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An integrated source rock characterization using geochemical analysis and well logs: a case study of Taranaki Basin, New Zealand

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Abstract

This paper attempts to evaluate the source rock potential of the major source rocks of the Taranaki Basin, which are the Rakopi and North Cape formations of the Upper Cretaceous Pakawau Group and the Mangahewa Formation of the Paleocene Kapuni Group, using conventional borehole well log data. This has been conducted based on the application of three renowned mathematical models for total organic carbon (TOC) content evaluation on eight selected wells distributed across the basin. Source zones have been first identified based on responses of well logging tools to the presence of source rocks. The models are applied on the source rock intervals and the results were calibrated with geochemical analyses. Good correlation can be observed between well log and core geochemical TOC values for the studied wells based on all three models, suggesting that they are all applicable in the study area. This indicates that well log data can be used with confidence to evaluate organic source quantity of Taranaki Basin in the absence of geochemical data.

Keywords: *well logging; total organic content; source rock evaluation; taranaki basin; north cape; rakopi; mangahewa*.

1. Introduction

Taranaki Basin is the only commercially-producing sedimentary basin in New Zealand, with total recoverable reserves of 534.0 MMbbl of oil and condensate and 7,318.7 BCF of gas by the end of 2011 [1], and thus, has attracted a wide pool of researches. It covers a total area of 100,000 km^2, and is located predominantly offshore on the west coast of the North Island between latitudes 38° 00' - 41° 00' S and longitudes 172° 00' - 175°00' E (fig. 1). The petroleum source for the basin originated from the deeply buried hydrogen-rich coals and terrigenous carbonaceous mudstones of the Upper Cretaceous Pakawau Group and the Paleogene Kapuni Group [2-3]. This study focuses on integrated source rock evaluation of North Cape and Rakopi formations belonging to the Pakawau Group, as well as the Mangahewa source of the Kapuni Group (fig. 2).

Well log data may be used to characterize a source rock in the absence of geochemical data. The application of well logging techniques for the evaluation of total organic carbon (TOC) content in source rocks have produced various different models developed by various scholars [4-14]. Many studies have covered TOC evaluation using conventional well logging method based on the applications of these models, such as El Shawary & Gaafar [15] and Liu *et al.* [16]. In this study, the source rock characterization of Rakopi, North Cape and Mangahewa formations in Taranaki Basin is discussed by the integration of conventional well log data and the available geochemical data measured in the lab. This is done to produce a complete basin-scale study for the accuracy evaluation of conventional well log data to represent the source rock availability in the absence of geochemical data, as well as to conclude its applicability in the area of study.

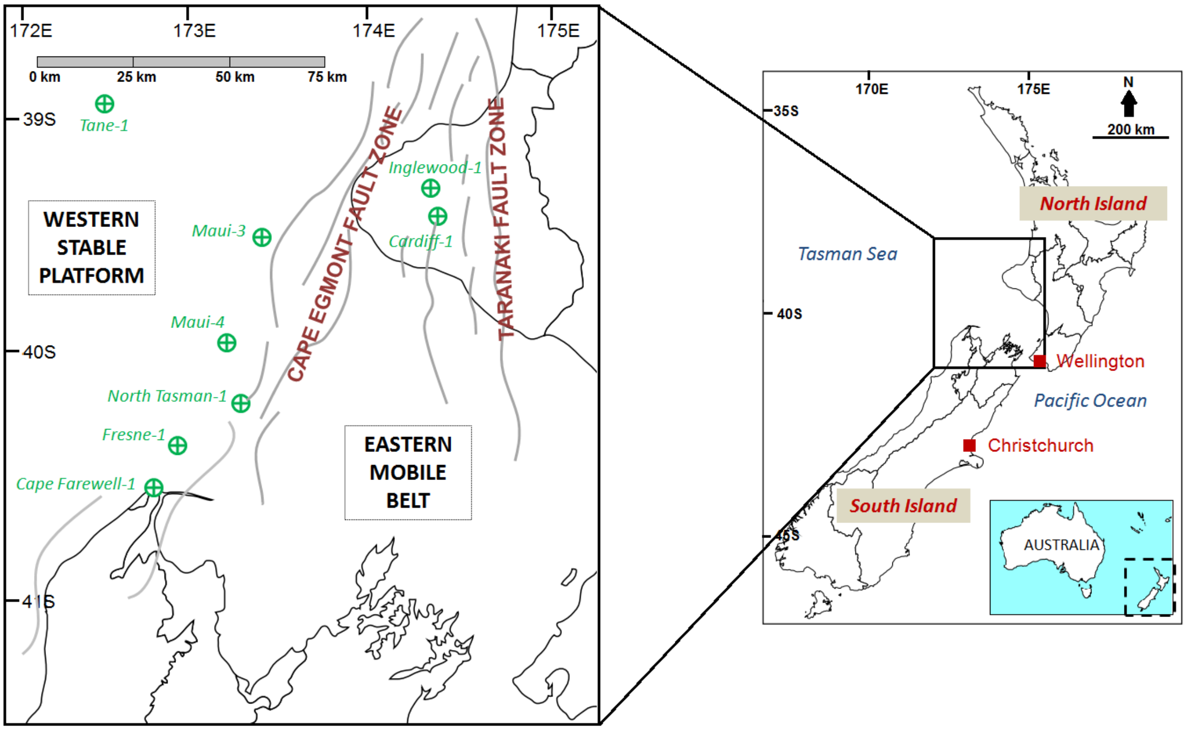

Figure 1. Map of study area

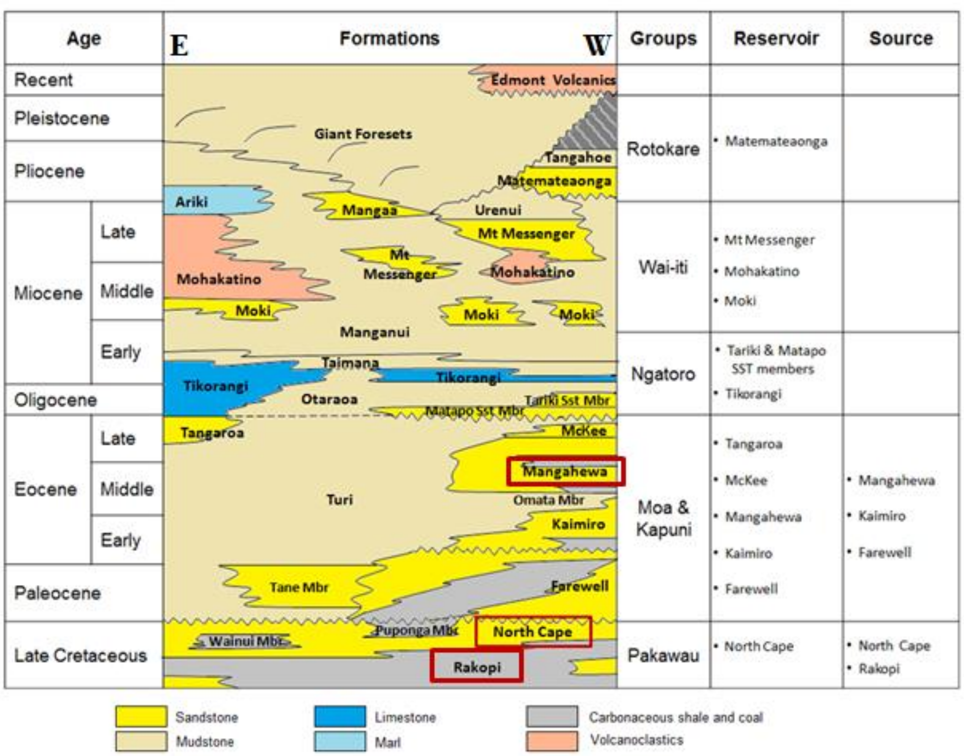

Figure 2. Generalized lithostratigraphy of Taranaki Basin (modified after King & Thrasher, 1996).

2. Geological setting & stratigraphy

2.1. General geology of Taranaki Basin

The formation of Taranaki Basin was initiated from the breakup of the supercontinent Gondwana, which resulted in the separation between Australia and Zealandia. This formed the Tasman Sea and numerous extensional basins on the New Zealand subcontinent, including an intra-plate rift that formed the Taranaki Rift, which later developed into the Taranaki Basin during the Late Cretaceous [17-19]. The Taranaki Basin was characterized by failed rift, subsidence and marine transgression in the Late Cretaceous, and intra-plate to back-arc subsidence during the Neogene period [1].

The structural setting of Taranaki Basin has been covered in various previous studies, most notably by Thrasher [19], King and Thrasher [3], Palmer and Geoff [20], Palmer [21], Uruski [22] and Pilaar and Wakefield [23]. Structural and facies modeling have been applied on different hydrocarbon fields within Taranaki Basin [24-25]. The basin is made up of two major structural blocks, the Western Stable Platform and the Eastern Mobile Belt (fig 1). The Western Stable Platform covers the entirely offshore western part of the basin [21]. It is composed of broad, simple structures and 2000-5000 m of Late Cretaceous to Recent. It was affected by Late Cretaceous-Eocene normal block faulting, which created local fault-angle depressions or half-grabens [23], but has remained relatively stable throughout the rest of the Tertiary. In contrast, the Eastern Mobile Belt consists of multiple grabens and compressional features (overthrusts, reverse faults, inversion).

The stratigraphy of the Taranaki Basin (fig 2) consists of a Cretaceous-Cenozoic succession of terrigenous and marine sedimentary and volcanic rocks. King and Thrasher [3] classified the succession into four megasequences:

1. Upper Cretaceous syn-rift sequence (Pakawau Group)
2. Paleocene-Eocene late-rift and post-rift transgressive sequence (Kapuni and Moa groups)
3. Oligocene-Miocene foredeep and distal sediment starved shelf and slope sequence (Ngatoro Group) and Miocene regressive sequence (Wai-iti Group)
4. Plio-Pleistocene regressive sequence (Rotokare Group)

2.2. Pakawau Group: Rakopi and North Cape formations

The Pakawau Group sediments are the oldest sediments within the Taranaki Basin. It consists of the Rakopi Formation and North Cape Formation. These syn-rift sediments were deposited within rift-controlled grabens across the basin, and are separated from the basement rock by a regional unconformity [18]. Rakopi Formation is the lowest stratigraphic unit with widespread distribution in Taranaki Basin. It comprises almost entirely of terrestrial coal measures, predominantly sandstone, cyclically interbedded with carbonaceous siltstone and mudstone, thin coal seams, and rare conglomerate. The North Cape Formation is the uppermost formation of the Pakawau Group, and is primarily distinguished from the Rakopi Formation by its marine depositional influence and by a more bland seismic reflection character. North Cape Formation consists of transgressive sandstones, with siltstone, mudstone and coal lithologies. There are two known coal measure members belonging to the North Cape Formation: The Wainui Member and the Puponga Member [3].

2.3. Mangahewa Formation

Regional post-rift subsidence resulted in the deposition of transgressive sequence during the Paleocene and Eocene. This phase is represented by the Kapuni Group and its marine equivalent, the Moa Group. The Kapuni group contains multiple formations: Farewell Formation, Kaimiro Formation, Mangahewa Formation, and McKee Formation [21]. The Moa Group encompasses mostly Turi and Tangaroa Formations marine mudstones. Turi Formation members interfinger with and divide the Kapuni Group sections [26]. The area of sedimentation of the Kapuni Group slowly decreased through the Eocene, as the extent of Moa Group marine sedimentation increased. Fine-grained, terrigenous sediment of the Moa Group covered most of the basin by the end of the Eocene [19]. The Mangahewa Formation consists mostly of sandstone, siltstone, mudstone and bituminous coal [21]. Its variability in lithologies contributes to it being both a source and reservoir. The Mangahewa Formation source rocks have been found to have oil-prone type-II, oil- and/or gas-prone type-II–III, and gas and condensate type-III kerogens, with very good generation potential on the bases of rock-eval pyrolysis results S_2 and TOC values [25].

3. Methodology

Well data and permission to publish results have been obtained from New Zealand Petroleum & Minerals, Ministry of Business, Innovation & Employment, as part of an ArcGIS database supplied to the MBIE by GNS Science New Zealand. In this study, eight wells (fig. 1) were selected to examine the TOC for the aforementioned formations; Tane-1 and Cape Farewell-1 wells for Rakopi Formation, Fresne-1, North Tasman-1 and Tane-1 wells for North Cape Formation, and Cardiff-1, Inglewood-1, Maui-3 and Maui-4 wells for Mangahewa Formation. Rakopi Formation is penetrated in Tane-1 well at 4000-4474m (474m thick) and Cape Farewell-1 at 1570-2700m (1130m thick). North Cape Formation is penetrated in Fresne-1 well at 1030-1300m (270m thick), North Tasman-1 well at 2240-2260m (420m thick), Tane-1 well at 3400-400m thick (600m). Mangahewa Formation is drilled at Cardiff-1 well at 4063-5065m (1002m thick), Inglewood-1 well at 3651.5-5059.68 m (1408.18m thick), Maui-3 well at 2030-2265.5m (235.5m thick) and Maui-4 well at 2713.5-2734.1 (300.8m thick).

These wells belong to separate oilfields in Taranaki Basin and are used to produce a basin-scale integrated source rock evaluation using well log and geochemical data. TOC values from the Rock-Eval pyrolysis results are available for all wells and have been obtained from GNS Science New Zealand (table 1).

Table 1. TOC (wt. %) values from geochemical core analyses and calculated TOC (wt.%) values for well log models of all core samples assessed in this study

Well	Depth (m)	Average well log TOC (wt. %)	Geochemical TOC (wt. %)
North Tasman-1	2471	9.94	8.10
	2504	2.30	2.58
	2529	2.56	2.44
	2534	9.17	9.17
	2551	2.79	2.52
	2575	3.58	3.78
	2600	4.37	5.08
	2618	7.87	8.51
	2627	5.94	5.90
	2649	6.09	5.93
Tane-1	3644	10.15	11.09
	3686	4.84	4.72
	3687	2.33	2.20
	3720	11.93	11.20
	4005	7.93	7.72
	4011	11.62	10.48
	4026	14.00	12.69
	4076	10.66	10.81
	4082	9.86	10.35
	4117	13.12	11.70
	4176	10.54	10.19
	4130	5.10	5.07
	4231	9.12	9.81
	4284	3.06	2.90

Well	Depth (m)	Average well log TOC (wt. %)	Geochemical TOC (wt. %)
Fresne-1	1197	1.02	1.03
	1158	0.85	0.90
	1204	1.91	12.22
	1237	0.50	0.50
	1279	0.81	0.81
Inglewood-1	3803	6.24	6.33
	3815	6.52	14.01
	3870	10.21	10.78
	3898	5.68	5.62
	4031	7.52	12.14
	4045	5.96	5.94
	4083	5.91	6.01
	4111	7.30	8.34
	4145	2.95	2.95
	4170	2.45	2.50
	4192	6.09	6.10
	4242	4.18	4.22
	4266	2.25	2.03
	4281	7.18	10.72
	4304	4.46	4.58
	4337	3.10	4.10
	4365	5.75	10.08
	4365	5.73	6.06
	4447	3.47	2.88
	4484	0.94	0.72
	4510	2.00	1.98
	4530	1.38	1.02
Maui-4	2030	9.56	3.16
	2076	9.53	9.00
	2012	4.78	6.74
	2134	10.42	8.56
	2161	6.73	8.36
	2171	13.88	12.09
	2185	10.68	19.14
	2204	3.78	5.56

The well log data used include the conventional well log tools: Gamma ray, sonic, neutron, density and true resistivity. The typical well log responses to the presence of source rocks can be described as follows:

(1) Gamma Ray (GR) log: Presence of organic matter leads to an increase in Gamma Ray readings due to associated Uranium content.

(2) True resistivity (Rt) log: Free oil fills voids and fractures when source rock becomes mature, and so, resistivity increases significantly by a factor of 10 or more [9].

(3) Density log: Non-source shale has density reading of 2.67-2.72 gm/cm^3. Presence of oil will lower the rock density dramatically.

(4) Neutron log: Source rock increases H index, so neutron reading increases.

Sonic (DTC) log: At the same lithology and compaction condition, immature source rocks show faster sonic travel time, whereas mature source rock takes longer sonic travel time.

Several published models were applied to determine the amount of TOC in this study and to determine the most applicable one in the study area according to correlation with the TOC results from the geochemical lab measurements: Schmocker & Hester [8], Passey *et al.* [11] and Zhao *et al.* [14].

The detailed workflow is shown in fig. 3. Similar workflow has been used in studies such as El Shawary & Gaafar [15] and Liu *et al.* [16], but a newer method has been adapted in this work flow to include the most recent method by Zhao et al. [14]. Several models were applied to determine the amount of TOC and to determine if well log data can be used to measure and evaluate TOC in the absence of geochemical data based on data suitability: Schmocker & Hester [8], Passey *et al.* [11] and Zhao *et al.* [14] models.

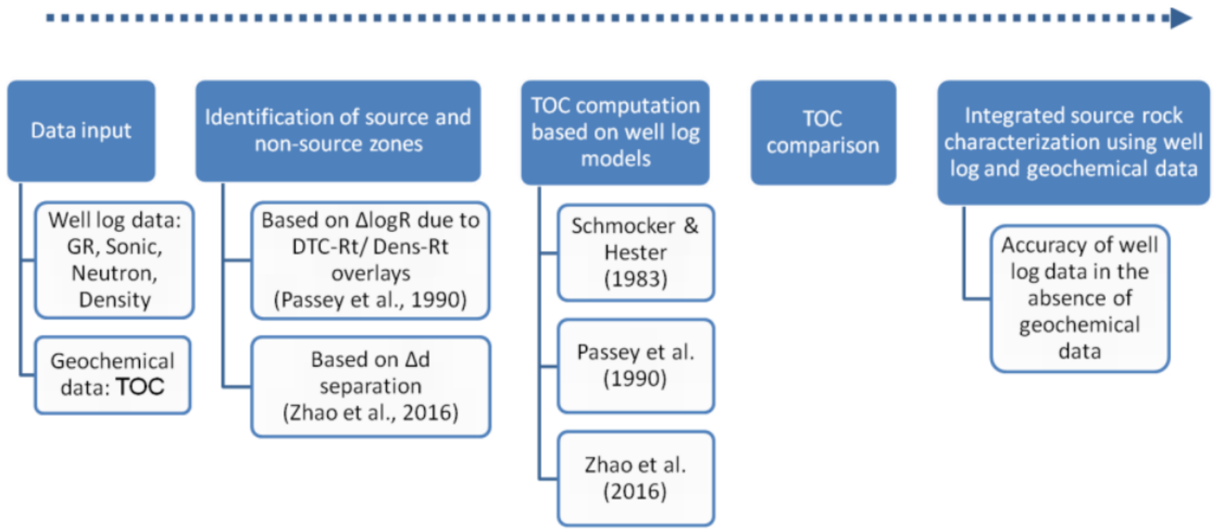

Figure 3. Workflow followed in this study

A. Schmocker and Hester [8] model:

Density log was used to calculate TOC of the Upper and Lower members of the Mississippian and Devonian black shale of Bakken Formation using the following relation:

$$TOC\ (wt\ \%) = (154.497/\rho) - 57.261\ . \quad (1)$$

B. Passey *et al.* [11] model:

This model utilizes a technique developed for both carbonates and clastics, using sonic-resistivity overlay (ΔlogR), which is linearly related to TOC and is a function of maturity. This model not only quantitatively evaluates TOC values, but also distinguishes between source and non-source rocks, whereby non-source interval shows no ΔlogR separation, while source rocks show positive ΔlogR separation.

In this method, sonic travel time Δt and true formation resistivity Rt are scaled as a ratio of 50μs/ft to one resistivity cycle [11]. The separation between two curves (Δt to the left and Rt to the right) is defined as ΔlogR, which can be calculated from the following equation:

$$\Delta logR = \log10(Rt/R_{baseline}) + 0.02*(\Delta t - \Delta t_{baseline}) \quad (2)$$

In a case where a suitable transit-time curve is unavailable, the density or neutron log can be used instead:

$$\Delta logR_{Den} = \log10(Rt/R_{baseline}) - 2.50*(\rho_b - \rho_{baseline}) \quad (3)$$

$$\Delta logR_{Neut} = \log10(Rt/R_{baseline}) + 4.0*(\Phi_N - \Phi_{Nbaseline})\ . \quad (4)$$

TOC is then calculated using the following:

$$TOC = \Delta logR*10(2.297-0.1688LOM)\ . \quad (5)$$

In this case study, LOM was obtained from correlation with the mean vitrinite reflectance value fig. 4, following Waples [27], Hood *et al.* [28] and Biswas *et al.* [29]. According to Passey *et al.* [11] (1990), 0.8 TOC (wt %) must be added to the TOC calculated by this technique.

This model is valid only for values of Δt ranging between 80 and 140 μs/ft. Error in TOC calculation can be expected at extreme low or high Δt because the proposed scale is invalid in this situation.

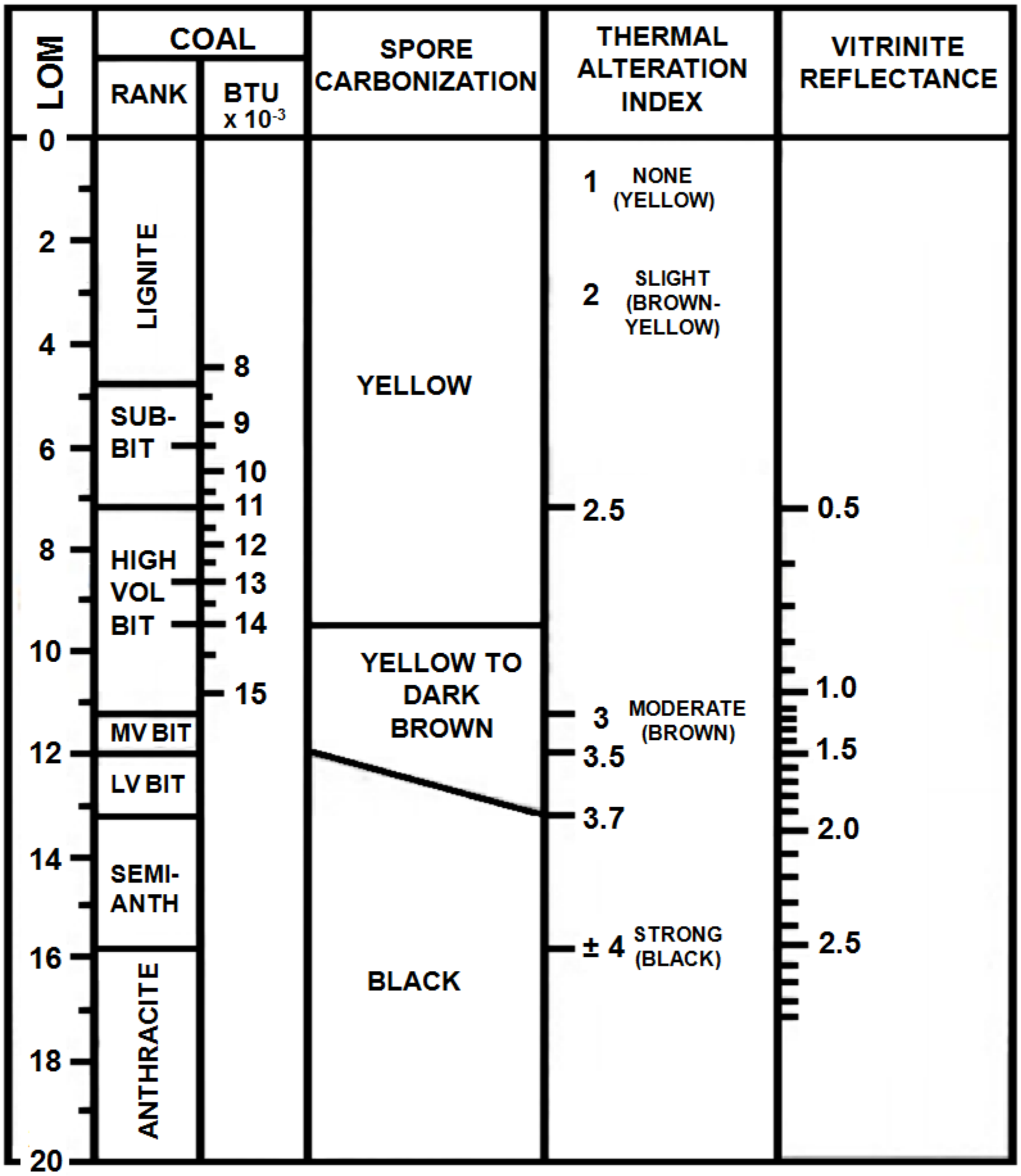

Figure 4. Correlation of LOM with other indices including Ro (Waples, 1980; Hood et al., 1975; Biswas et al., 2011)

C. Zhao *et al.* [14] model:

On the basis of GR log responses of source rocks being predominantly contributed by clay minerals and organic matter, a practical clay indictor is established to reflect the clay content using density and neutron logs. The relations are as follows:

$\Phi_{Na}=\Phi_N/100$ (6)

$\Phi_{Da} = (\rho_b - \rho_{ma})/(\rho_f - \rho_{ma})$ (7)

$I_{cl} = \Phi_{Na} - \Phi_{Da}$ (8)

Zhao *et al.* [14] developed a new method by overlaying the properly scaled clay indicator curve on the GR curve. This was developed to solve the Rt abnormal regularity that is typically present in the source rock Rt log readings. This model also helps determine source against non-source intervals. In non-source rocks, two curves overlay each other, while in organic-rich source rocks, separation exists between the curves. The separation between the curves was defined as Δd and is expressed as:

$\Delta d = GR' - I_{cl}'$, where (9)

$GR' = (GR - GR\_left) / (GR\_right - GR\_left)$ (10)

$I_{cl}' = (I_{cl} - I_{cl}\_left) / (I_{cl}\_right - I_{cl}\_left)$ .. (11)

Δd separation increases as the kerogen increases. If a relationship between core TOC and Δd is established, then TOC of the well section can be calculated. This can be described as:

$TOC = a\Delta d + b$. (12)

Variables *a* and *b* are obtained by correlating the values of Δd with the core TOC data. Variable a must be positive because of the positive correlation of the separation and TOC, and variable *b* should be equal to or greater than 0% and less than 0.5%, because the TOC contents in the non-source rocks vary over the range [30]. In only North Tasman-1 and Fresne-1 wells all these conditions are met and hence, this model is applicable only for two wells (fig. 5).

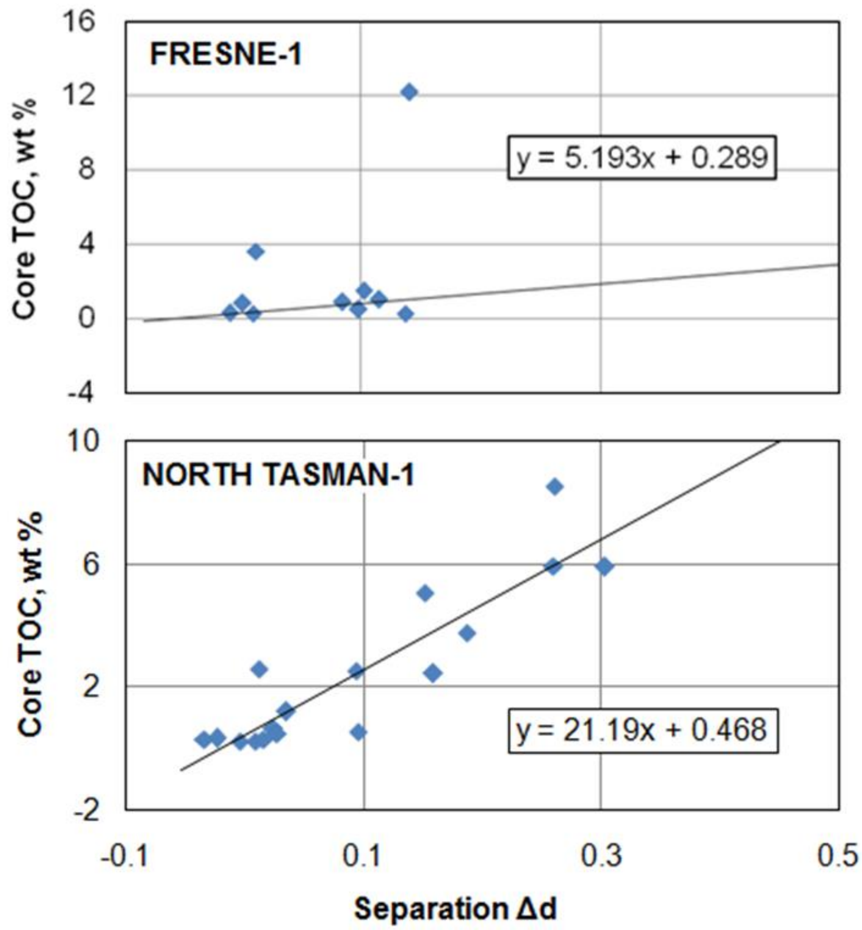

Figure 5. TOC (wt%) and separation Δd relationships are positive for the application of Zhao *et al.* [14] model, where TOC = aΔd + b, where variable *a* must be positive because of the positive correlation of the separation and TOC, and variable *b* should be equal to or greater than 0% and less than 0.5%

In core geochemical analyses, Rock-Eval pyrolysis is undergone to obtain the TOC values. Rock-Eval pyolysis tells about the quantity, type and thermal maturity of the organic matter concerned. It involves the breaking down of a complex subsidence into fragments by heating it under inert atmosphere. According to Peters [31], TOC of 0.5% is poor, 0.5-1% fair, 1-2%

good, >2% very good source rock. This classification used in this paper. Rock-Eval data include 4 basic parameters:

- S_1: the quantity of free hydrocarbons within the source rock, and is roughly equivalent to the solvent extractable portion of the organic matter.
- S_2: the quantity of hydrocarbons released by the kerogen in the sample during pyrolysis.
- S_3: the carbon dioxide yield during thermal breakdown of kerogen.
- T_{max}: temperature at which the maximum rate of generation (of the S_2 peak) occurs and can be used as an estimate of thermal maturity.

4. Results and discussion

4.1. Identification of source rock zones and lithology

Based on ΔlogR and Δd logs from both Passey et al. [11] and Zhao et al. [14] methods, respectively, it can be clearly seen that the non-source zones are in perfect overlay between (a) deep resistivity (Rt) and sonic porosity (DTC) log curves for ΔlogR separation, and (b) Gamma Ray (GR) and I_{cl} for Δd separation. On the other hand, source zones have positive separation. Gamma Ray readings for source rock zones are relatively high, which is attributed to the presence of organic matter.

In North Tasman-1 well, the North Cape Formation is found at interval 2240-2670m. Between 2240 and 2430m, the formation consists of massive sandstone unit, which highly likely consists of several water-bearing reservoir zones with no indication of oil shows. This is suggested by the relatively low Rt readings which are consistent throughout the interval. Presence of hydrocarbons will produce higher Rt readings as hydrocarbons are highly resistive fluids. At the lower part of this well from 2430m is the Wainui coal measure member, which consists of sandstone and shale sequence [32]. The source rock interval can be found in this lower sequence, which can be inferred from the high Gamma Ray readings and large ΔlogR separation with high resistivity readings (fig. 6). The Δd separation within the section is also observed.

The lithology of North Cape Formation in Fresne-1 well is reported to be sandstone with alternating siltstone, shale and coal [33]. As observed on fig. 7, the source rock interval is at the lower part of the North Cape Formation, within interval 1155-1300m. This source rock is coaly, as indicated by the consistent spikes in both the Gamma Ray and ΔlogR log readings. Coals are typically indicated by low Gamma Ray readings with high Rt values [34]. These source rock zones throughout this section are mature, and their organic matter presence is interpreted from the high sequences of Gamma Ray readings and positive ΔlogR. Above depth 1155m, the interval is non-source. The Δd separation using I_{cl} method is also observed in the same interval (fig. 7), which is in good agreement with Passey et al. [11].

Tane-1 well penetrates both North Cape (3400-4500m) and Rakopi (4000-4500m) formations. There are two major source zones, one source zone from North Cape Formation at depth 3635 - 3725 m, and another one from Rakopi Formation starting at a depth of 3980 m (fig. 8). These zones show good positive ΔlogR separation between the Density and Gamma Ray logs. The I_{cl} method is also not applicable for Tane-1 well as the formula by Zhao et al. (2016) (eq. 12)is not satisfied.

For Cape Farewell-1 well, the whole interval between 1570 and 2700 m is Rakopi Formation. Based on the responses from Rt and Density log, there is a ΔlogR separation, which is characteristic of source rock zones (fig. 9). The source rocks may be mature as inferred by the large positive separation. The I_{cl} and Δd model is also not applicable for this well as the formula by Zhao et al. [14] (eq. 12) is not satisfied.

Mangahewa Formation is penetrated by five wells. In Cardiff-1 well, the formation is found at depth between 4063 and 5065m. Good overlay between DTC and Rt logs with no Δd separation is observed at 4140-4165m and 4780-4850m (fig. 10). This is characteristic of non-source rocks. The low Rt readings suggest that the formation does not contain any hydrocarbons. On the other hands, source rocks may be found at three separate zones, at intervals 4060-4145m,4165-4780m and 4850-5065m. The spiky pattern observed in these sections with good ΔlogR separations is indicative of coals. This is in accordance with the lithology of Mangahewa Formation in Cardiff-1 well, which consists of interbeds of sandstone, silt, clay and coal seams [35]. Cardiff-1 well was not subjected to the I_{cl} method by Zhao *et al.* [14] (eq. 12) as the formula is not compatible with the results.

For Inglewood-1 well, the Kapuni Group is drilled from 3655.5 to 5059.68m. The upper part of Kapuni in this well is sandstone and glauconitic sandstone interbebbed with carbonaceous claystone and thin coal seams [36]. This is in good agreement with the spikes in DTC-Rt readings observed between 3655.5-4490m (fig. 11), which is typical for the presence of thin coal beds. From 4490-5050, the Gamma Ray logging tool measured low readings, which indicates that the relatively fewer presence of source organic matter. In addition, there is good overlay between Rt and DTC log curves within this interval, with minimal ΔlogR separation. No I_{cl} model was applied for this well.

In Maui-3 well, the Mangahewa Formation is recorded from 2713.5 to 3014.3m. Shale lithology is reported at 2713.5-2743.1m, whereas there is a predominance of sandstone below this depth [37]. In this well, the source is concentrated at the interval 2713.5-2810m and 2971-3014.3m, as indicated by the good positive Δd separation between DTC and Rt logs (fig. 12). Below 2810m is the non-source zone with predominantly good overlay and minimal ΔlogR separation. No I_{cl} model was applied for this well.

Mangahewa Formation can be found in Maui-4 well between 2030 and 2265.5 m. Its reported lithology here is argillaceous sandstone with many interbedded carbonaceous shales [38]. The Passey model applied here indicates that the source rock is from 2030 to 2200m, where good ΔlogR separation is observed (fig. 13). I_{cl} model was also not able to be used for Maui-4 well.

4.2. Comparison of TOC values from well log and geochemical data

A. Schmocker and Hester [8] model

Calculation of TOC using Schmocker and Hester [8] using eq. 1 gives great degree of accuracy when applied to different wells. This method has been applied to three wells: Tane-1, North Tasman-1 and Maui-4 wells. It was observed that the TOC values for the Rakopi source zones produced by the Schmocker and Hester model agrees very well with the available TOC values derived from geochemical results (figs.14, 15, 16, table 1). This is verified by the cross-plot between TOC data from well log against geochemical analysis, which shows good correlation at $R^2 = 0.684$ (fig. 19).

B. Passey *et al.* [11] model

This method using ΔlogR separation between sonic DTC or density and deep resistivity Rt curves yielded TOC well log values that are in very good agreement with the TOC values obtained from lab measurements for all wells applied: Tane-1, North Tasman-1, Maui-4 and Inglewood-1 wells (figs. 14-17). Good TOC values are observed in zones with positive ΔlogR separation. They yielded similar results when calibrated with TOC values obtained from geochemical measurements (table 1). This accuracy is validated by a cross-plot developed between TOC core data and TOC well log data, which shows $R^2=0.748$ (fig 20). This good correlation strongly implies that the Passey *et al*. model may be used to quantify TOC in the study area where the geochemical data may be absent.

C. Zhao *et al.* [14] model

The I_{cl} method was applicable for two wells, North Tasman-1 and Fresne-1 wells. TOC values from I_{cl} method applied on both wells show good correlation when calibrated with geochemical TOC values (figs. 14, 18, table 1). This is supported by fig 21, where $R^2 = 0.795$. This indicates a good agreement between both TOC datasets, which suggests that conventional well logging data may be used in the absence of core geochemical data using this method developed by Zhao *et al.*

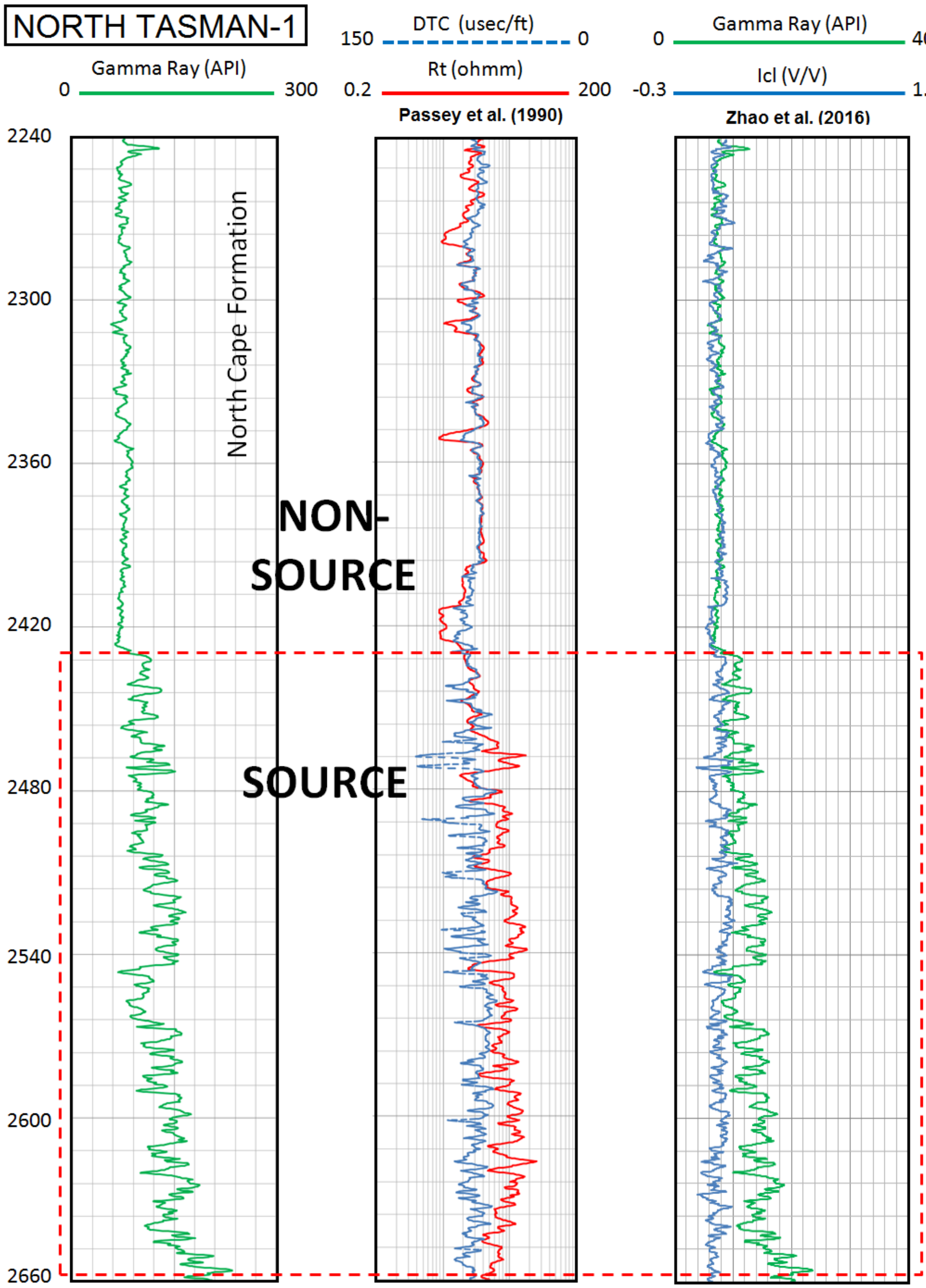

Figure 5. Identification of source intervals in North Cape Formation penetrated in North Tasman-1 well based on conventional well log responses using Passey *et al.* (1990) and Zhao *et al*. (2016) models

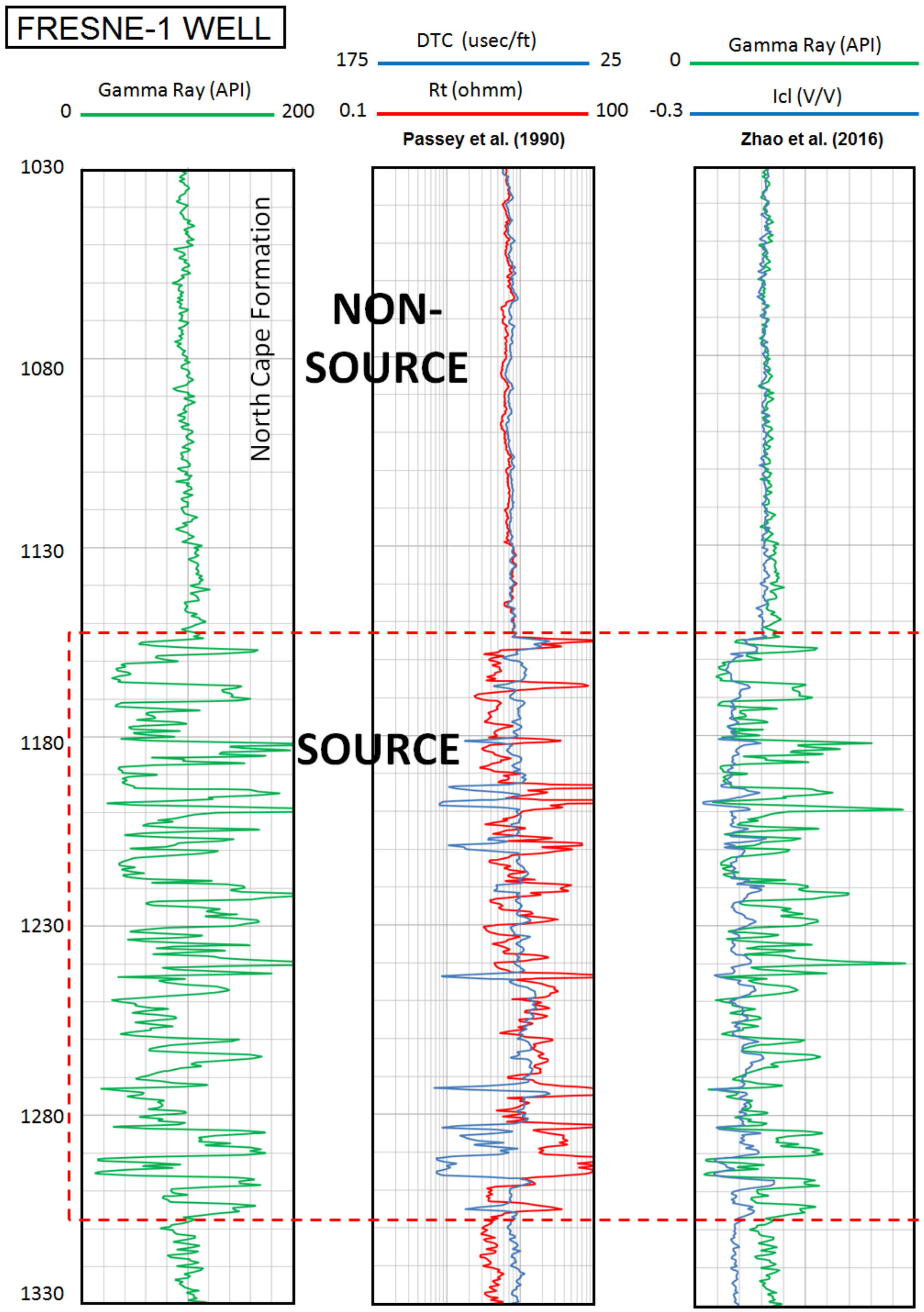

Figure 6. Identification of source intervals in North Cape Formation penetrated in Fresne-1 well based on conventional well log responses using Passey *et al.* (1990) and Zhao *et al.* (2016) models

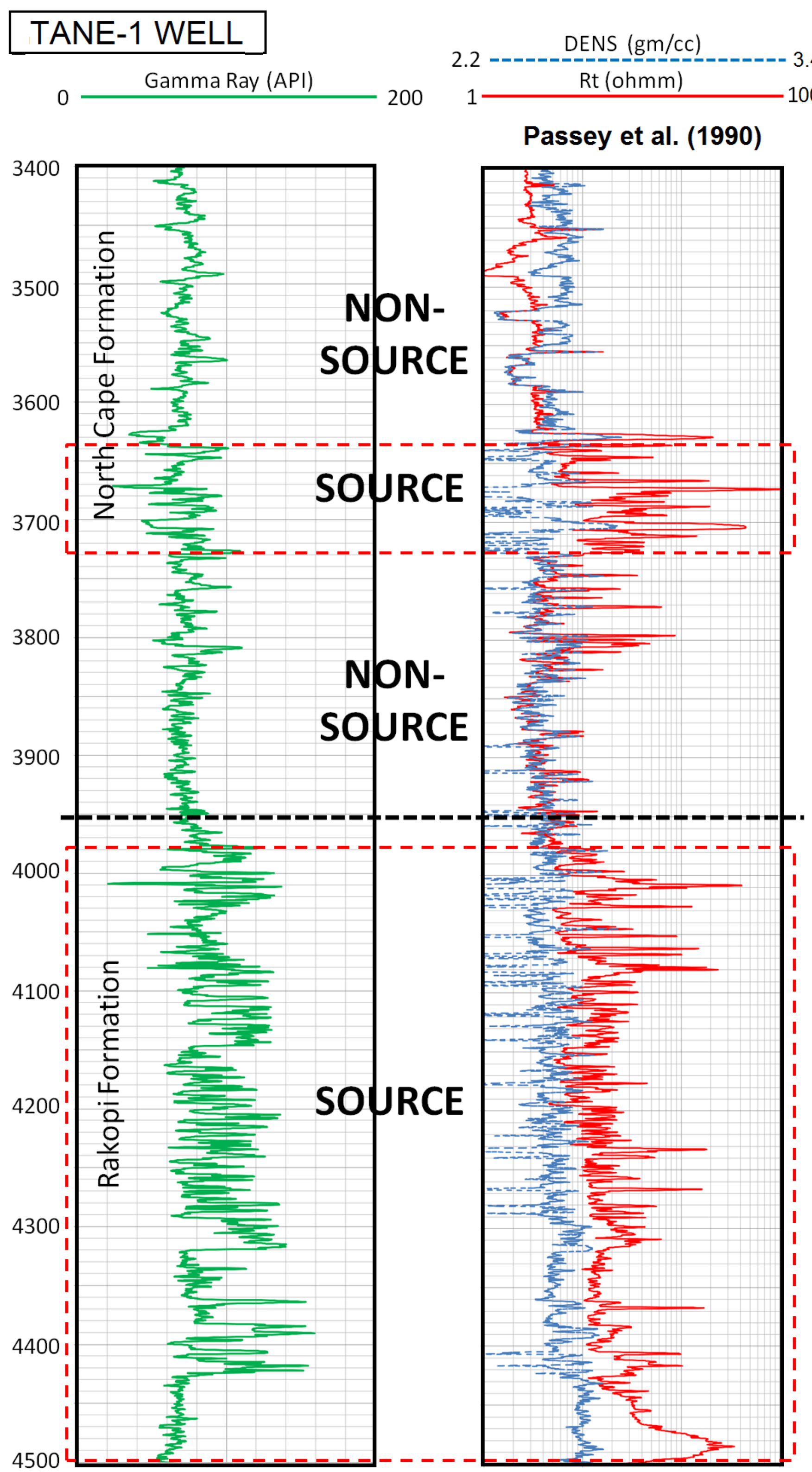

Figure 7. Identification of source intervals in Rakopi and North Cape Formations in Tane-1 well based on conventional well log responses using Passey *et al.* (1990) model

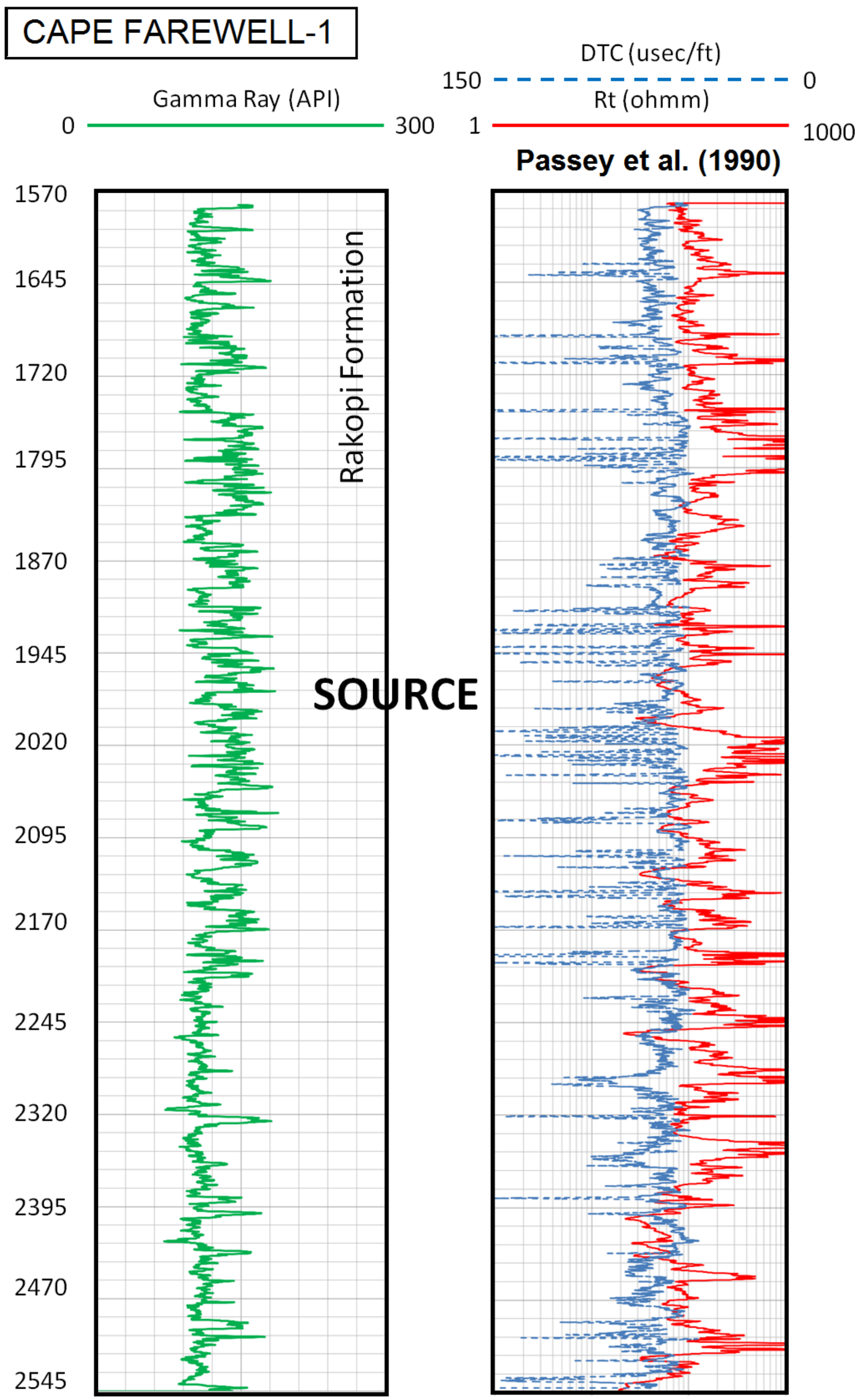

Figure 8. Identification of source intervals in North Cape Formation in Cape Farewell-1 well based on conventional well log responses using Passey *et al.* (1990) model

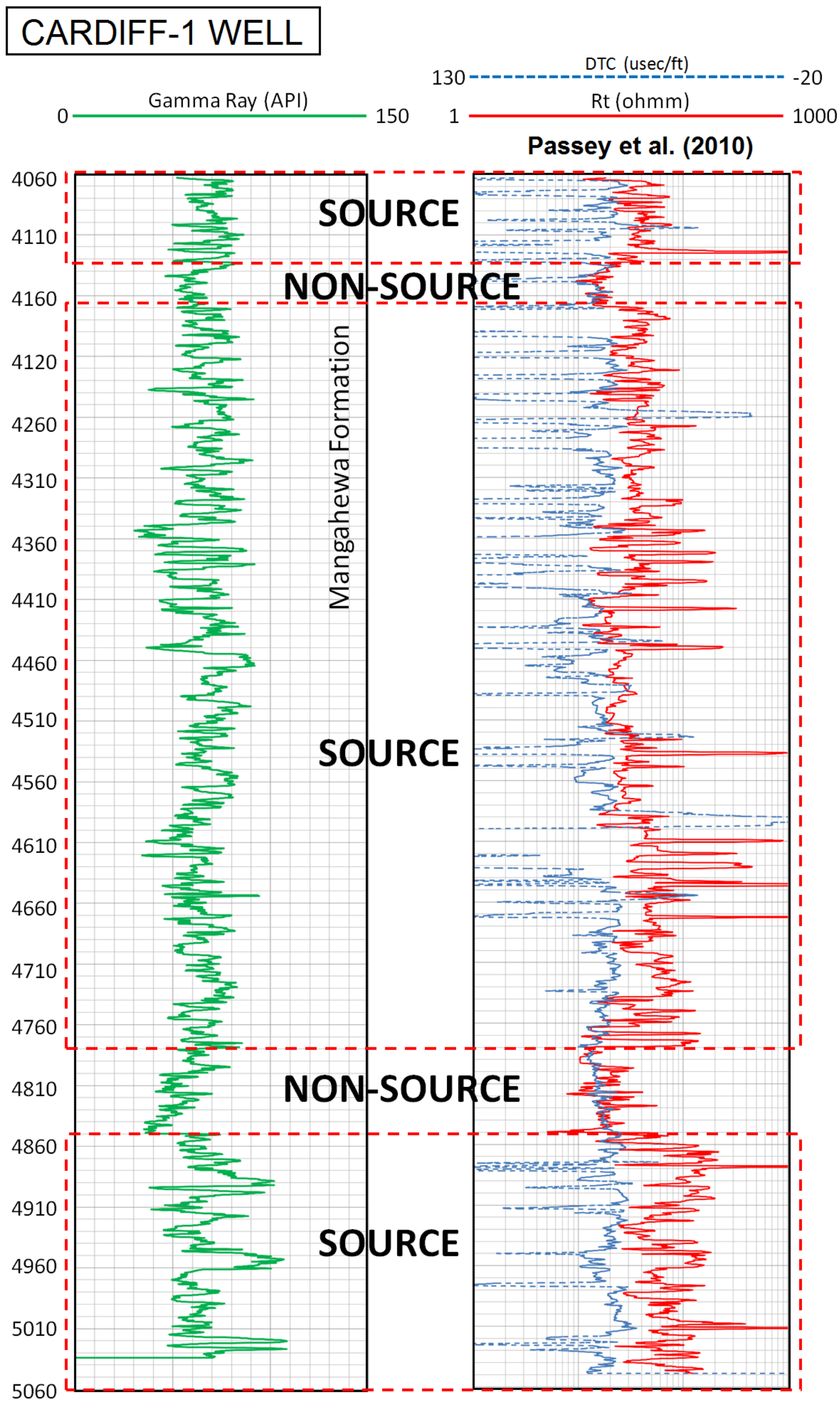

Figure 9: Identification of source intervals in Mangahewa Formation in Cardiff-1 well based on conventional well log responses using Passey *et al.* (1990) model

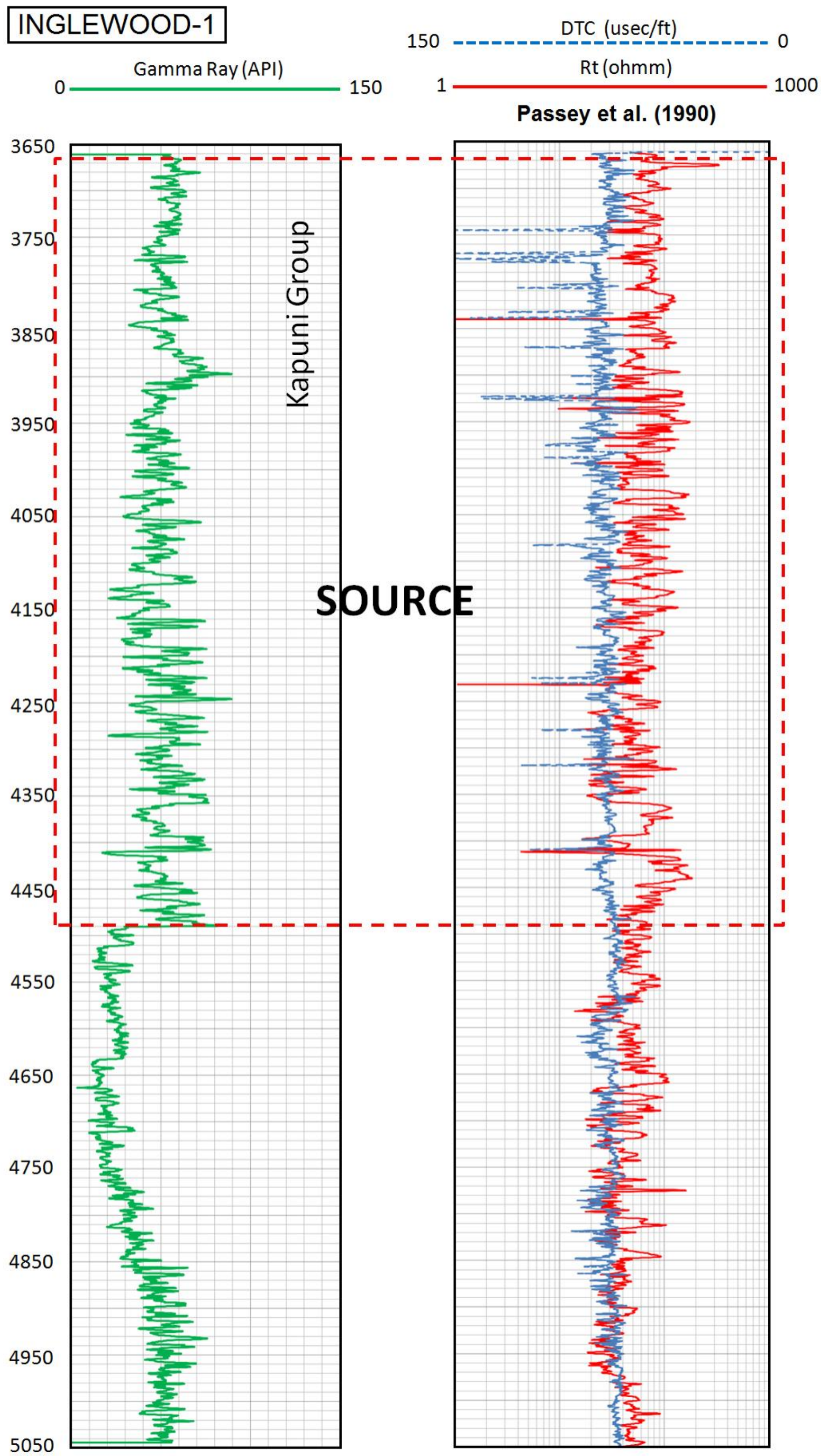

Figure 10. Identification of source intervals in Kapuni Mangahewa Formation in Inglewood-1 well based on conventional well log responses using Passey *et al.* (1990) model

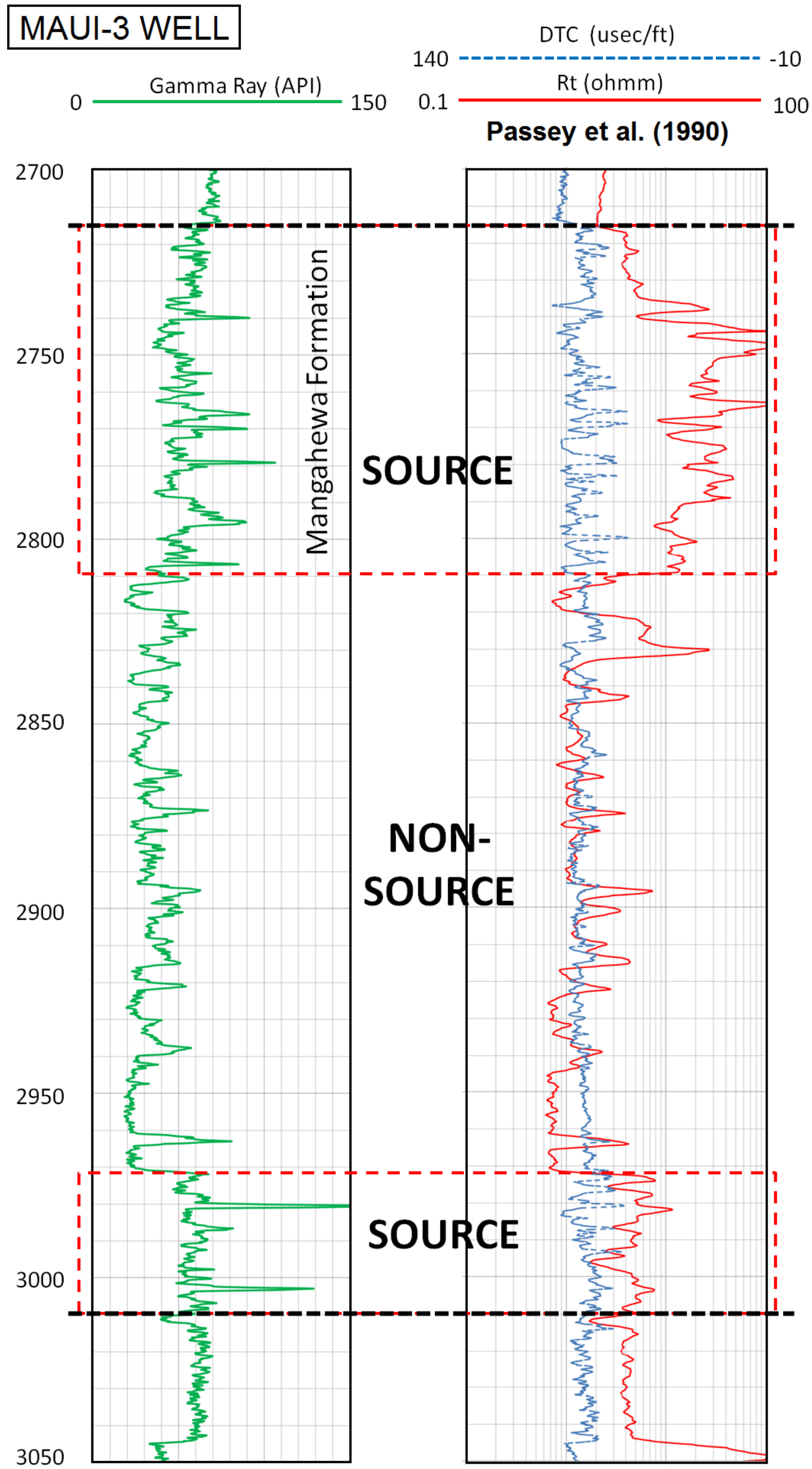

Figure 11. Identification of source intervals in Kapuni Mangahewa Formation in Maui-3 well based on conventional well log responses using Passey *et al.* (1990) model

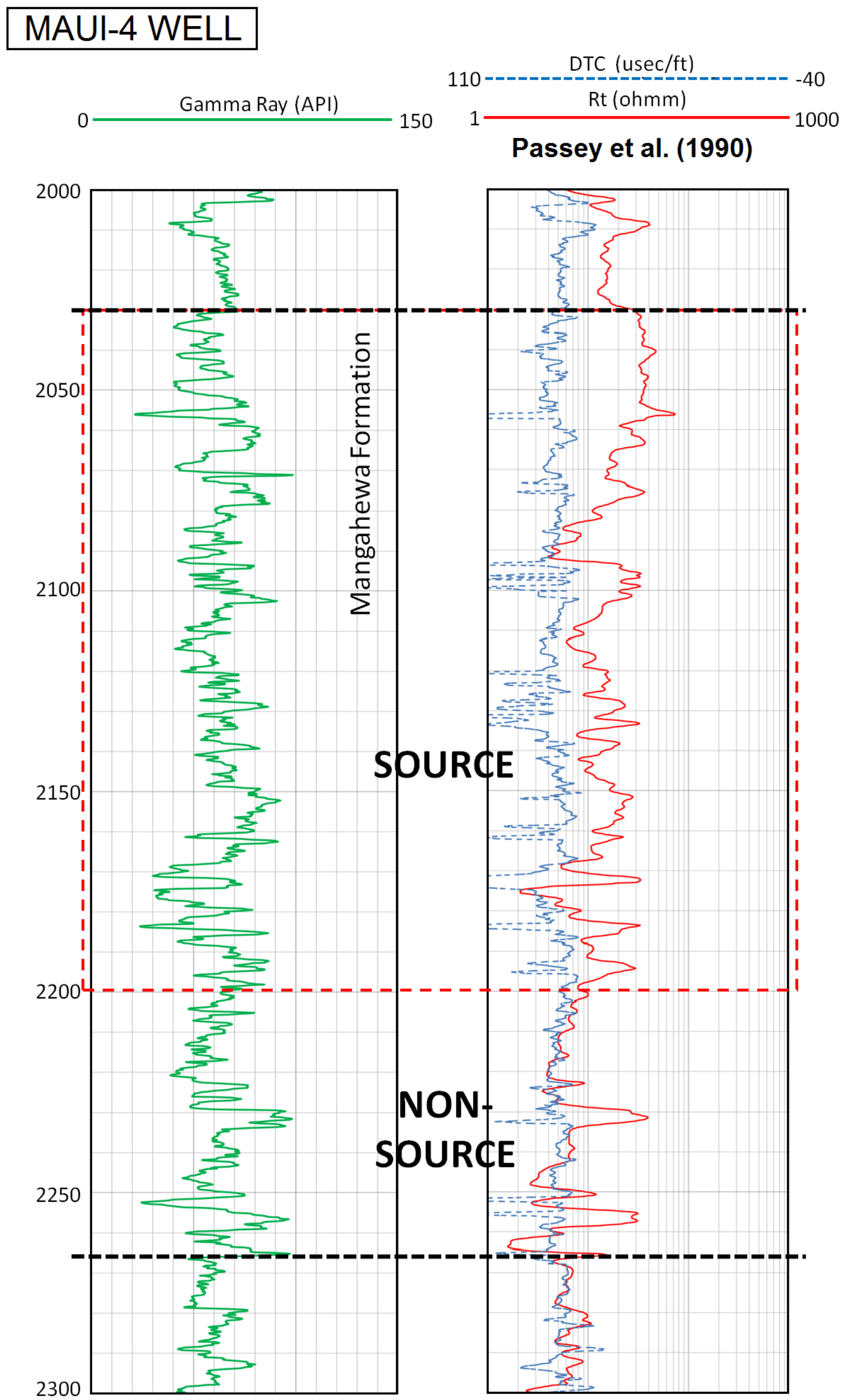

Figure 12. Identification of source intervals in Mangahewa Formation in Cardiff-1 well based on conventional well log responses using Passey *et al.* (1990) model

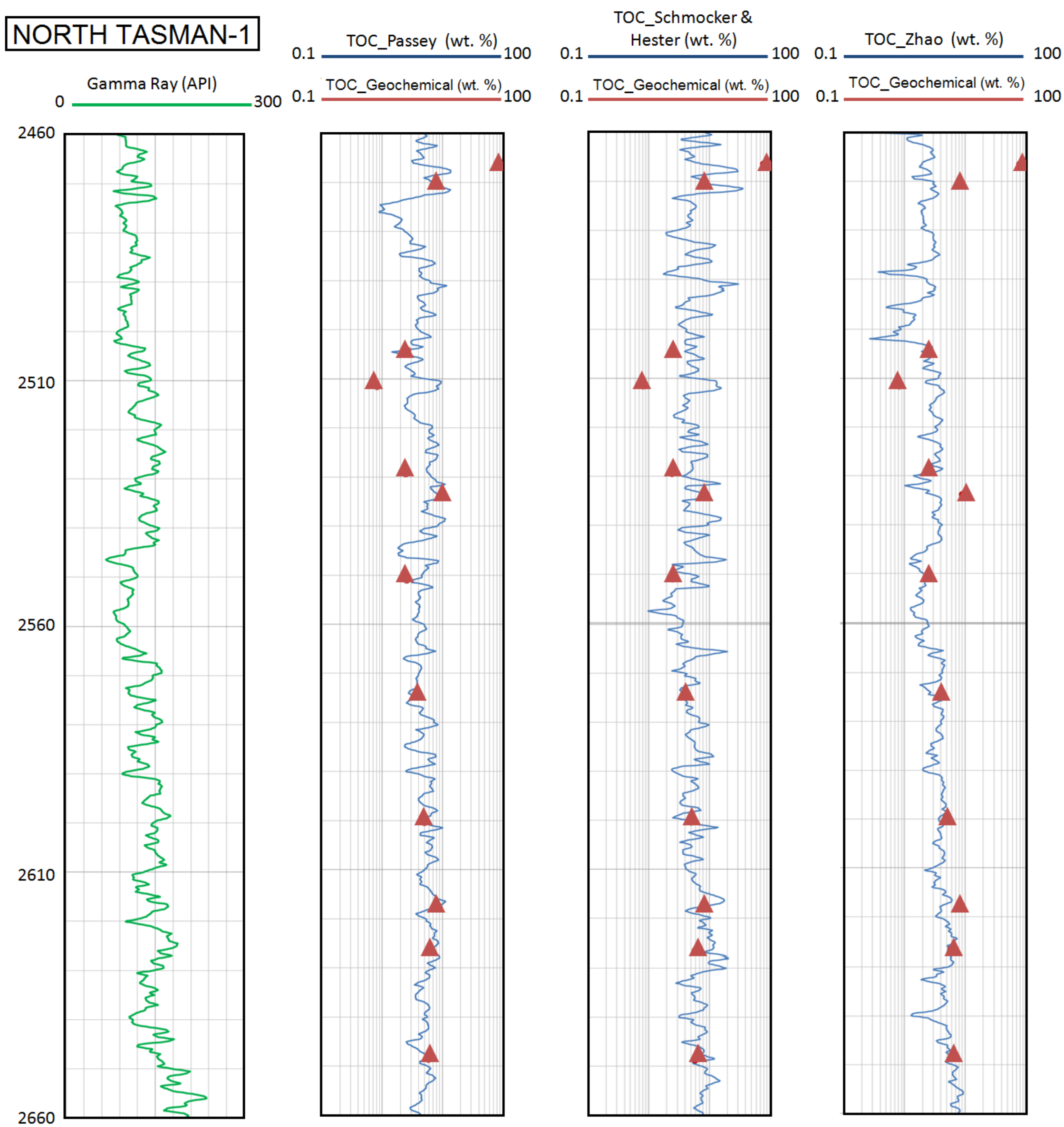

Figure 13. Correlation of TOC results between well log models and geochemistry data for the source intervals in North Tasman-1 well, based on Passey *et al.* (1990), Schmocker & Hester (1983) and Zhao *et al.* (2016) models

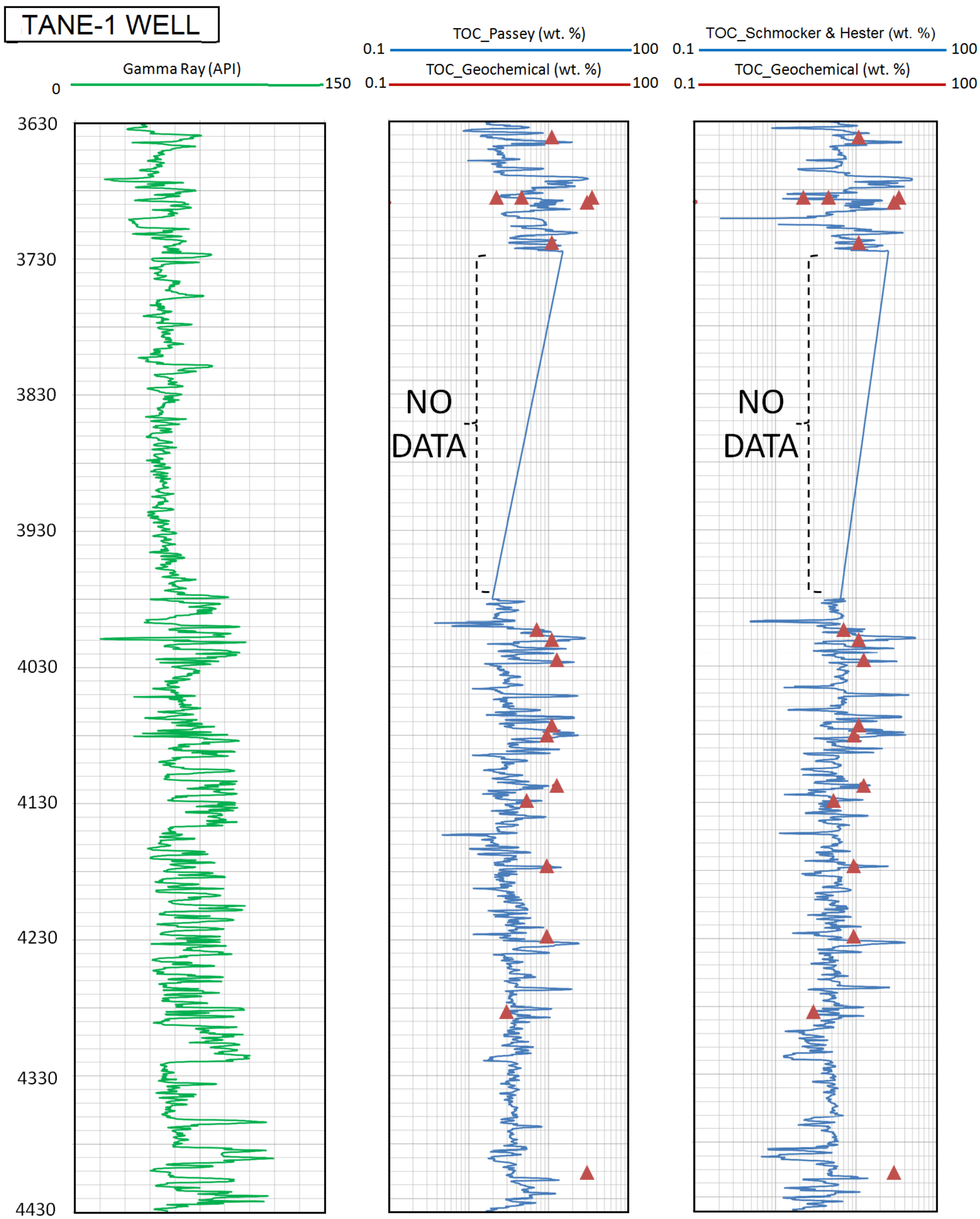

Figure 14. Correlation of TOC results between well log models and geochemistry data for the source intervals in Tane-1 well, based on Passey et al. (1990) and Schmocker & Hester (1983) models

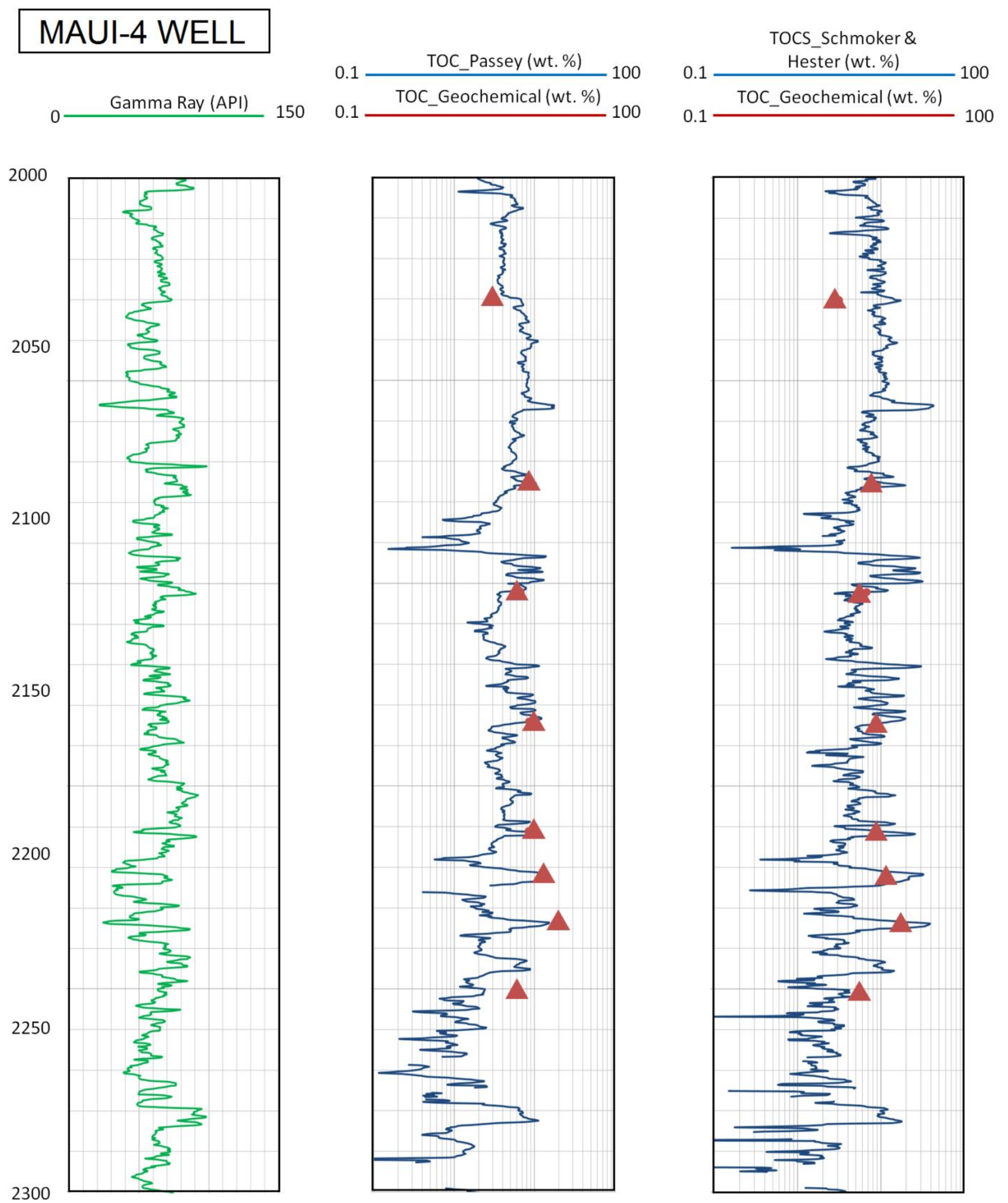

Figure 15. Correlation of TOC results between well log models and geochemistry data for the source intervals in Maui-4-1 well, based on Passey *et al.* (1990) and Schmocker & Hester (1983) models

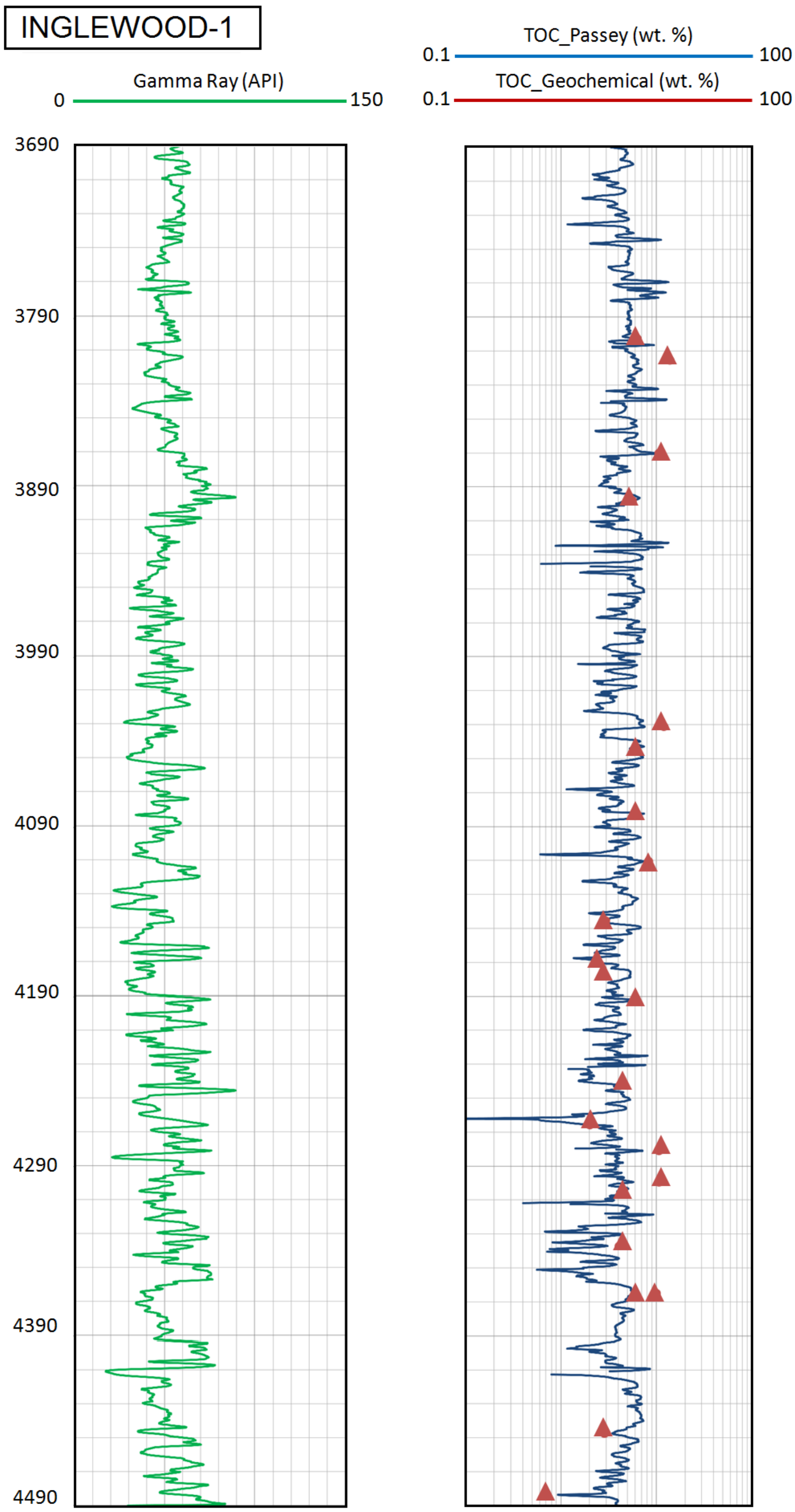

Figure 16. Correlation of TOC results between well log models and geochemistry data for the source intervals in Inglewood-1 well, based on Passey *et al.* (1990) model

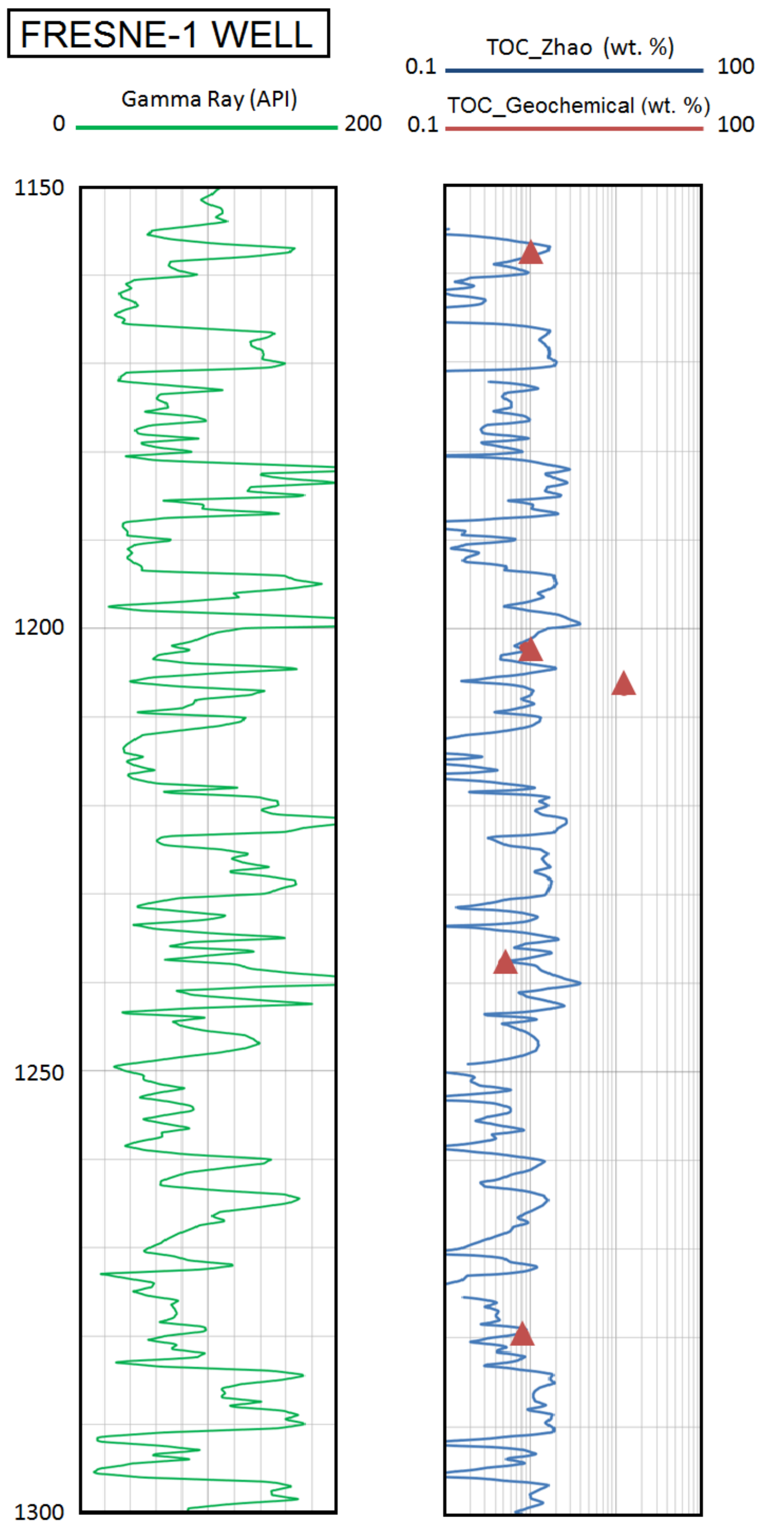

Figure 17. Correlation of TOC results between well log models and geochemistry data for the source intervals in North Tasman-1 well, based on Zhao (2016) model

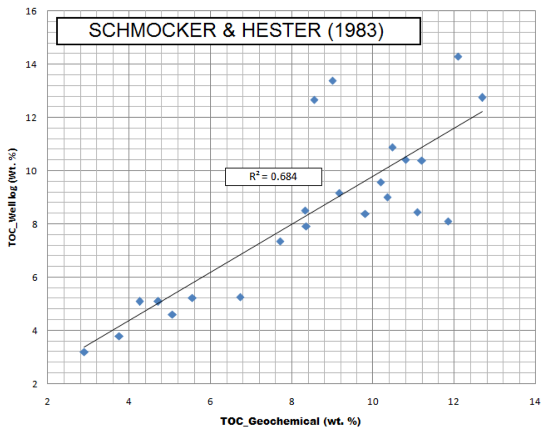

Figure 18. Crossplot between TOC from well log and TOC from core data for Schmocker & Hester (1983) model

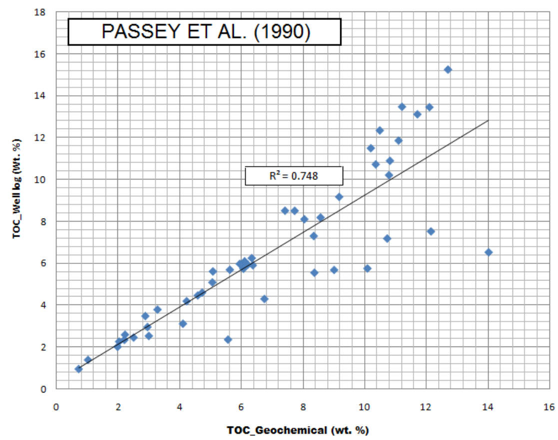

Figure 19. Crossplot between TOC from well log and TOC from core data for Passey *et al.* (1990) model

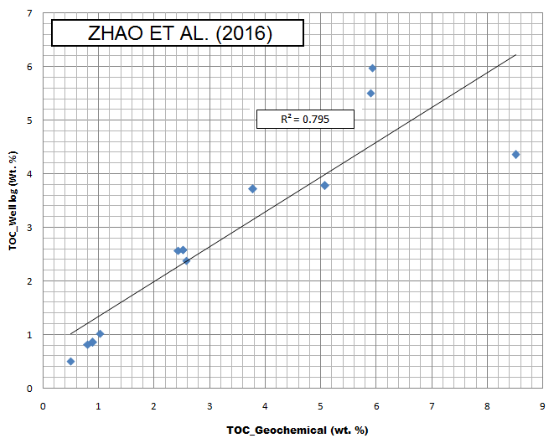

Figure 20. Crossplot between TOC from well log and TOC from core data for Zhao et al. (2016) model.

5. Conclusions

In this paper, eight wells were selected to produce a basin-scale integrated source rock characterization using well log and geochemical data for the main source rocks, Upper Cretaceous Pakawau Group and Paleocene Mangahewa formations of Taranaki Basin. Source zones have been identified based on the responses of conventional well log tools to the presence of source rocks using the ΔlogR separation method between deep resistivity Rt and sonic porosity DTC log readings and the Δd separation method between I_{cl} and Gamma Ray log curves. TOC values have been produced carefully from well log interpretation based on three renowned mathematical models, where it was concluded that all models applied show good correlation with the TOC values obtained from core geochemical measurements. The results showing strong agreement with geochemical data in all three models suggest their good applicability in the study area of Taranaki Basin. Hence, in the absence of geochemical data, well log data may be used to characterize Taranaki Basin source rocks where there is sufficient dataset.

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Abbreviations

TOC	*Total organic carbon content in weight %*
GR	*The Gamma Ray logging tool value reading in API gravity*
ΔlogR	*The curve separation between sonic log and resistivity log measured in logarithmic resistivity cycles*
Rt	*True resistivity measured in ohm.m*
DTC	*The sonic porosity log measured by the logging tool in μs/ft*
$R_{baseline}$	*The resistivity corresponding to the* $\Delta t_{baseline}$ *values when curves are baselined in non-source, clay-rich source rocks*
Δt	*The transit time for sonic porosity log in μs*
Δlog_{RDen}	*The curve separation between density log and resistivity log measured in logarithmic resistivity cycles*
P	*The density log value measured by the logging tool in* g/cm^3
ρ_b	*The bulk density in* g/cm^3
ρ_{ma}	*The density value of limestone, 2.71* g/cm^3
ρ_f	*The fluid density value, 1.0* g/cm^3
$\rho_{baseline}$	*The density porosity baseline value*
$\Delta logR_{Neut}$	*The curve separation between neutron log and resistivity log measured in logarithmic resistivity cycles*
Φ_N	*The neutron log value in porosity units*
$\Phi_{Nbaseline}$	*The neutron porosity baseline value*
LOM	*The level of organic maturity*
Φ_{Na}	*The apparent neutron porosity of the limestone calibration in volume/volume*
Φ_{Da}	*the apparent density porosity of the limestone calibration in volume/volume*
I_{cl}	*The clay indicator*
Δd	*The separation between GR' and* I_{cl}' *curves*
GR_left	*The left scale of the GR curve in API gravity*
GR_right	*The right scale of the GR curve in API gravity*
I_{cl}*_left*	*The left scale of the clay indicator curve*
I_{cl}*_right*	*The right scale of the clay indicator curve*
A	*The slope of the linear relationship TOC = aΔd + b*
B	*The intercept of the linear relationship TOC = aΔd + b*
R^2	*The coefficient of determination*

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