied significant amounts of sediments into the basin, probably via a river system (Cook et al., 1999). To the west and south (partly outside the map) the basin was bounded by low-lying land areas surrounded by coastal plains (Zhu et al., 1996). The red line represents the wells transect shown in Figs 4 and 5. Figure modified from Sutherland et al. (2002). Paleogeography modified from Cook et al. (1999).

The depositional environment of the Tartan Formation is a subject of ongoing debate. Killops et al. (1996, 1997, 2000) suggested that the deposition of the Tartan Formation and its time equivalent Waipawa Formation elsewhere around New Zealand, was controlled by regional upwelling along an oceanic front. Outside the GSB, the unit was deposited in water depths equivalent to the upper slope, under highly anoxic conditions. In the GSB, deposition took place in shallower waters, in a c. 40 km wide belt east of a northeast-southwest trending near-surface ridge. Killops et al. (1997) further inferred that the kerogen of the Tartan Formation was predominantly of marine origin, but acknowledged a terrestrial contribution and the presence of black coaly material in the four GSB wells studied by them. A mixed oil and gas potential was suggested for the Tartan Formation (Killops et al. 1997). Cook et al. (1999) suggested deposition of the Tartan Formation in a nearshore, shallow marine, possibly lagoonal setting with subnormal salinity, and also anticipated a mixed oil-gas potential for the Tartan Formation. Both depositional models imply a limited distribution area for the

Tartan Formation: either restricted to a narrow belt in the central part of the basin or in a coast-near lagoon.

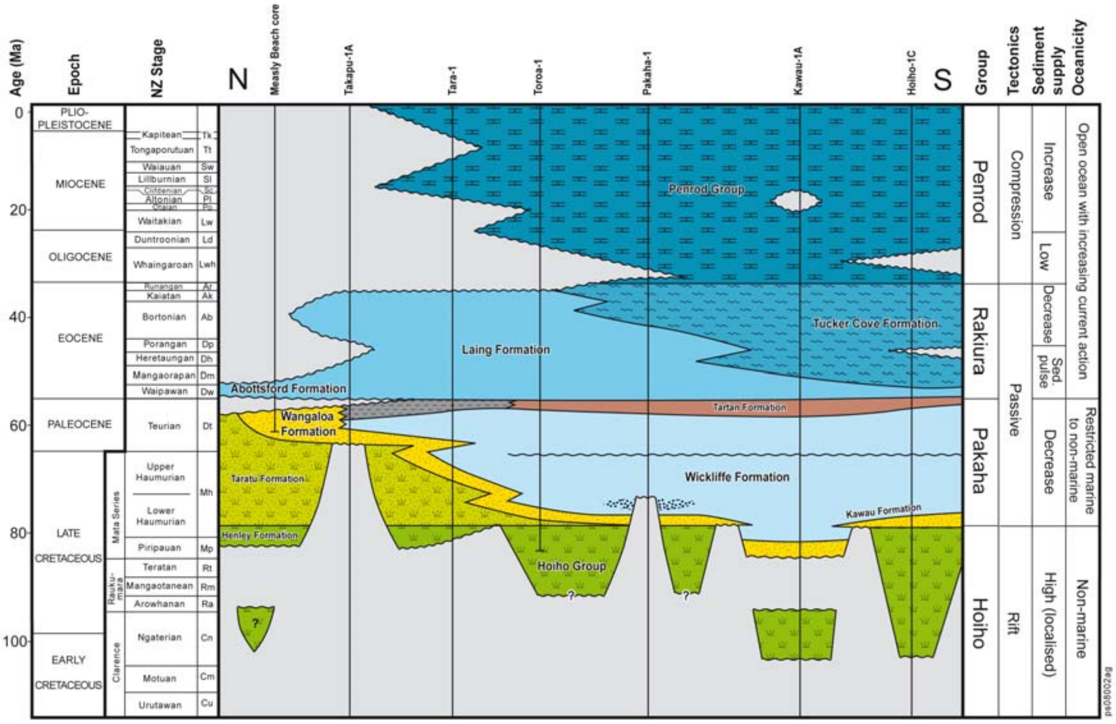

Figure 2. Stratigraphy of the Great South Basin. Modified from Cook et al. (1999) and Schiøler et al. (2007).

Depositional environment and the history of base-level changes are important controls of the spatial distribution of sediment packages through time; a better knowledge about these controlling factors can improve prediction of distribution of petroleum sources and reservoirs. In the present study, we have undertaken palynological analyses, including a palynofacies analysis of sidewall core (swc) samples from above, within and below the Tartan Formation in the GSB, in order to:

- determine the origin and composition of the organic material
- better understand the depositional environment of the Tartan Formation
- determine dinoflagellate events useful for correlation of the Tartan Formation
- identify base-level changes based on trends in palynofacies, lithology and wire-line logs

Methods

Thirty-one swc samples were studied from the GSB wells Hoiho-1C, Kawau-1A, Pakaha-1 and Toroa-1. The four wells together constitute a N–S oriented proximal–distal transect through the GSB (Fig.1). There is no swc material available from the Tartan and Laing Formations in the Pukaki-1 well. All samples were processed using standard palynological techniques (e.g. Batten, 1999) and 300 kerogen specimens >6 µm were counted for palynofacies analysis in each sample. The dinoflagellate assemblages were analysed for biostratigraphy; the succession of key palynological events is summarised in Fig. 3.

Table 1. Depth (m below rotary table, mbrt) to top/base of Tartan Formation used in this study

	top	base	thickness (m)
Hoiho-1C	1556	1595	39
Kawau-1A	2220	2264	44
Pakaha-1	2510	2551	41
Pukaki-1	2288	2318	30
Toroa-1	2138	2195	57

Palynofacies results were plotted in two ways:

- as ternary Tyson-Roncaglia-Kuijpers plots (Tyson, 1993; Roncaglia and Kuijpers, 2006) in order to assess depositional environments (Fig. 4)
- against depth in order to identify stratigraphic trends (Fig. 5)

The following end-members were used in the ternary plots (Fig. 4):

- 100% phytoclasts and miospores (excluding opaque matter and bisaccate pollen): assemblages heavily dominated by phytoclasts (higher land plant tissue debris) are characteristic of depositional settings under strong terrestrial/freshwater influx.
- 100% amorphous organic matter (AOM): high percentages of granular AOM are indicative of bottom water anoxia and typical of a distal setting.
- 100% marine algae: kerogen assemblages with high percentages of marine algae cysts indicate an open marine setting.

In Figure 4, samples are plotted with the following colour code: green, Wickliffe Formation; orange, Tartan Formation; blue, Laing Formation.

The following key palynofacies parameters were used in the stratigraphic plots (Fig. 5):

- LOG black:brown phytoclasts: a high ratio of black to brown phytoclasts generally indicates distal depositional settings. However, the ratio may also be high in turbulent proximal settings (eg. shoreface sands).
- % phytoclasts: a high percentage of brown-coloured phytoclasts indicates proximal conditions and/or the vicinity of a major point source of detrital plant material, e.g. a river delta.
- LOG marine algae:sporomorphs: a high ratio of marine algae to sporomorphs indicates a distal setting.
- % *Spiniferites* group dinoflagellates: the dinoflagellate genera *Spiniferites* and *Impagidinium* (together with minor, similar genera) occur abundantly in fully marine conditions. A high percentage of taxa from these genera is therefore taken to indicate an open marine setting.

Temporal (stratigraphic) changes in these parameters reflect coastline progradation or backstepping through time and are interpreted in terms of base-level change (Fig. 5). Wire-line log suites and lithology from mud logs and swc samples were analysed and stratigraphic trends compared with trends in palynofacies. The combined results from palynofacies and lithological analyses have been constrained by biostratigraphy and are interpreted in terms of sequence stratigraphy in Fig. 5.

Results

Biostratigraphy

Seven palynological key events bracket the interval from the uppermost Wickliffe Formation to the lowermost Laing Formation (Fig. 3). All seven events occur in the two distal wells, Kawau-1A and Hoiho-1C, whereas fewer marine events can be detected in the two proximal wells, four in Pakaha-1 and only two in Toroa-1. This is a result of increased inundation by non-marine kerogen (consisting almost entirely of brown, degraded phytoclasts), possibly accentuated by decreasing salinity. However, the key events present occur in the same sequence in all wells, indicating that the Tartan

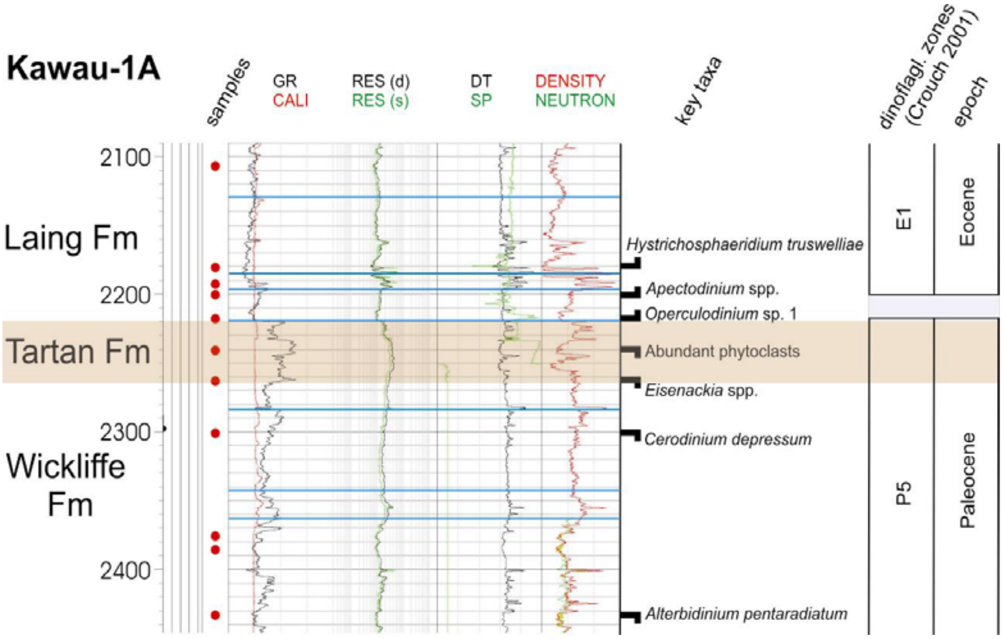

Figure 3. Key palynological events around the Tartan Formation, exemplified by the Kawau-1A well.

Formation represents a largely synchronous unit in the GSB. The event succession indicates that the study section is of Paleocene to earliest Eocene age and places the Tartan Formation in the uppermost Paleocene NZP5 dinoflagellate zone of Crouch (2001), corresponding to the international nannofossil Zones NP7–9a, of Thanetian age. This is at the same stratigraphic level as the Waipawa Formation in the East Coast Basin (Crouch, 2001; Hollis et al., 2005).

Palynofacies

Samples from the upper Wickliffe Formation are characterised by a rich, mixed kerogen assemblage with relatively high percentages of spores, pollen and phytoclasts and low to intermediate percentages of AOM and marine algae cysts (Figs 4, 5 and 6), indicating deposition in a normal to marginally marine, proximal, oxic to suboxic environment.

All samples from the Tartan Formation stand out in being heavily dominated by degraded brown phytoclasts, with only a few other kerogen groups represented (Figs 4, 5 and 6). This assemblage was deposited in a marginal marine, proximal setting with a strong influx of terrestrial plant matter. Bottom environments were probably oxic to dysoxic, based on relatively low AOM contents. It should be noted that all swc samples from the Tartan were shot in GR high intervals in the formation. Because of this sample bias, it is unclear if the kerogen of the formation is dominated by phytoclasts throughout, or if this feature is restricted to the three GR high intervals.

The Laing Formation samples in the distal wells have elevated percentages of marine algae cysts and AOM compared to the two underlying formations, whereas phytoclast percentages are lower than those of the Tartan and Wickliffe Formations (Figs 4, 5 and 6). The assemblage indicates deposition in an open marine, moderately distal, oxic to suboxic environment.

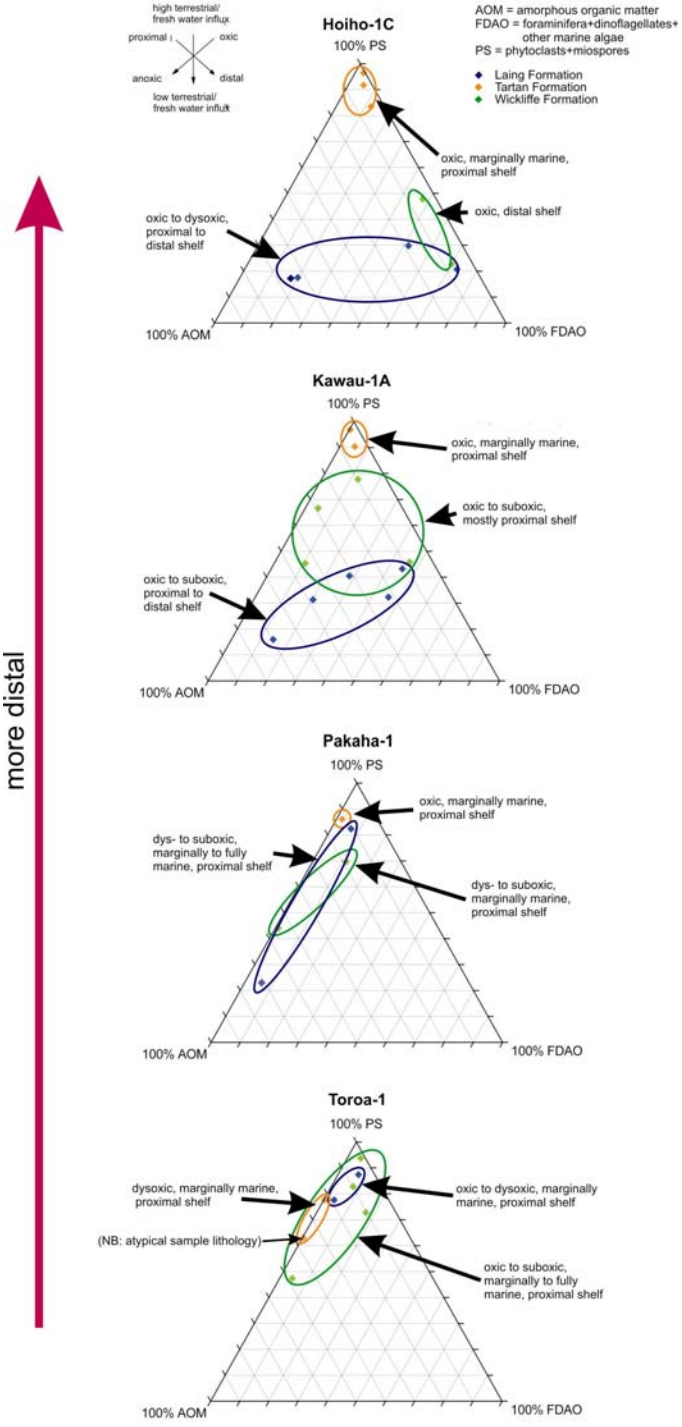

Figure 4. Ternary Tyson-Roncaglia-Kuijpers plots of kerogen data from the four study wells. The wells form a N–S trending proximal–distal transect. Notice that kerogen from both the Wickliffe and Laing Formations (green and blue points, respectively) plot together with kerogen from the Tartan Formation (orange points) in the proximal Toroa-1 well, whereas samples from the two formations plot away from (distal of) the Tartan samples in the more distal wells. This reflects a general increase in non-marine kerogen groups in a proximal direction for all three formations. The Tartan Formation invariably plots along the left side of the diagrams, in a highly proximal setting. The swc sample at 2159.7 mbrt from the Tartan Formation in Toroa-1 (lower orange point) has an atypical lithology and may instead belong to the lowermost Laing Formation.

Figure 4 shows a significant difference between the plot pattern of Wickliffe and Laing Formation samples in the distal (Hoiho-1C, Kawau-1A) and proximal wells (Pakaha-1, Toroa-1). The samples from the distal wells plot in the central to lower part of the diagrams (most pronounced in the Hoiho-1C well) as a result of stronger influence of marine palynomorphs and AOM, whereas samples from the proximal wells plot along the upper left side of the diagrams as a result of higher percentages of non-marine kerogen. This difference reflects changes in setting along a distal-proximal transect and confirms that the main source area was to the north of the well transect rather than to the south.

With its kereogen dominated by non-marine, degraded woody matter, the Tartan Formation is likely to be gas prone, and its oil-generation potential may have been overestimated in previous works.

Sequence stratigraphy

A stratigraphic analysis of palynofacies and wire-line log trends indicates that the study succession was deposited during an overall aggradational to slightly regressive trend in the Paleocene Wickliffe Formation followed by transgression in the latest Paleocene–earliest Eocene Laing Formation (Fig. 5). Marine proxies are stronger in the Laing Formation than in the Wickliffe Formation, especially in the two distal wells; trends are not so clear-cut in the two proximal wells due to masking by a massive influx of non-marine organic matter in all three formations (see above). In the three distal wells, the GR response is generally lower in the distal setting of the Laing Formation than in the proximal setting of the Wickliffe Formation, probably due to an increase in carbonate contents and a decrease in organic material. Phytoclast percentages are high in all samples from the most proximal Toroa-1 well, such that the Tartan regression is obscured (Fig. 5). In this well, the GR response level is generally high and fluctuating in both the Wickliffe and Laing Formation, indicating that the organic and carbonate contents of the two formations is at a similar, albeit fluctuating, level.

The overall aggradational to slightly regressive trend through the Wickliffe Formation terminated in a peak regression in the late Paleocene during which the Tartan Formation was deposited. This regression is shown clearly by a conspicuous increase in non-marine proxies in the Tartan Formation in the three most distal wells (Fig. 5). Interestingly, the peaks in non-marine proxies in the middle part of the Tartan Formation are associated with a GR maximum, showing that a GR maximum in this setting reflects maximum regression rather than maximum transgression. Being a regressive deposit, the Tartan Formation may have a larger offshore distribution area than previously thought.

Cook et al. (1999) noted the presence of a number of fining-upwards (FU) cycles on the GR log in the upper, Paleocene part of the Wickliffe Formation, but did not comment further upon them. The uppermost two to four of these cycles are covered incompletely by swc samples from the four wells of the present study (Fig. 5). Most of the GR peaks of the cycles differ from that of the middle part of the Tartan Formation in being associated with high density and low neutron readings, indicating either more compaction or less organic material present, or both. Alternatively, the high GR response may be due to high concentrations of glauconies. Thus, the FU cycles observed by Cook et al (1999) may either represent regressive pulses similar to that of the Tartan Formation and, in that case, the GR peaks may be interpreted as maximum regressive surfaces (sequence stratigraphic terminology follows Embry et al., 2007) or the cycles may represent transgressive pulses with the GR peaks representing maximum flooding surfaces. At present, the swc coverage of these cycles is too scattered to resolve this.

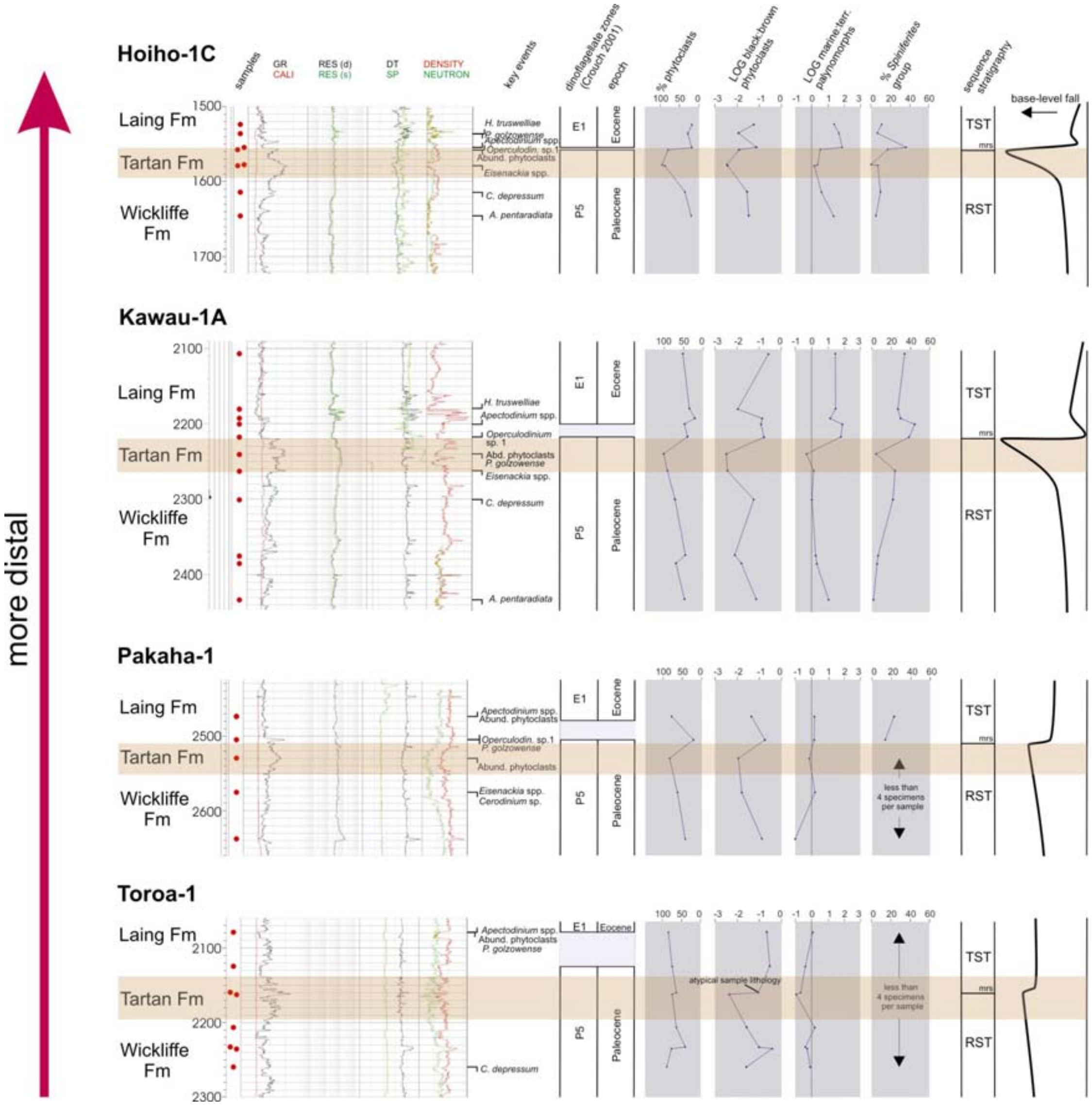

Figure 5. Litho-, bio-, palyno- and sequence stratigraphy of the four study wells. Changes in kerogen composition and interpreted changes in base-level around the Tartan interval are more subtle in the two proximal wells; this is due to masking by massive influx of phytoclasts. Cyclic fining-up successions below the Tartan Formation (best developed in the Hoiho-1C and Kawau-1A wells) may represent pre-Tartan regressive pulses. However, they differ from the Tartan regression in having the maximum regressive surface (sequence stratigraphic terminology follows Embry et al., 2007), at the GR maximum, associated with a density low rather than a density high. Alternatively, they may represent maximum flooding surfaces of transgressive pulses. The scale of the amplitudes of base-level rise and fall is arbitrary and based on the amplitudes of changes in the log response and palynofacies parameters and therefore appear higher in the two distal wells. The true magnitude of the base-level changes recorded remains unknown. TST=transgressive systems tract, RST=regressive systems tract, mrs=maximum regressive surface.

Other GSB wells and onshore sections

The Tartan Formation is absent from the proximal Tara-1 well, located north of Toroa-1 (Fig.1). There is no direct evidence of an erosion event with an associated hiatus in the Paleocene–lowermost Eocene well section. However, it should be noted that the biostratigraphic resolution is not very high in this interval, due to the dominance of proximal sands and the resulting scarcity of marine microfossils.

The Rakiura-1 well southwest of Pakaha-1 did not penetrate the Tartan Formation. Instead, the Lower Paleocene is overlain directly by a 123 m thick clean sandstone, assigned to the lowermost Eocene by Schiøler et al. (2007) based on the lack of Paleocene microfossils and a lowermost Eocene age of a fossiliferous sample from 10 m above the top of the sandstone unit. The Tartan Formation was either removed by the erosional base of the sandstone or was never deposited in the area due to sediment bypass. Alternatively, the sandstone may represent a regressive unit of Late Paleocene age correlatable with the Tartan Formation. In either case a base-level fall is the most plausible explanation for the absence of the Tartan Formation from the well.

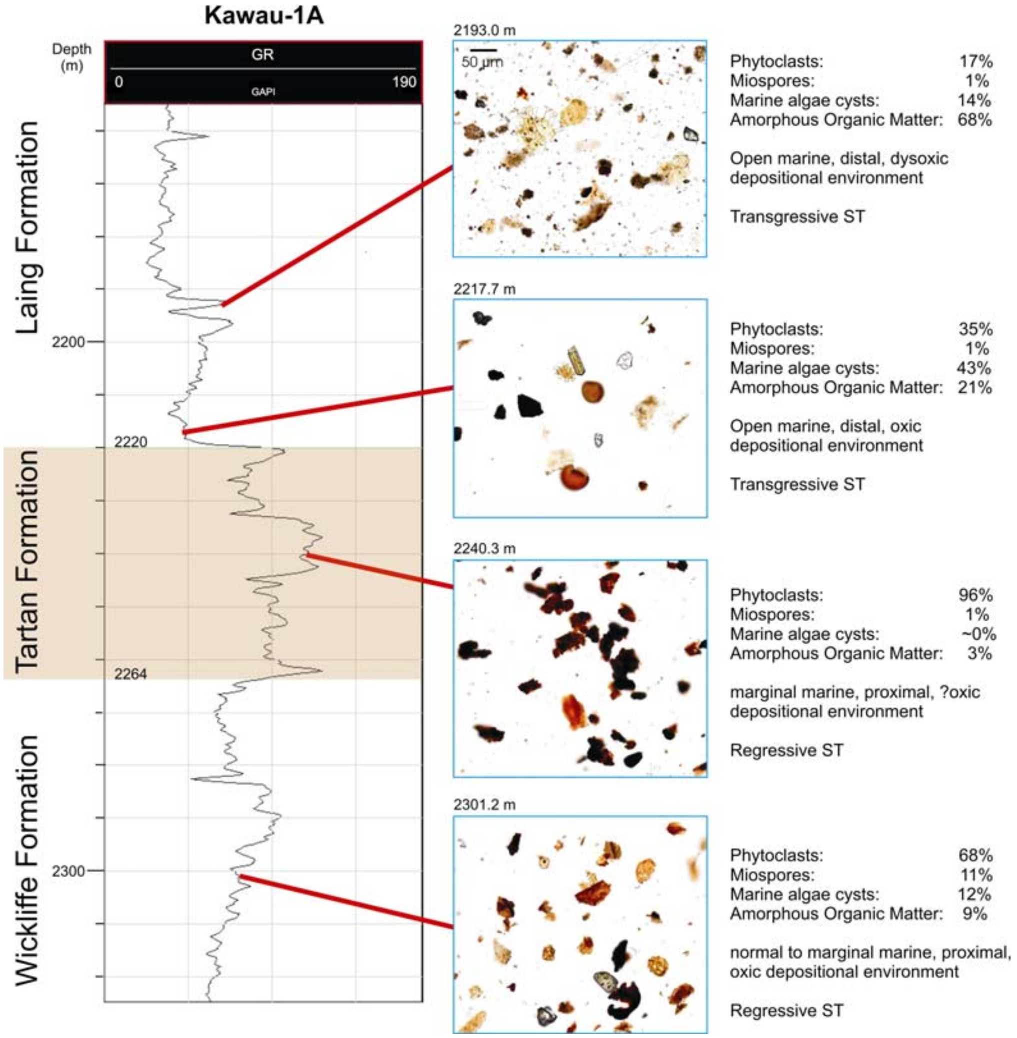

Figure 6. Representative palynofacies assemblages from the Wickliffe, Tartan and Laing Formations in the Kawau-1A well. Note the overwhelming dominance of degraded brown phytoclasts in the Tartan Formation.

The Tartan Formation was previously considered absent from the Pukaki-1 well (Fig. 1), because biostratigraphy indicated that the Late Paleocene–Early Eocene interval was lacking (R. Cook, pers. commun., 2008). However, recent revision of the biostratigraphy has shown that this stratigraphic interval is present and that the Tartan Formation is located between 2288 and 2318 mbrt in the well, based on log characteristics (Schiøler et al., 2007). Unfortunately, there is no swc material available from the Tartan or Laing Formations in that well, so a palynofacies analysis cannot be carried out.

The Tartan Formation was suggested present between 680 and 700 m in the Takapu-1A well by Cook et al. (1999). However, based on detailed log analysis, examination of sidewall cores and biostratigraphic results from preparation of new samples, Schiøler et al. (2007) concluded that the Tartan Formation is absent from the well. Instead, an unconformity at 680 m in the well separates Lower Paleocene strata of the Wickliffe Formation from lowermost Eocene strata of the Laing Formation, similar to the situation for the Rakiura-1 well, further supporting sediment bypass and/or erosion near the basin margin.

A significant intra-Paleocene unconformity has previously been recorded in drill hole cores onshore Otago: in the Measly Beach core (Fig. 1), a deepening unconformity at 38.9 m separates shoreface sands of the Wangaloa Formation from overlying offshore mudstones of the Abbotsford Formation (Lindqvist, 1995). A sample from the basal shoreface sands, at 83.8 m, indicates a mid to Late Paleocene age (Crouch, 2001) correlatable with pre-Tartan Wickliffe Formation in the GSB. A sample from the basal Abbotsford Formation, at 36.8 m indicates a general Late Paleocene age (Crouch, 2001). True Eocene strata are reached c. 13 m higher up, at 24 m (Lindqvist, 1995). There is no indication of Tartan Formation in the core. It is therefore possible that the shoreface sand package may either represent a regressive unit correlatable with the Tartan Formation, or that the boundary between the Wangaloa and Abbotsford Formations is an unconformity identical to the one that separates Wickliffe from Laing Formation in the Takapu-1A well.

In the Fairfield Estate core (c. 50 km northeast of the Measly Beach borehole, Fig. 1) an unconformity within the Abbotsford Formation, at 34.7 m (=unconformity U/C6.1 of McMillan and Wilson, 1997) separates silt and sandstones, time-equivalent with pre-Tartan Paleocene Wickliffe Formation, from overlying silty, carbonaceous greensands of a broad mid–late Paleocene age (McMillan, 1995). A meter-thick bed of dark-coloured carbonaceous mudstones was reported from the basal part of a high GR interval in the siltstones of the H and I siltstone Members, c. 20 m above unconformity U/C6.1, and it is possible that this mudstone bed, together with the overlying c. 9 m thick high GR interval of the H and I Members may be correlatable with the Tartan Formation of the GSB. However, dinoflagellate biostratigraphy of the I Member shows that this unit is of Early Eocene age and that the H Member is of uppermost Paleocene age (McMillan, 1995), and thereby most likely younger than the Tartan Formation in the GSB and time equivalent with the initial latest Paleocene–earliest Eocene transgression of that basin. Presence of indisputable Tartan Formation in the Fairfield Estate core has yet to be fully demonstrated.

In summary, the Tartan Formation is missing from the three most proximal wells drilled in the GSB. These wells together form a coast-parallel transect landward of the remaining five GSB wells (Fig.1). The absence of the Tartan Formation from the three wells and lack of firm evidence for its presence in onshore coastal Otago is most likely due to sediment bypass and/or erosion and strongly suggests that the Tartan Formation was deposited in the central, southern and eastern parts of the basin during a period of base-level fall and coastline progradation. Support for this comes from reconnaissance seismic mapping of the Late Cretaceous–Early Cenozoic interval of the Campbel Plateau immediately south of the GSB by Zhu et al. (2006). In that work, the authors noted clear signs of a regression in the Paleocene, punctuating an overall first to second order passive margin transgression taking place during the Late Cretaceous–Eocene interval.

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