

CHAPTER 8 Source rock distribution

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INTRODUCTION

Numerous source rocks occur throughout the Late Jurassic to Tertiary section of the western Otway Basin, but knowledge of the source potential of Crayfish Group sediments is currently restricted to an area north of the Tartwaup Hinge Zone. These source rocks contain non-marine Type III–IV kerogens derived from land plants with some Type II algal-rich shales present, especially in the early rift succession.

The source potential of the Tertiary section is not discussed here due to limited analyses and its obvious lack of maturity.

Basal coals of the Eumeralla Formation are probably the best source rocks of the Early Cretaceous. By comparison, the source potential of the Late Cretaceous section is generally low and is restricted to the area south of the Tartwaup Hinge Zone. Shales tend to be dominated by Type IV (inertinitic) kerogens but improve in the offshore. However, potential for more abundant source rocks, which are possibly oil prone, exist beyond the present day shelf, but as yet have not been drilled (Figure 5.4)

The approach taken here is to detail the major source rocks within the western Otway Basin, in some instances extending this knowledge to the eastern Otway Basin. Each structural province within the basin shows highly variable source rock distribution, richness, and kerogen type and quality.

CASTERTON FORMATION

Source richness

Source rock geochemical data for the Casterton Formation are summarised in Table 8.1 and Figure 8.1. In general, organic richness is good, with total organic carbon (TOC) values commonly exceeding 1.5%. Genetic potential ($S_1 + S_2$) is moderate (mean 1.92 kg hydrocarbons per tonne). However, individual values vary considerably with locally excellent source quality (Casterton 1 (Vic.): 2389–2396 m, TOC = 45.90%, $S_1 + S_2 = 100.86$). Although thin, these intervals are capable of generating significant quantities of oil where mature.

Kerogen type and source potential

Hydrogen index (HI) values in Sawpit 1 are commonly low (~100) with correspondingly high oxygen index (OI) values (~300) indicating oxidised and/or Type III kerogen. However, in the basal Casterton Formation (Sawpit 1, 2501 m; Fig. 6.13) there is an increase in source potential and a terrestrial Type II–III kerogen is inferred. Pyrolysis gas chromatography (PGC) results indicate a prominence of mid range (C_5 – C_{14}) aliphatic compounds for this sample, suggesting a capacity to source light oil or condensate.

In Casterton 1, HI values (mean 128 mg S_2 /g TOC) range from 59 to 459 (Table 8.1), suggesting that some intervals have the capacity to source oil, although in general the formation is gas and oil prone. The richest source intervals also occur towards the base of the unit, possibly reflecting high concentrations of terrestrial detritus in localised rift lakes. As the rift widened, these lakes presumably enlarged and the terrestrial input was diluted and dispersed.

Organic petrology

Samples at 2498 and 2505 m in Sawpit 1 have up to 40% lipid-rich detritus (i.e. land-plant derived) that is partly degraded and oxidised (Price, 1993). The prominence of fresh planktonic algae supports the notion of a deeper anaerobic water system (i.e. deep rift lake). Minor oxidisation of the lipids occurred possibly during transport, and the restricted diversity of aquatic flora suggests specialised water nutrient conditions, possibly dystrophic. Lamalginite is common to abundant. Dispersed organic matter (DOM) is abundant, with

inertinite and liptinite common to abundant, and vitrinite rare. Oil drops fluorescing greenish yellow with a rare oil haze were observed in one sidewall core at 2498 m.

Table 8.1 Rock-Eval pyrolysis data, western Otway Basin

Well	Depth (m KB)	TOC (%)	Genetic potential (S1+S2)	Oxygen index	Hydrogen index	Kerogen Type	Unit
Casterton 1	2211	1.01	0.75	57	111	3	Casterton
	2281	1.8	3.23	10	153	2	Casterton
	2302	3.65	5.9	56	143	2	Casterton
	2323	1.3	2.48	62	175	2	Casterton
	2360	1.07	1.3	59	108	3	Casterton
	2363	2.1	1.34	63	59	3	Casterton
	2389	45.9	100.86	5	192	2	Casterton
	2396	1.35	2.47	48	151	2	Casterton
	2422	0.44	2.29	59	459	1+	Casterton
Sawpit 1	2482	1.46	1.95	32	107	3	Casterton
	2501	1.29	3.21	33	216	2	Casterton
	2505	0.7	1.21	501	139	2	Casterton
Camelback 1	1683	0.79	1.04	339	108	3	Unnamed shale
	1710	0.81	0.74	308	79	3	Unnamed shale
	1753	1.26	1.31	271	88	3	Unnamed shale
Sawpit 1	2450	1.56	2.03	462	108	3	Unnamed shale
	2458	1.89	2.72	112	490	1	Unnamed shale
	2461	1.88	2.7	422	118	3–2	Unnamed shale
Lake Hawdon 1	1981	1.46	1.54	108	89	3	Unnamed shale
	2002	1.67	1.17	532	57	3	Unnamed shale
	2048	1.43	1.22	806	71	3	Unnamed shale

PRETTY HILL FORMATION

The source potential of the Pretty Hill Formation is discussed in two parts. The basal section is predominantly shalier and referred to informally as the ‘unnamed basal shale’; Lovibond et al. (1995) referred to it as *C. australiensis* shale. The remainder of the formation comprises interbedded sandstone, siltstone and shale with rare coal laminae.

Basal shale

Source richness

Source rock geochemical data for the ‘basal shale of the Pretty Hill Formation are summarised in Table 8.1 and Figure 8.2. The source richness of the unnamed basal shale is highly variable between wells and even within individual sections. For example, in Robertson 1 (1749 and 1765 m; Fig. 6.13), ~10% of cuttings are oil shale with telaginite and lamalginite as major constituents (McKirby et al., 1994). These authors noted that the oil shale lithofacies is quite thin, located between 1762 and 1765 m, and is interbedded with siltstone containing high concentrations of Type III–IV DOM. Within this zone, TOC values of 7% (i.e. excellent source richness) have been recorded although the mean for the unnamed basal shale in Robertson 1 is 2.81%. Likewise, the genetic potential for this thin oil shale is 37 kg hydrocarbons/tonne (i.e. excellent source richness and quality) compared to a mean of 8 kg hydrocarbons/tonne for the entire unit.

With the exception of Robertson 1, where it appears that selective sampling may have given a weighted bias, the remaining wells intersecting this shale have good source richness (mean TOC = 1.44%) and marginal, to at best moderate, source quality (mean genetic potential = 1.61 kg hydrocarbons/tonne). Source richness and quality are summarised in Table 8.1.

Kerogen type and source potential

In terms of the DOM composition, the humic, inertinite-rich sediments of the unnamed basal shale are organically lean (excluding the thin oil shale zones in Robertson 1 and Penola 1), and are considered to be gas prone. The oxidised, humic-rich, gas-prone nature of the section is supported by Rock-Eval data (Table 8.1). HI values are commonly <100 with OI values mostly >300, indicating oxidised Type III kerogen.

Oil shales in Robertson 1 and Penola 1 have excellent potential to generate oil and are typically Type II kerogen. Kerogen type and source potential parameters are summarised in Table 8.1.

Organic petrology

Organic matter is dominated by humic detritus, often finely divided, and the lipid-rich detritus fraction rarely exceeds 25% of the residue. In Sawpit 1, the lipid detritus tend to be partly degraded and oxidised.

Intra-Pretty Hill Formation (Sawpit) shales

There are numerous potential source rock intervals within the Pretty Hill Formation other than the unnamed basal shale. On seismic evidence, the thickest source intervals occur on the northern flanks of the Penola Trough where they have been intersected by Sawpit 1 (Fig. 6.13), Jacaranda Ridge 1 and Viewbank 1 (Fig. 6.12). Characteristics of this interval are summarised below.

Source richness

Source richness of the intra-Pretty Hill Formation shale is fairly uniform and constitutes a good source rock (mean TOC = 1.22%). Source quality is marginal to moderate (mean genetic potential = 1.84 kg hydrocarbons/tonne). By comparison, mean TOC values for the Pretty Hill Formation across the basin are highly variable (Figs 8.3, 8.4).

Kerogen type and source potential

There is little variation in kerogen type and source potential between the unnamed basal shale and intra-Pretty Hill shale. The shale is slightly less oxidised (mean OI = 220) and HI values are quite consistent (mean = 131), both indicating a humic-rich, gas-prone Type III kerogen.

Organic petrology

Organic matter in the sampled section is dominated by humic detritus, often finely divided (Price, 1993). Inertinite dominates almost all samples, with vitrinite common to abundant and liptinite sparse. Lamalginite, cutinite and sporinite are sparse.

LAIRA FORMATION

Source richness

The source potential of the Laira Formation has been studied by Austin (1992) and Hill (1995). Its prospectivity has been elevated as a result of high TOC and genetic potential values which correspond to discrete zones containing high yields of the acritarch

Microfastra evansii identified in sidewall cores and cuttings in the Katnook – Ladbroke Grove region (Morgan, 1993).

Algal-rich zones, which correspond to lake maxima, occur in five mappable units (Fig. 8.5) and are best developed in the upper Laira Formation. They reflect a transition from the fluvial coastal plain depositional environment of the Pretty Hill Formation and lower Laira Formation to a shallow lacustrine environment in the upper Laira Formation. In Ladbroke Grove 1, *M. evansii* comprises 40–70% of the fossil assemblage in some sidewall cores in the upper Laira Formation. These algal maxima can be correlated over the Katnook – Ladbroke Grove – Laira–Zema region (Hill, 1995) and have fair to excellent source richness. They are more frequent near to the top of the formation, where they are associated with a distinct gamma ray peak. This increase is presumably in response to a broadening of the lake system prior to uplift and adjustment of the basin associated with the transition from rift to sag phase, culminating in the unconformity at the top of the Crayfish Group.

Mean TOC values vary from 0.25 to 2.02% (i.e. poor to good source richness) with the richest source rocks occurring along the axes of troughs (Fig. 8.6). Genetic potential values range from poor to moderate and follow a similar trend to source richness, with the best quality source rocks occurring in the Chama Terrace and eastern Penola Trough.

Kerogen type and source potential

HI values indicate that the Laira Formation is predominantly Type IV grading to at best Type III kerogen, and is mainly gas prone (Fig. 8.7); OI values are commonly low. In the Ladbroke Grove – Katnook region, intervals coincident with algal maxima have HI values >150 and contain Type III kerogen capable of generating some liquids, although these zones have limited thickness and variable source richness and quality. In Ladbroke Grove 1, algal maxima constitute 9% (66 m) of the total Laira Formation.

EUMERALLA FORMATION

The source potential of the Eumeralla Formation has been investigated by Struckmeyer and Felton (1990) and Tupper et al. (1993). These authors identified a thick potential source sequence within the lower Eumeralla Formation characterised by thin bituminous coal seams up to 1 m thick which constitute ~30% of the total source interval.

Two broad source intervals were identified by Tupper et al. on the Chama Terrace (Fig. 8.8). The lower occurs within the *Pilososporites notensis* palynological zone and has a maximum thickness of 140 m in Geltwood Beach 1 and Chama 1A. It is absent from wells drilled close to the basin margin. The upper interval is less well developed and occurs at the base of the *Crybelosporites striatus* zone. It has a maximum thickness of 120 m in Geltwood Beach 1.

Source richness

TOC and Rock-Eval analyses have been summarised by McKirdy and Padley (1992) and Hill (1995). These data consistently demonstrate marked differences in kerogen type between the lower Eumeralla source intervals and the siltstone and mudstone dominated upper Eumeralla Formation. In the Chama Terrace, coal is best developed in the *P. notensis* source interval (Tupper et al., 1993) where TOC values (mean = 31%) and potential yields (mean $S_1 + S_2 = 85$ kg hydrocarbons/tonne) indicate excellent source richness. In contrast, upper Eumeralla source rocks have low to moderate organic richness (mean TOC = 1% and poor to fair genetic potential (mean $S_1 + S_2 = 1.1$ kg hydrocarbons/tonne).

Kerogen type and source quality

Hydrogen indices for the *P. notensis* source interval are high (mean HI = 244 mg S_2 /g TOC), consistent with Type II–III kerogen and potentially capable of generating oil and gas

(Fig. 8.9). Source quality in the upper Eumeralla Formation deteriorates (mean HI = 59), indicating gas-prone Type IV kerogen.

The most basinward well intersection of the Eumeralla Formation occurs at the southern margin of the Chama Terrace where the sedimentary package thickens and improves in source quality. The extent and likely direction of source quality improvement beyond well control can only be surmised from seismic interpretation. Figure 12.30 shows a thick package of high amplitude reflectors associated with the coals near the base of the Eumeralla in Troas 1 on the Chama Terrace. Similar high amplitude reflectors can be seen extending out into the basin and increasing in amplitude. In Figure 5.4 these have been tentatively mapped as upper Eumeralla Formation coals to possibly Waarre Sandstone equivalent, but they could also be as deep as the lower Eumeralla because the correlation across the Tartwaup Hinge Zone is very difficult. The Songliao Basin of NE China (Yang et al., 1985) has significant oil production in an almost identical setting to the Eumeralla Formation. Source rock quality changes from Type IV at the basin margin where the sediments are predominantly fluvial, grading to Type II–III and eventually Type I kerogen associated with lacustrine sediments at the basin centre. The difficulty with predicting source quality for the Eumeralla Formation is determining its depocentre.

Organic petrology

The *P. notensis* source interval maceral assemblage is dominated by vitrinite with variable amounts of liptinite and subordinate inertinite. Exasudatinite infills fractures and open cell lumens in inertinite (Tupper et al., 1993). Solid bitumen and oil oozing from cracks in detrovitrinite occur in Chama 1A (2502–2505 m) and Crayfish 1A (1539–1542 m). The *C. striatus* hydrocarbon source interval comprises mostly siltstone with low to moderate amounts of DOM of mixed algal and plant origin. Vitrinite and liptinite predominate over inertinite.

WAARRE SANDSTONE

Coals have been intersected near the base of the Waarre Sandstone in some Victorian wells (Normanby 1, Flaxman 1 (Fig. 6.32) and Minerva 1). These have been assigned to a lower delta plain to delta front environment (Lavin, 1998) with consequent marine influence. Geochemical data (Geary and Reid, 1998) suggests that some of the oil found within the Waarre Sandstone (Minerva 2A) was sourced from these coals.

Source richness

Lavin (1998) stated that:

there has been little work studying the source potential of Waarre coals ... 'cores cut through the upper Waarre Formation [Sandstone] in Minerva-1 and 2A demonstrate the presence of thin coals that are extremely rich in resinite nodules. It is not known whether these resinites are abundant in the lower Waarre Formation, as there are no petrographic descriptions of the lower Waarre coals.

In addition Constantine et al. (2001) also stated that:

characteristics conforming to rich, marine-influenced perhydrous coaly source rocks in the Waarre Formation [Sandstone] are conjectural and relate to a small number of analyses undertaken on samples from Normanby-1, Minerva-2A and Eric the Red-1, together with assumptions about facies development in postulated kitchen areas.

Kerogen type and source potential

Having made the above statement, Constantine et al., (2001) then displayed a Van Krevlin diagram (their figure 8) containing >50 samples for the Waarre Sandstone, with 10 having HI values from Rock-Eval >400. Previously Lavin (1998) had stated that 'only four samples have

been evaluated from the Waarre Sandstone coals in the Otway Basin'. Furthermore when modelling maturity of source rocks in the Waarre, Constantine et al. (2001). assigned them to Type II. However, further investigation has revealed that Rock-Eval conducted on samples from Bridgewater Bay 1 appear to have been included in their figure 8 despite the fact that the section over the Waarre Sandstone in Bridgewater Bay 1 was drilled with up to 10% diesel in the mud system and this may account for the high HI values.

Overall in the absence of access to raw Victorian data, Lavin (1998) appears to be the more reliable source of information and he went on to state that 'three of the four samples indicate HI values over 200, which include two samples from the oil mature Normanby 1'

If the high amplitude reflectors seen in the deepwater sector of the basin (Fig. 5.4) are of similar age to the Waarre Sandstone then it is quite possible that these represent a thick coal sequence and a prolific oil source rock not previously recognised in the Otway Basin. Such a petroleum source rock may be related to, but not responsible for the abundant coastal asphaltites (assigned to an anoxic marine source, CJ Boreham, Geoscience Australia, pers. comm., 2002) that are periodically stranded along the nearby coast with an increased frequency after earthquake activity (Edwards et al., 1998).

BELFAST MUDSTONE

Source richness

TOC ranges from 2.40 to 3.0% (i.e. fair to very good) with an observed increase in source richness to the south in the vicinity of Breaksea Reef 1 (mean TOC = 1.5%). The genetic potential of the Belfast Mudstone ranges from poor to moderate, with the richest source rocks occurring in the vicinity of Breaksea Reef 1 (mean $S_1 + S_2 = 2.63$, range 0.30–5.92; Fig. 8.10). This confirms the view that both source quality and richness improve to the south and that more favourable source rocks could occur in the deeper offshore areas.

Kerogen type and source potential

Gravestock et al. (1986) likened the Sherbrook Group to the Tertiary succession of the Niger Delta. In terms of source potential, however, there is limited similarity with this analogue. Geochemical data indicate a Type IV (inertinitic) grading to at best Type III kerogen (Fig. 8.11). The Belfast Mudstone is composed of terrigenous DOM rich in inertinite (I = 75–90%) and lean in vitrinite ($V \leq 20\%$). Moreover, the majority of inertinite is reworked (McKirdy et al., 1984). Exinite remains a minor component of DOM ($E \leq 5\%$). McKirdy et al. (1984) highlighted an obvious discrepancy between the highly inertinitic character of the DOM within the Belfast Mudstone and the overall Type III kerogen composition in Breaksea Reef 1. A possible explanation may be provided by the widespread occurrence of trace oil and bitumen in the cuttings which would elevate the S_2 peak on pyrolysis. In contrast, prodelta muds of the Niger Delta are commonly of Type III and to a lesser extent Type II kerogen. A key to the viability of the Belfast Mudstone as an oil source may be to delineate a more distal facies to the south and west of Breaksea Reef 1 (Figure 5.5) and beyond the present day shelf break.

HI values are highly variable and indicate that the Belfast Mudstone is predominantly gas prone (i.e. $HI < 100$). In Breaksea Reef 1, HI values range between 17 and 181 mg S_2/g TOC. Although considered to be predominantly gas prone, HI values frequently exceed 150, indicating some potential to generate liquids.

FIGURES

- 8.1 HI versus T_{max} plot, Casterton Formation
- 8.2 HI versus T_{max} plot, basal unnamed shale
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- 8.4 HI versus T_{max} plot, Pretty Hill Formation
- 8.5 Cross-section from Banyula 1 to Ladbroke Grove 1 showing the informal subdivision of the Laira Formation based on algal maxima, Penola Trough
- 8.6 Mean TOC map, Laira Formation
- 8.7 HI versus T_{max} plot Laira Formation
- 8.8 Cross-section from Geltwood Beach 1 to Crayfish 1A showing source rock development within the lower Eumeralla Formation
- 8.9 HI versus T_{max} plot Eumeralla Formation
- 8.10 Mean genetic potential, Belfast Mudstone
- 8.11 HI versus T_{max} plot Belfast Formation

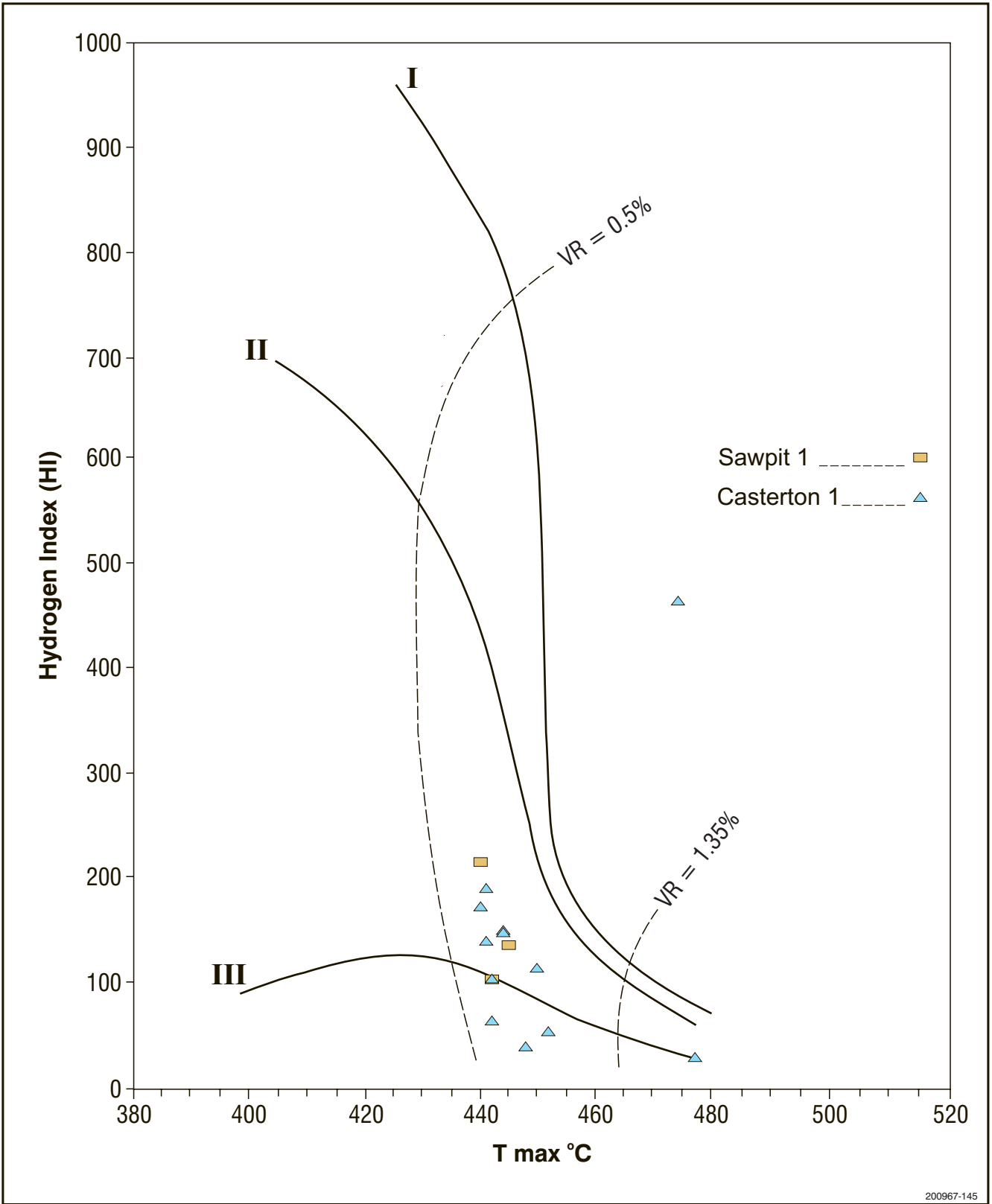


Figure 8.1 HI versus T_{max} plot, Casterton Formation

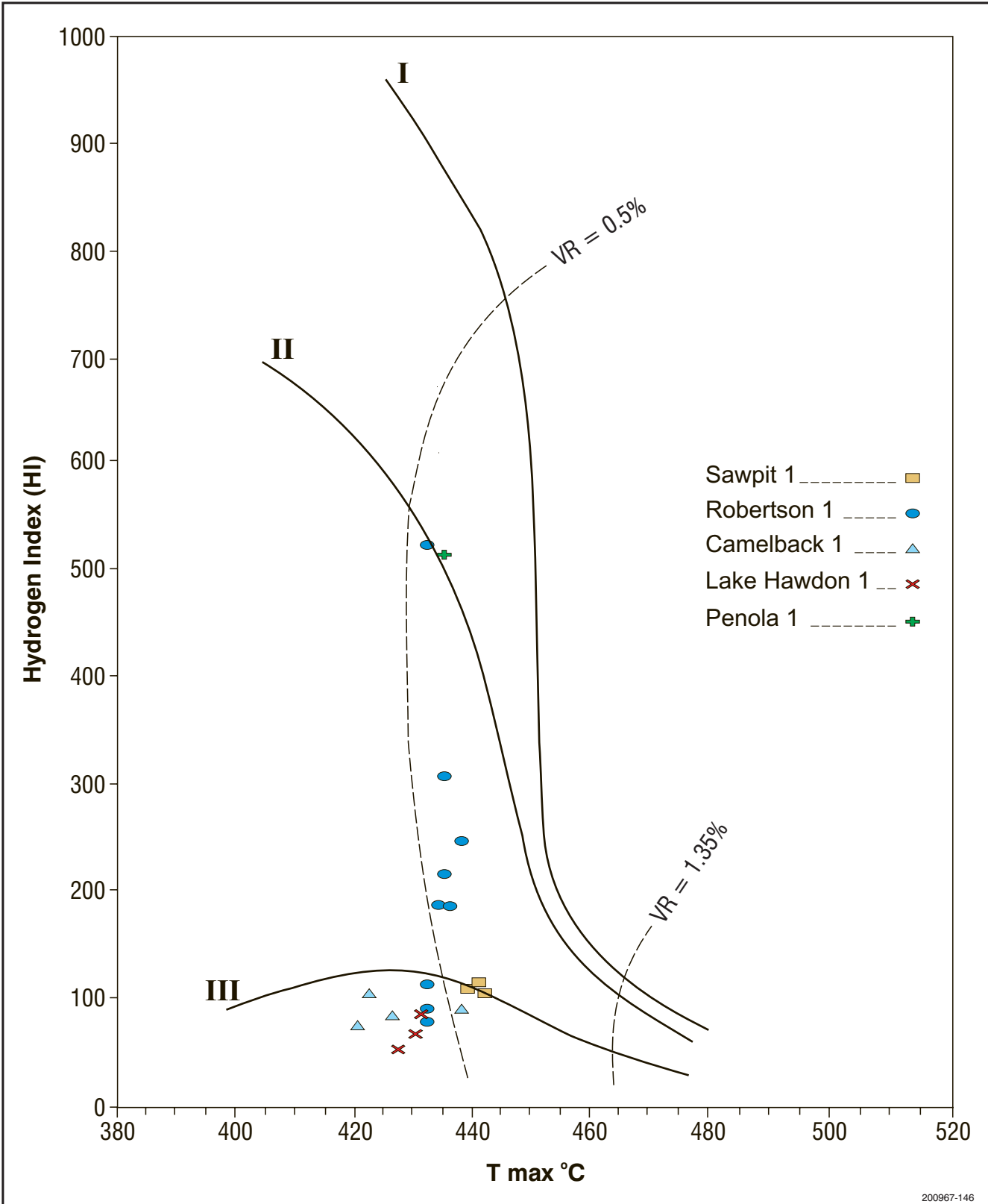


Figure 8.2 HI versus T_{max} plot, basal unnamed shale

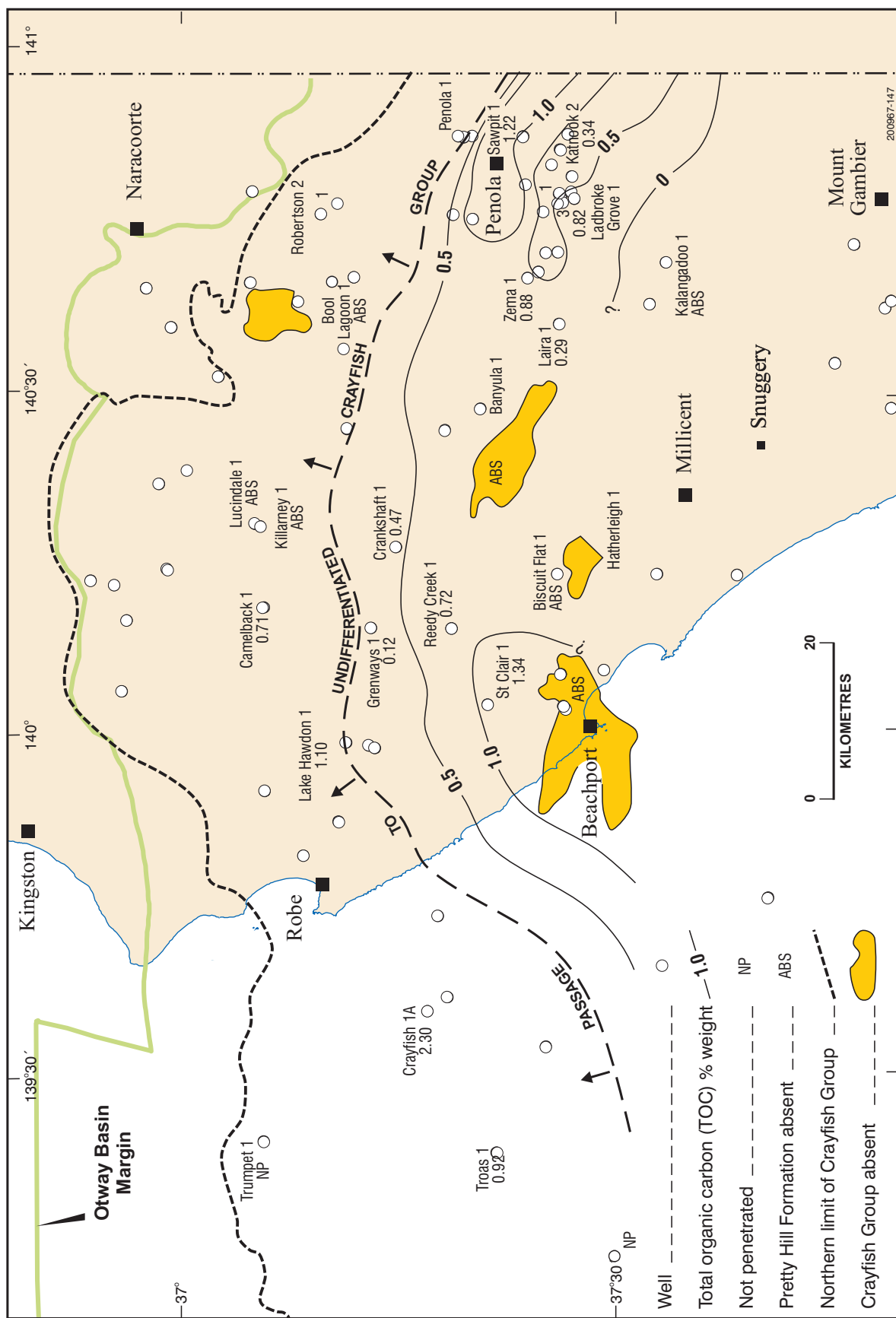
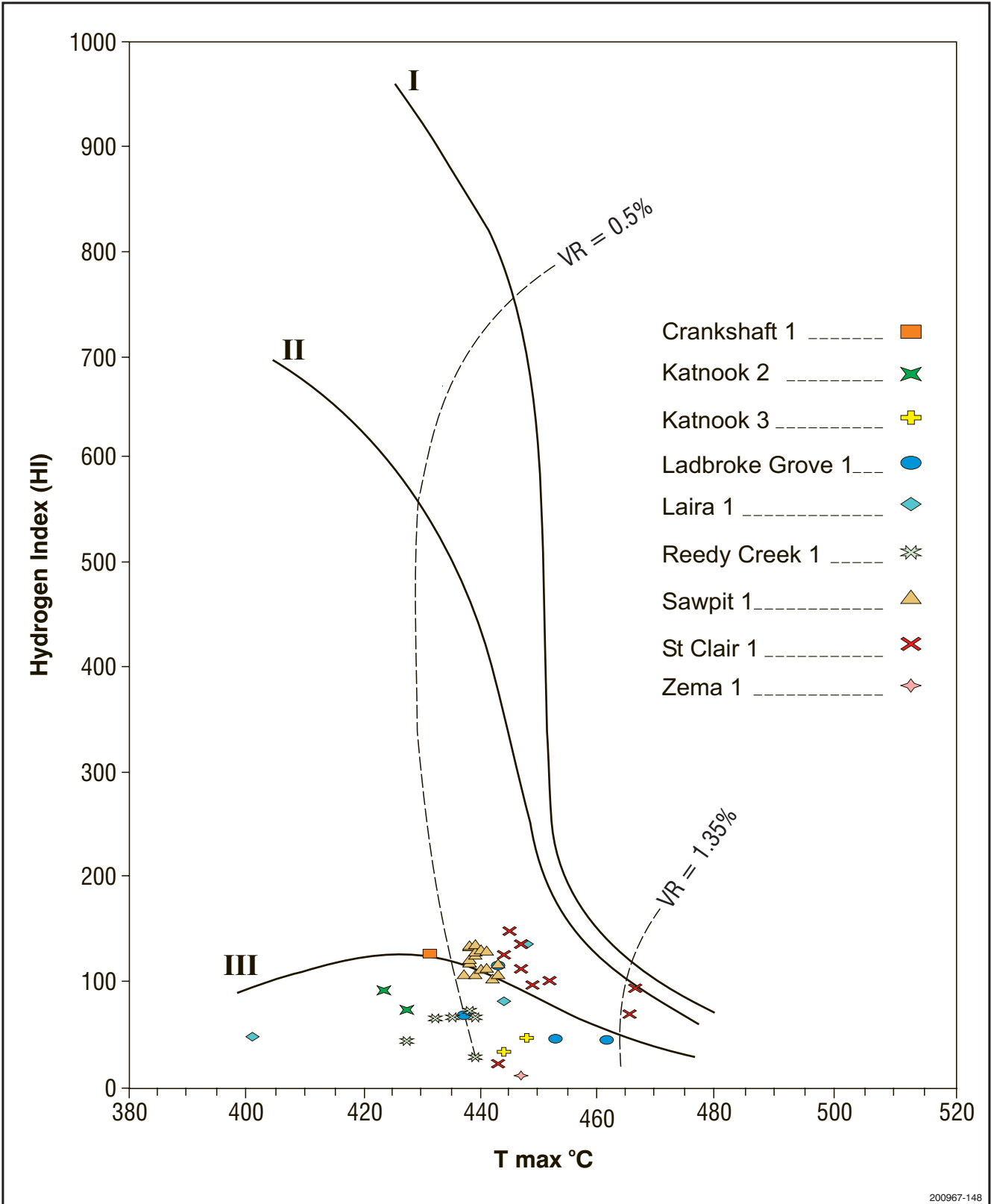
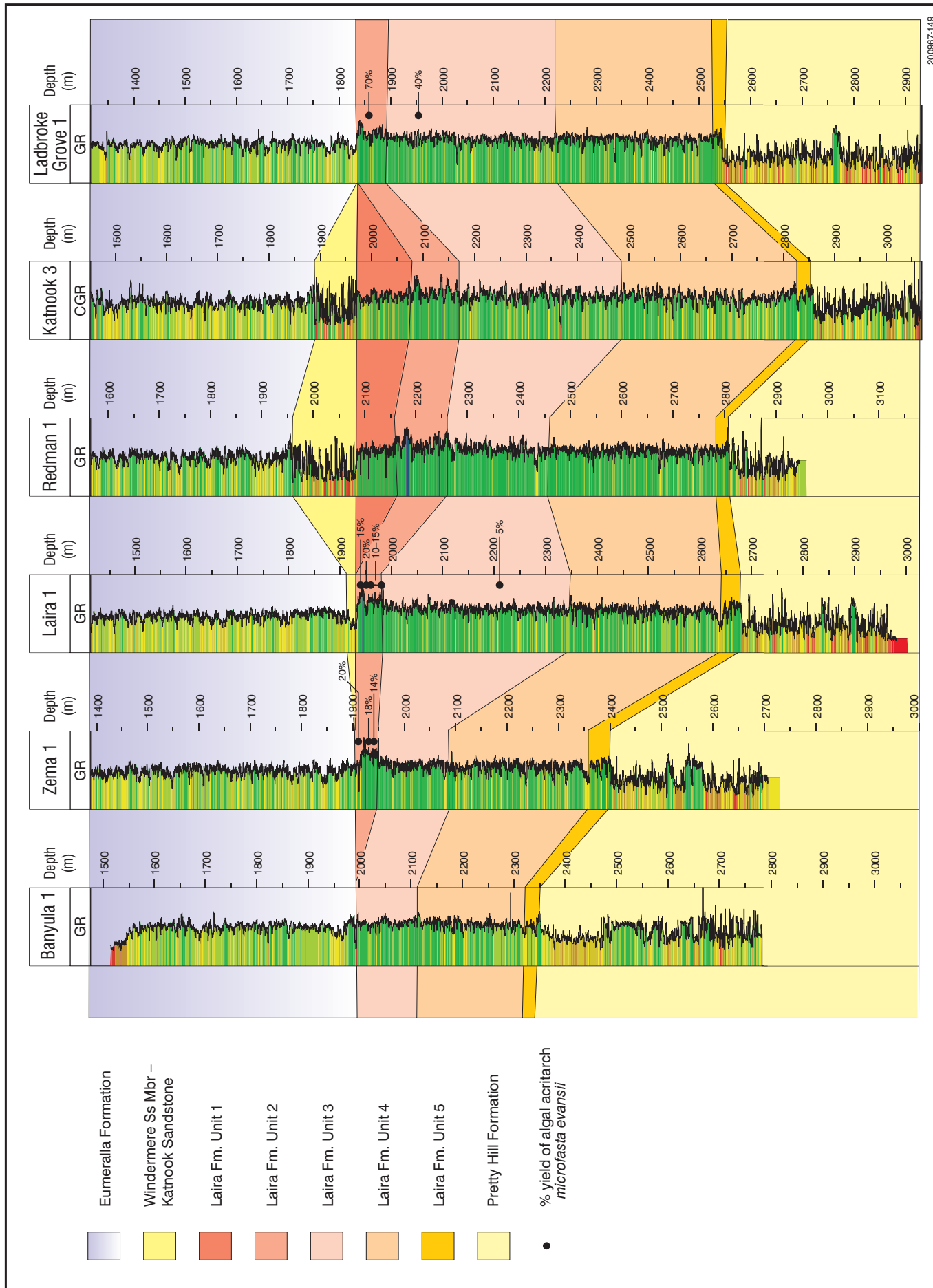


Figure 8.3 Mean TOC map, Pretty Hill Formation



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Figure 8.4 MHI versus T_{max} plot, Pretty Hill Formation



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Figure 8.5 Cross-section from Banyula 1 to Ladbrooke Grove 1 showing the informal subdivision of the Laira Formation based on algal maxima, Penola Trough. Line of section is located in Figure 1.5.

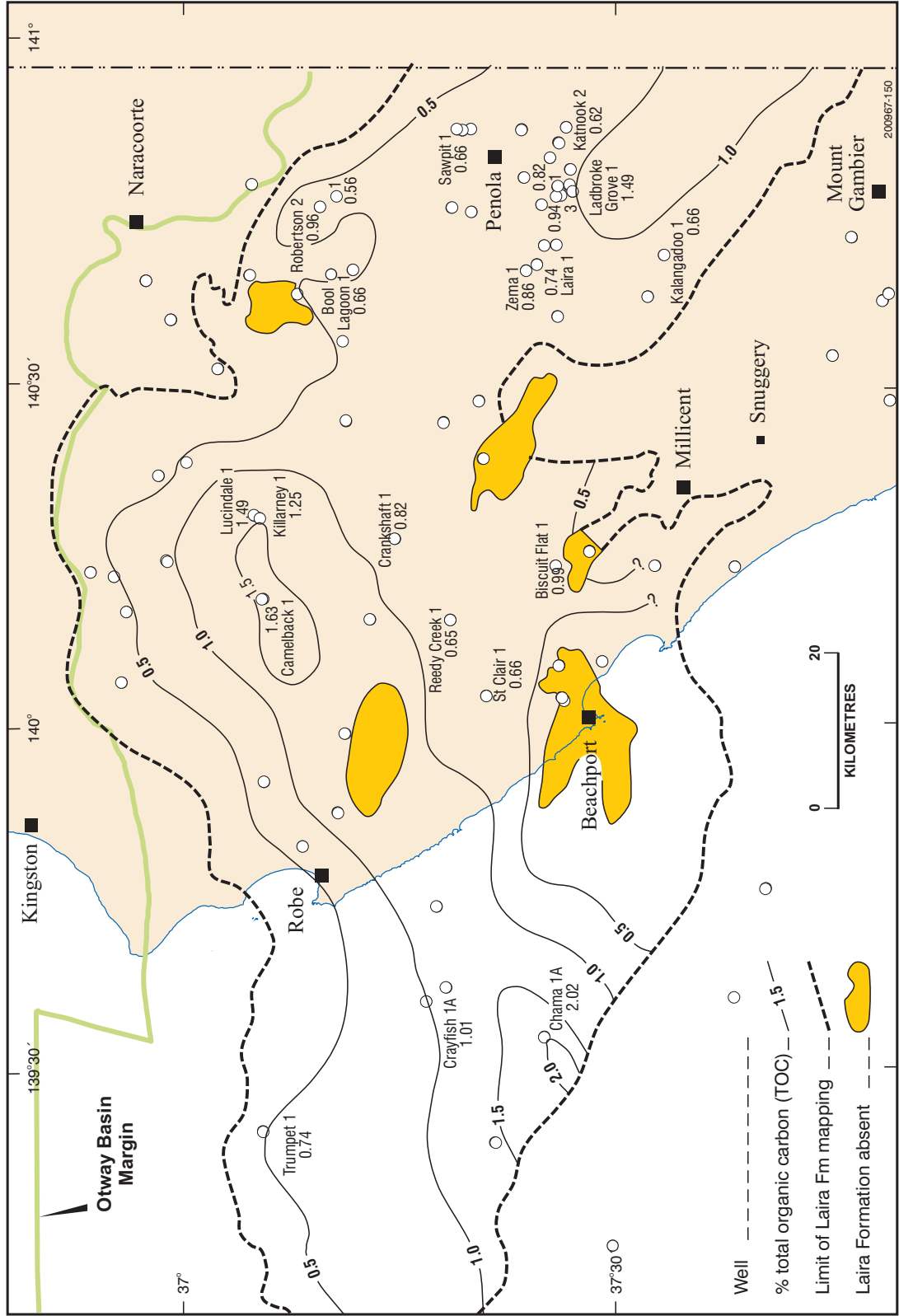


Figure 8.6 Mean TOC map, Laura Formation

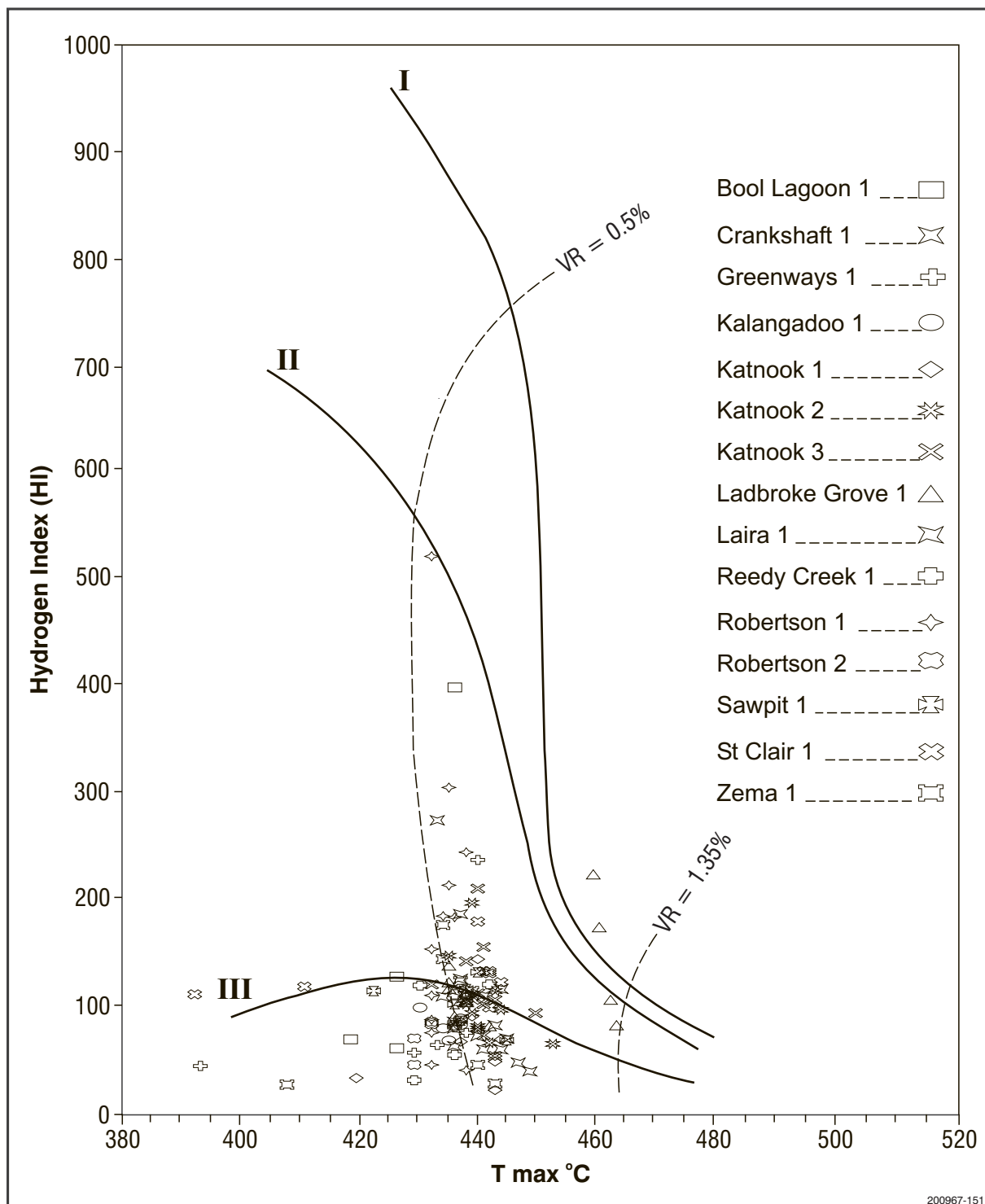


Figure 8.7 HI versus T_{max} plot Laira Formation

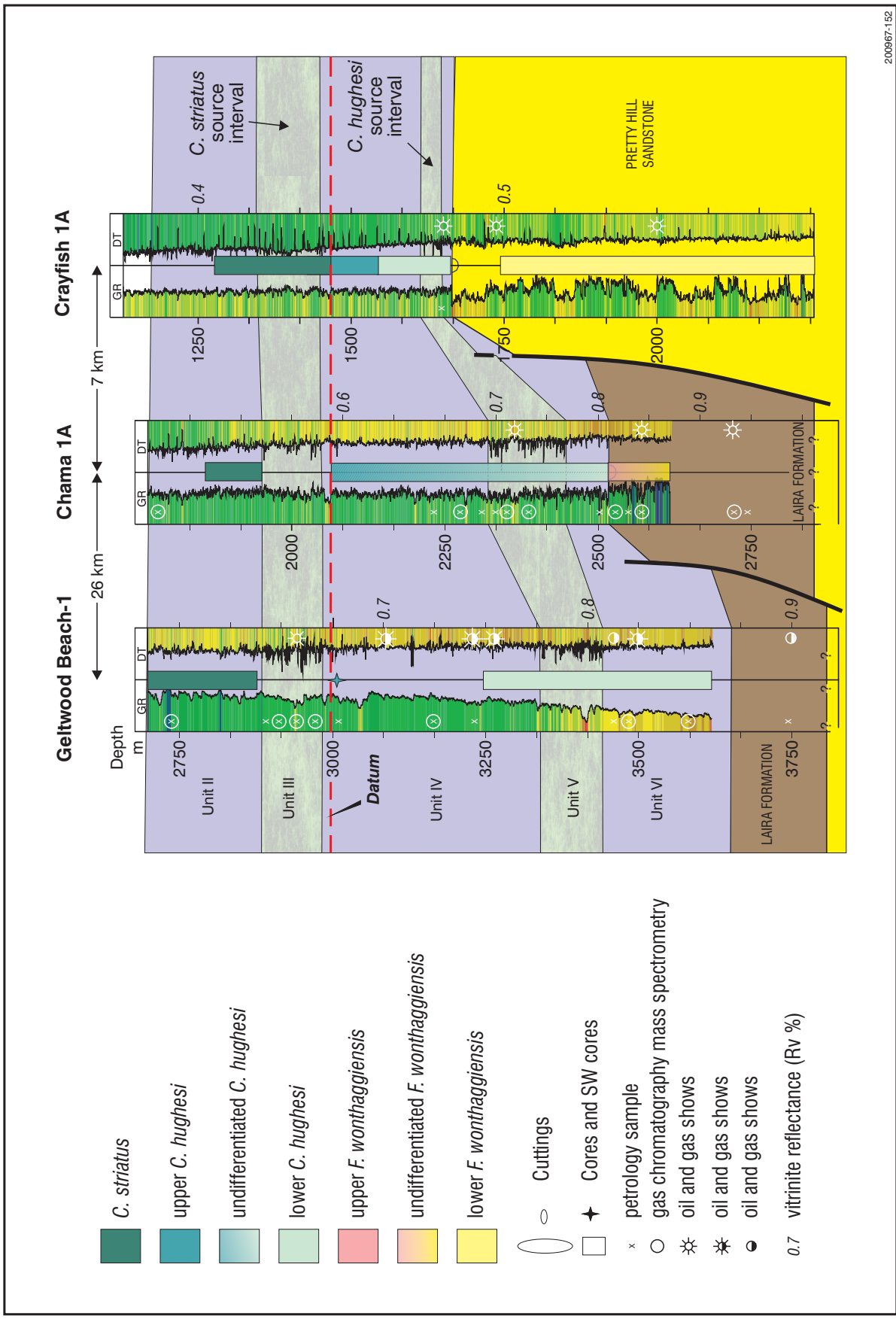


Figure 8.8 Cross-section from Geltwood Beach 1 to Crayfish 1A showing source rock development within the lower Eumeralla Formation (after Tupper et al., 1993). Line of section is located in Figure 1.5.

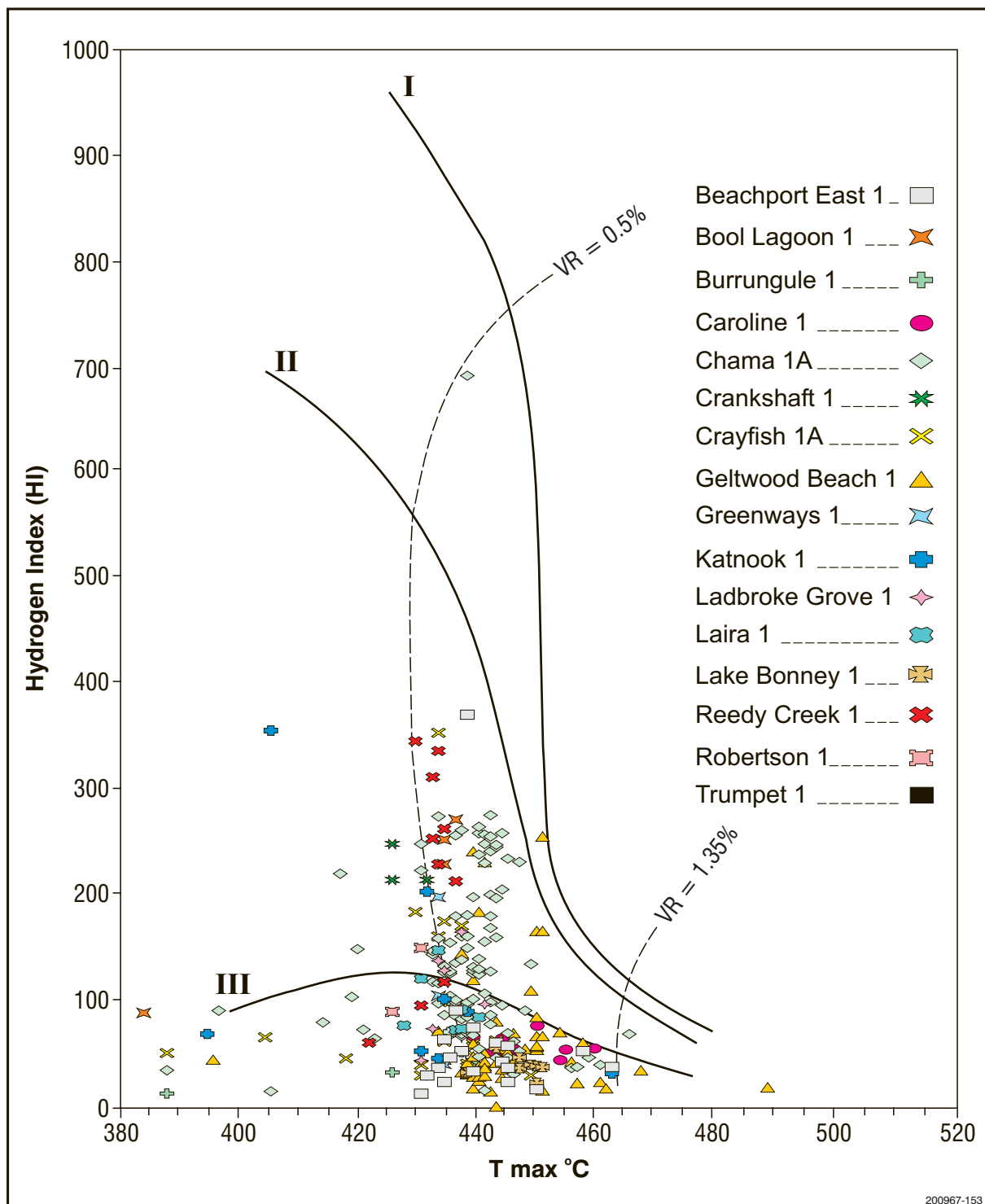


Figure 8.9 HI versus T_{max} plot Eumeralla Formation

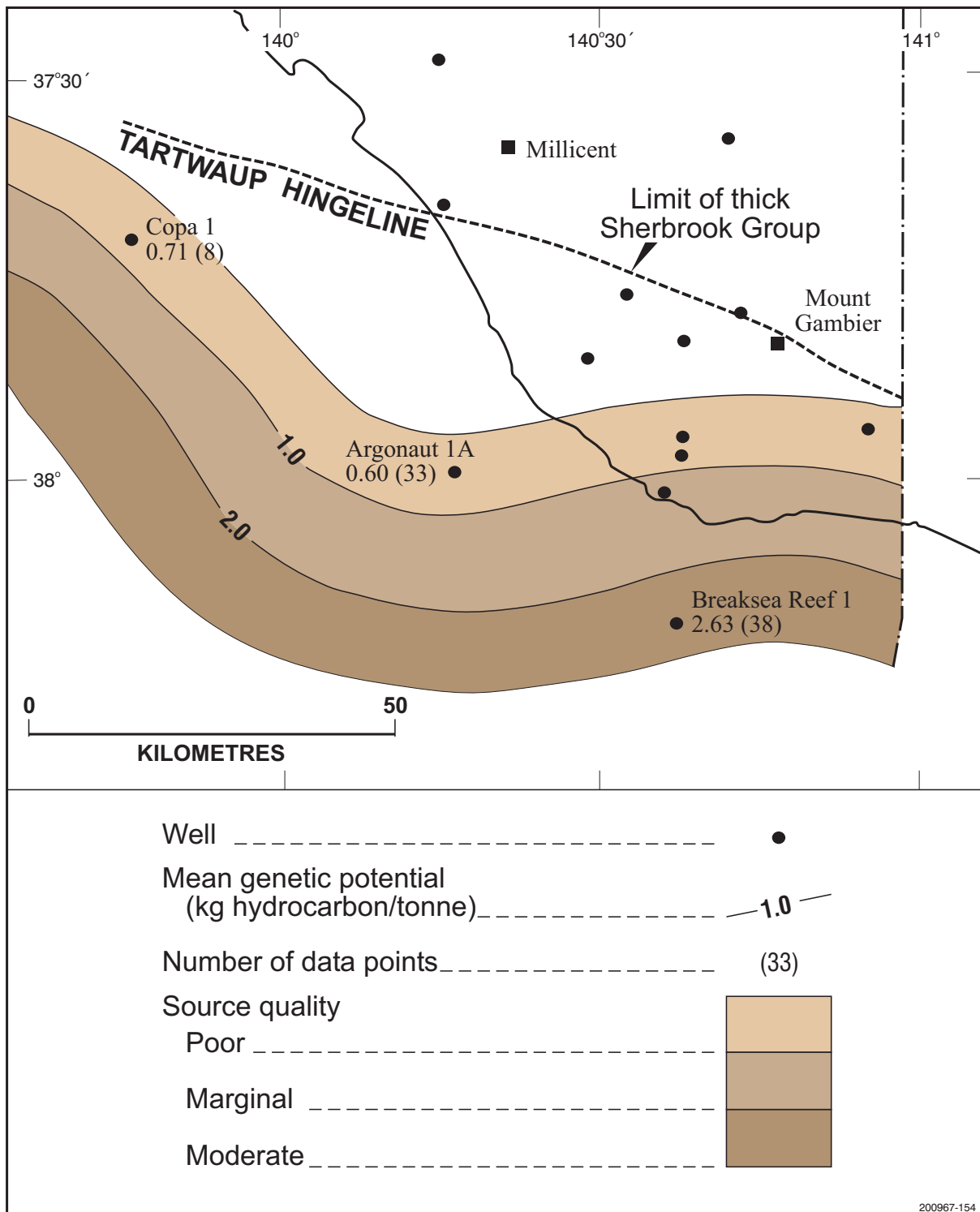
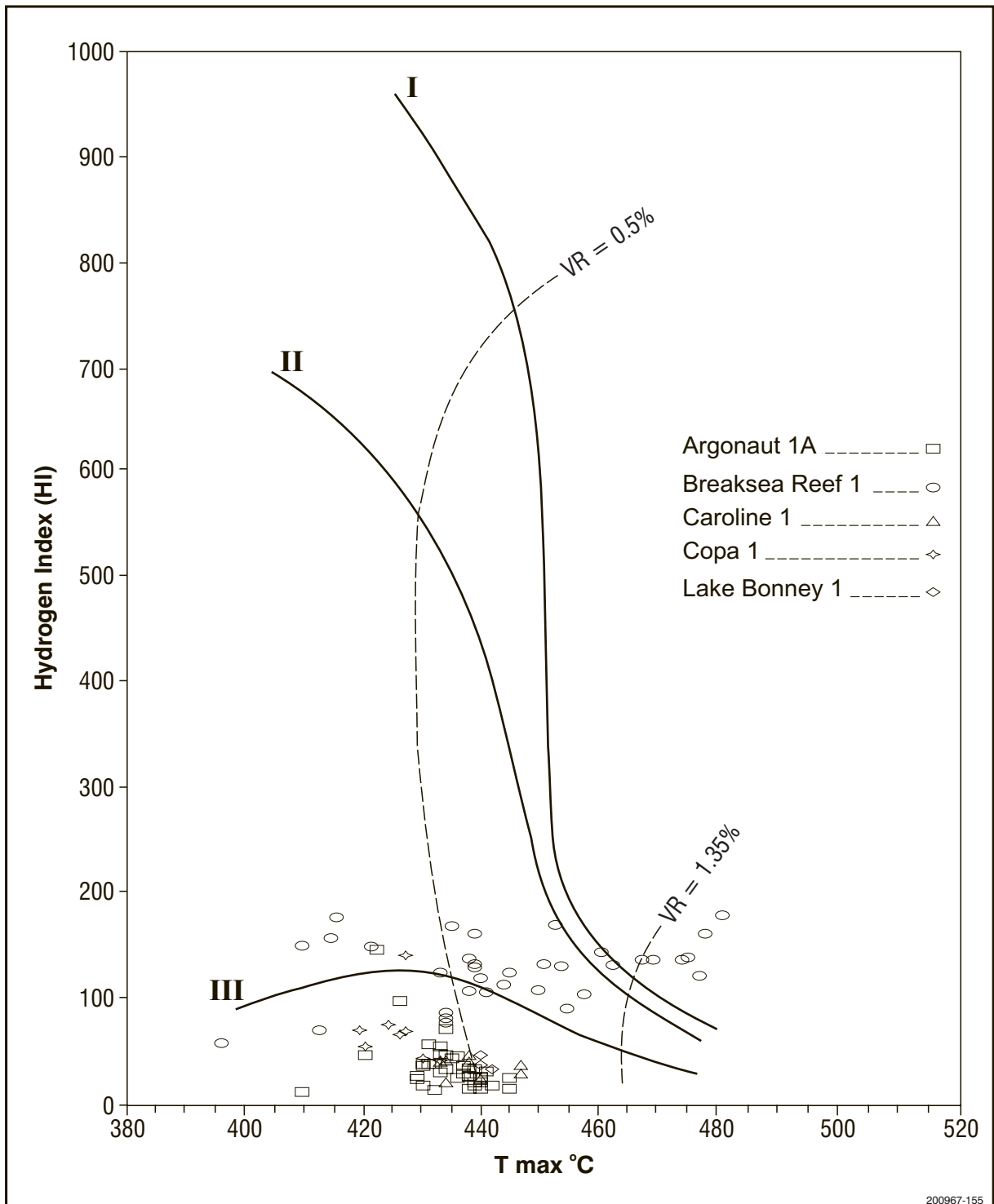


Figure 8.10 Mean genetic potential, Belfast Mudstone



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Figure 8.11 HI versus T_{max} plot Belfast Formation