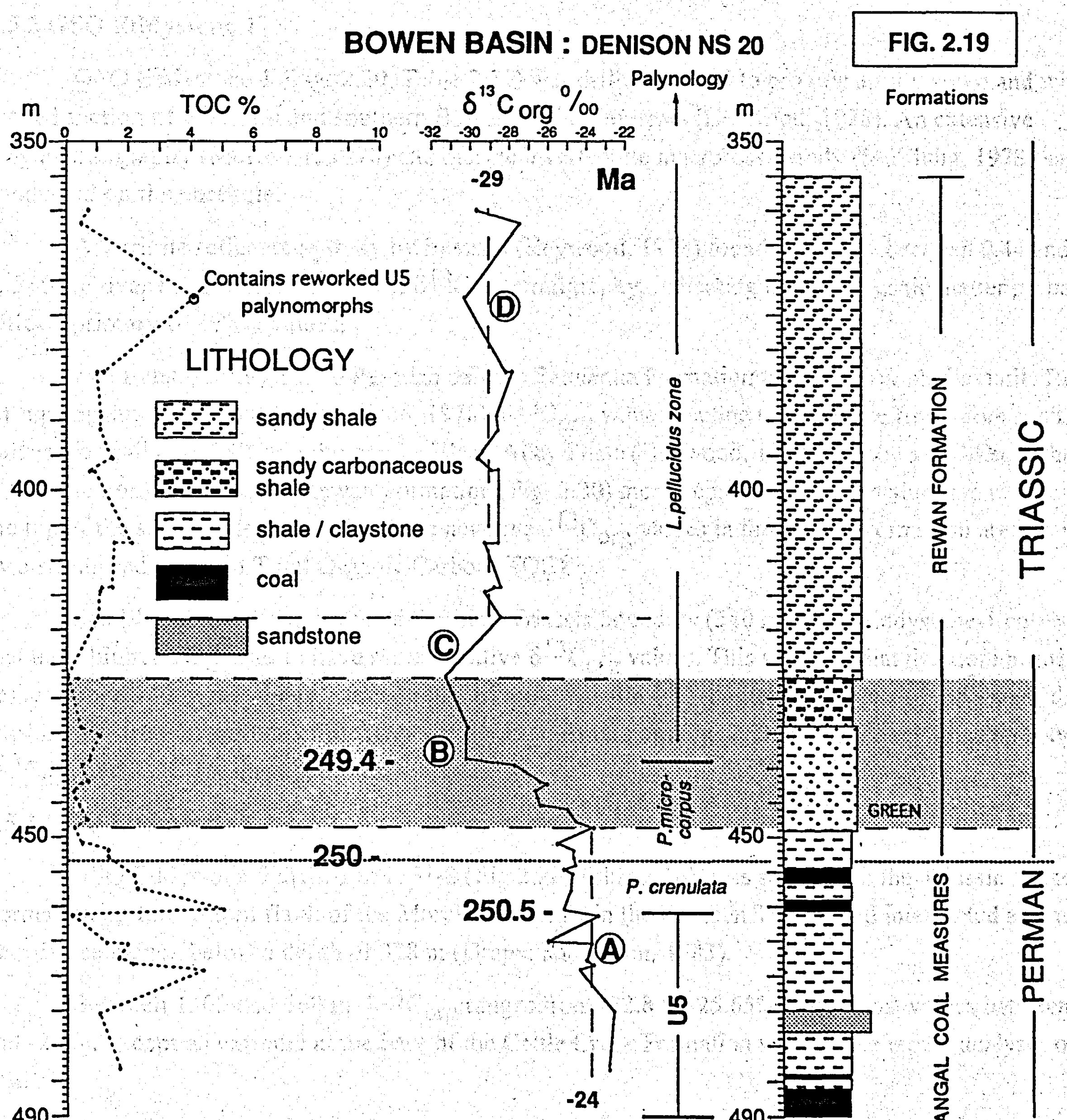

Figure 2.19 Denison NS 20, Bowen Basin, eastern Australia. Total organic carbon (TOC), $\delta^{13}C_{org}$, palynological zones (Foster, 1982), lithological log, and formations (GSQ Denison NS20 coal section geological log, 1978). The negative excursion in $\delta^{13}C_{org}$ is between mean values of -24 ‰ for the Permian and -30‰ for the Triassic and is within the *P. microcorpus* Zone that extends from 461.75 m to 439 m (Foster, 1982, fig. 5). The interval of the $\delta^{13}C_{org}$ excursion (B) is shaded. The *Playfordiaspora crenulata* Zone extends from 461.75 m to 453.48 m (Foster, 1982, p.173, not as in fig. 5, p. 175). The dotted line at 453.48 m is my pick of the Permian-Triassic boundary.

2.5.2 GSQ Eddystone 1

GSQ Eddystone 1 (Fig. 2.20, Table 2.15) was drilled in 1976 to provide a fully cored and wireline logged section of the Surat and southern Bowen Basin sediments (Heywood, 1978). An extensive palynostratigraphy (McKellar, 1978) and marine invertebrate macrofossil study (McClung, 1978) has been conducted on the corehole.

A vitrinite reflectance study by Beetson (Heywood, 1978) found R°max % between 0.44 and 0.69 at 545 nm over the interval studied for $\delta^{13}C_{org}$ stratigraphy, indicating that the organic matter probably reflects primary $\delta^{13}C_{org}$ values.

The transition from Late Permian paludal Bandanna Formation to Early Triassic fluviatile Rewan Group appears conformable (Heywood, 1978). $\delta^{13}C_{org}$ values decline up sequence from more positive values generally (> -24‰) in the paralic Black Alley Shale (Heywood, 1978) to values < -24‰ in the Bandanna Formation. In the Rewan Formation (Fig. 2.20) more negative $\delta^{13}C_{org}$ values are maintained to the top of the sampled interval. The more negative $\delta^{13}C_{org}$ values in the Rewan Formation are paralleled by a strong reduction in Total Organic Carbon (TOC).

Samples above the interpreted Permian-Triassic boundary (340 m) in the Eddystone-1 corehole that have higher TOC tend to have more negative $\delta^{13}C_{org}$ values. This suggests that the more positive values above 340 m may be reflecting a loss of more volatile ^{13}C- depleted products of diagenesis that is masking the true magnitude of the negative $\delta^{13}C_{org}$ excursion. Fig. 2.21 shows the relationship between $\delta^{13}C_{org}$ and TOC for these samples.

2.5.3 GSQ Eddystone 5

GSQ Eddystone 5 drilled in 1981-2 (Fig 2.22, Table 2.16), was spudded in the Triassic Arcadia Formation on the eastern flank of the Morella Anticline in the Denison Trough and intersected a complete Permian sequence below a depth of 328 m (Draper and Green, 1983).

Between 1302 and 560 m, $\delta^{13}C_{org}$ ranges from -22.8 to -25.65‰, with most values between –23 and -24‰, except an extreme at the base of the Cattle Creek Formation which gave repeat analyses of –27. 1‰.

Calcitic fossils (brachiopods) in and below the Ingelara Formation provide material for determining $\delta^{13}C_{CO3}$, $\delta^{18}O_{CO3}$, and $^{87}Sr/^{86}Sr$. The $^{87}Sr/^{86}Sr$ analyses are discussed in Chapter 3 and the $\delta^{13}C_{CO3}$ and $\delta^{18}O_{CO3}$ results in Chapter 4.

2.5.4 GSQ Taroom-10

GSQ Taroom-10, drilled in 1975, provided a cored and wireline logged reference section of the lower Rewan Formation and the underlying Permian sequence to the base of the Cattle Creek Formation (Fig. 2.23; Table 2.17). Palynological studies by McKellar (1977) and invertebrate paleontology studies by McClung (1977) provide biostratigraphical information. The current $\delta^{13}C$ study concentrates on analysis of samples wholly from the upper Cattle Creek Formation in the interval 830 to 960 m in sediments of Upper Stage 4 age. The $\delta^{13}C_{org}$ is within the range of -23 to -25‰. The $^{87}Sr/^{86}Sr$ analyses are discussed in Chapter 3 and the $\delta^{13}C_{CO3}$ and $\delta^{18}O_{CO3}$ results in Chapter 4.

Table 2.15 GSQ Eddystone-1. $\delta^{13}C_{org}$, TOC, $\delta^{13}C_{CO3}$, $\delta^{18}O_{CO3}$, biostratigraphy and formations.

Corehole	Depth m	$\delta^{13}C_{org}$‰	TOC%	$\delta^{13}C_{CO3}$‰	$\delta^{18}O_{CO3}$‰	Palynology Zone	Formation
Eddystone-1	150	-25.41	< 0.1			undetermined	REWAN FM.
Eddystone-1	160	-24.76	< 0.1			undetermined	REWAN FM.
Eddystone-1	171.5	-27.73	0.2			undetermined	REWAN FM.
Eddystone-1	191	-25.50	< 0.1			undetermined	REWAN FM.
Eddystone-1	200.5	-26.17	< 0.1			undetermined	REWAN FM.
Eddystone-1	214	-25.27	< 0.1			undetermined	REWAN FM.
Eddystone-1	223	-26.77	< 0.1			undetermined	REWAN FM.
Eddystone-1	269.5	-27.18	0.8			undetermined	REWAN FM.
Eddystone-1	279.8	-26.58	0.1			undetermined	REWAN FM.
Eddystone-1	280	-27.79	< 0.1			undetermined	REWAN FM.
Eddystone-1	284.9	-28.34	0.7			undetermined	REWAN FM.
Eddystone-1	289.6	-27.81	0.7			undetermined	REWAN FM.
Eddystone-1	297	-25.40	0.1			undetermined	REWAN FM.
Eddystone-1	309.1	-27.44	0.2			undetermined	REWAN FM.
Eddystone-1	314	-25.65	0.2			undetermined	REWAN FM.
Eddystone-1	331.2	-25.54	0.1			undetermined	REWAN FM.
Eddystone-1	343	-26.88	0.4			?TR1a	BANDANNA
Eddystone-1	343.5	-26.00	2.5			undetermined	BANDANNA
Eddystone-1	353.3	-25.84	7.7			undetermined	BANDANNA
Eddystone-1	360	-25.28	2.4			U5	BANDANNA
Eddystone-1	361.5	-25.63	8.3			U5	BANDANNA
Eddystone-1	366.2	-24.30	3.5			U5	BANDANNA
Eddystone-1	372	-24.44	4.1			U5	BANDANNA
Eddystone-1	373.9	-25.15	4.0			U5	BANDANNA
Eddystone-1	374.3	-24.62	2.8			U5	BANDANNA
Eddystone-1	380.3	-26.59	3.0			U5	BANDANNA
Eddystone-1	392.9	-24.48	3.8			U5	BANDANNA
Eddystone-1	394.9	-25.42	1.4			U5	BANDANNA
Eddystone-1	400	-24.72	4.2			U5	BANDANNA
Eddystone-1	403	-25.01	1.5			U5	BANDANNA
Eddystone-1	451	-23.67	1.4			U5	BLACK ALLEY
Eddystone-1	464	-23.66	1.6			U5	BLACK ALLEY
Eddystone-1	473.3	-24.38	2.6			U5	BLACK ALLEY
Eddystone-1	489.4	-23.95	2.4			U5	BLACK ALLEY
Eddystone-1	502.5	-23.32	1.2			U5	BLACK ALLEY
Eddystone-1	517	-23.77	2.1			U5	BLACK ALLEY
Eddystone-1	525	-23.96	17			U5	BLACK ALLEY
Eddystone-1	536.4	-23.42	1.0			U5	BLACK ALLEY
Eddystone-1	557	-23.93	2.0			U5	BLACK ALLEY
Eddystone-1	543	-23.87	1.2			U5	BLACK ALLEY
Eddystone-1	570.2	-24.00	1.8			U5	BLACK ALLEY
Eddystone-1	580.7	-23.41	1.4			U5	BLACK ALLEY
Eddystone-1	592	-23.45	2.5			U5	BLACK ALLEY
Eddystone-1	600.8	-24.78	1.7			U5	BLACK ALLEY
Eddystone-1	612.26	-24.38	1.7			U5	PEAWADDY

Table 2.15 continued

Corehole	Depth	$\delta^{13}C_{org}$	TOC%	$\delta^{13}C_{CO3}$	$\delta^{18}O_{CO3}$	Palynology Zone	Formation
Eddystone-1	616	-23.40	1.0			U5(P3c)	PEAWADDY
Eddystone-1	628	-24.47	0.2			U5	PEAWADDY
Eddystone-1	645	-24.73	1.0			U5	PEAWADDY
Eddystone-1	647	-25.26	0.5	5.00	-0.43	U5	PEAWADDY
Eddystone-1	660	-23.83	1.4			U5	INGELARA
Eddystone-1	664.5	-23.47	1.1			U5	INGELARA
Eddystone-1	677	-23.69	2.2			U5	INGELARA
Eddystone-1	687	-23.25	2.3			U5	INGELARA
Eddystone-1	692	-23.57	1.4	4.16	-2.81	U5	INGELARA
Eddystone-1	693.8	-23.55	1.4	4.50	-1.31	U5	INGELARA
Eddystone-1	701.8	-23.40	1.8	6.40	-0.25	U5	INGELARA
Eddystone-1	702	-23.22	1.9	6.83	0.03	U5	INGELARA
Eddystone-1	709	-23.17	2.1			U5	INGELARA
Eddystone-1	718.5	-23.06	3.0			U5	INGELARA
Eddystone-1	728.3	-23.38	2.9			U5	INGELARA
Eddystone-1	736	-23.31	2.8			U5	INGELARA
Eddystone-1	748	-23.90	1.5			U5	INGELARA
Eddystone-1	750.5	-24.46	2.0			U5	INGELARA
Eddystone-1	765	-24.27	1.3			U5	INGELARA
Eddystone-1	780.5	-23.02	4.6			U5	UNDIFF
Eddystone-1	784	-23.91	3.2	5.82	-0.98	U5	UNDIFF
Eddystone-1	793.1			4.25	-3.13	L5c	UNDIFF
Eddystone-1	793.5	-24.56	2.1			L5c	UNDIFF
Eddystone-1	803	-25.12	1.0			L5c	UNDIFF
Eddystone-1	809.5	-23.61	0.7			L5c	UNDIFF
Eddystone-1	831.5	-22.38	6.0			U4b	UNDIFF
Eddystone-1	842	-22.45	3.1			undetermined	UNDIFF
Eddystone-1	854	-22.39	1.0			undetermined	UNDIFF
Eddystone-1	864	-22.63	1.9			undetermined	UNDIFF
Eddystone-1	880	-23.88	2.1			U4A	UNDIFF
Eddystone-1	887	-23.12	1.7			U4A	UNDIFF
Eddystone-1	899	-25.28	2.4			U4A	UNDIFF
Eddystone-1	929.5	-23.53	1.7			U4A	UNDIFF
Eddystone-1	937	-23.53	1.7	6.34	-1.76	U4A	UNDIFF
Eddystone-1	937	-24.18	1.8	7.83	-1.33	U4A	UNDIFF
Eddystone-1	946.5	-23.46	2.1			undetermined	UNDIFF
Eddystone-1	947	-23.02	1.3	6.76	-1.56	undetermined	UNDIFF
Eddystone-1	973.5			5.34	0.05	L4/3b	REIDS DOME

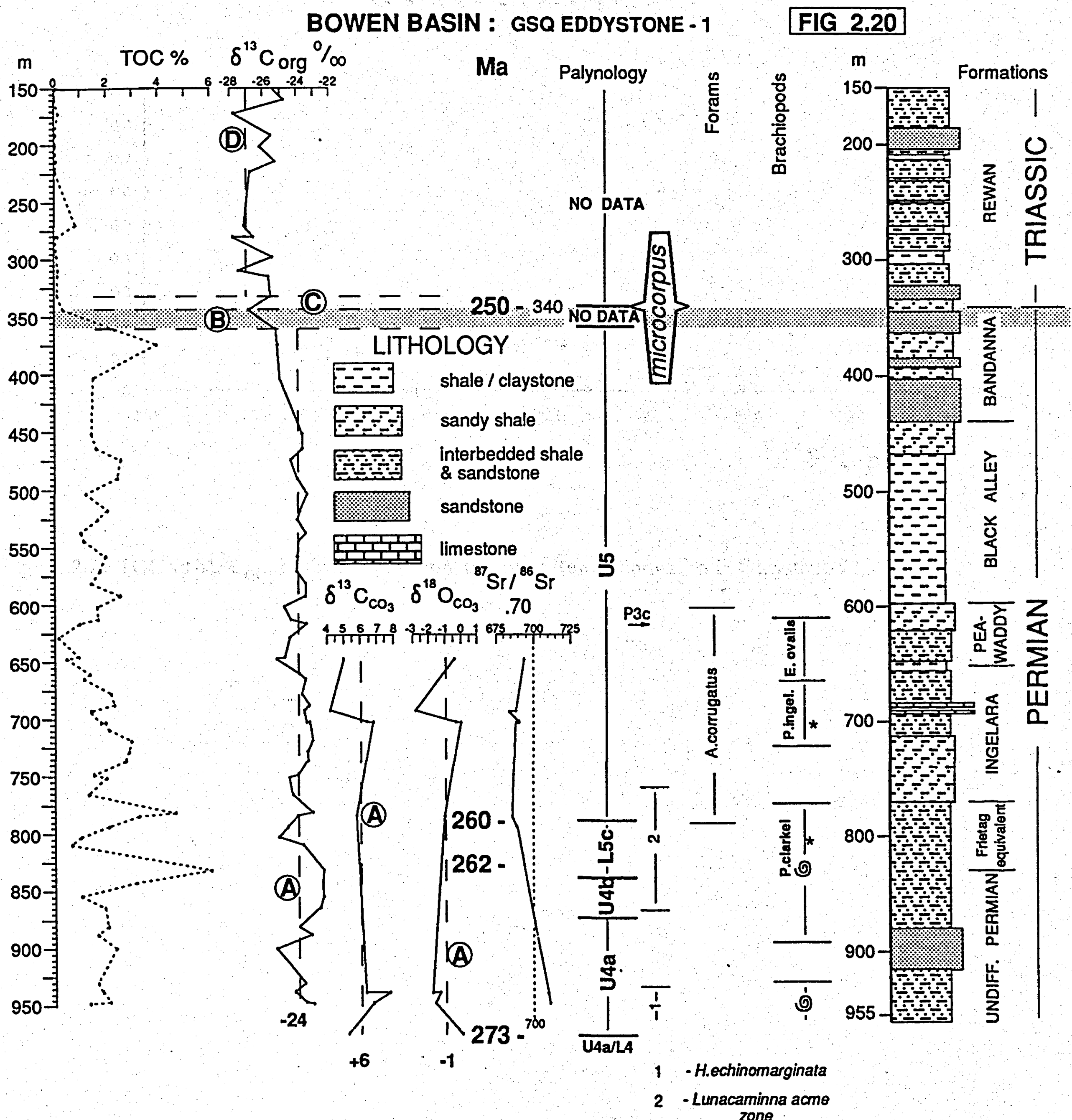

Figure 2.20 Eddystone-1, Bowen Basin, eastern Australia. Total organic carbon (TOC), $\delta^{13}C_{org}$, $\delta^{13}C_{CO3}$, $\delta^{18}O_{CO3}$, $^{87}Sr/^{86}Sr$, palynological zones (McKellar, 1978), foraminifera zones (Palmieri,1983), brachiopod zones (D. Briggs pers. comm., 1992), lithological log, and formations (Heywood, 1978). Determinations on carbonate samples are from non-cathodoluminescent brachiopods. The negative $\delta^{13}C_{org}$ excursion is between values of -24‰ for the Permian and -27‰ for the Triassic. The dotted line at 340 m is my pick of the Permian-Triassic boundary, and it coincides with the base of the Rewan Formation and the only determined sample of Tr1a (= *P. microcorpus*) Zone (McKellar, 1978). The interval of the negative $\delta^{13}C_{org}$ excursion (B) is shaded.

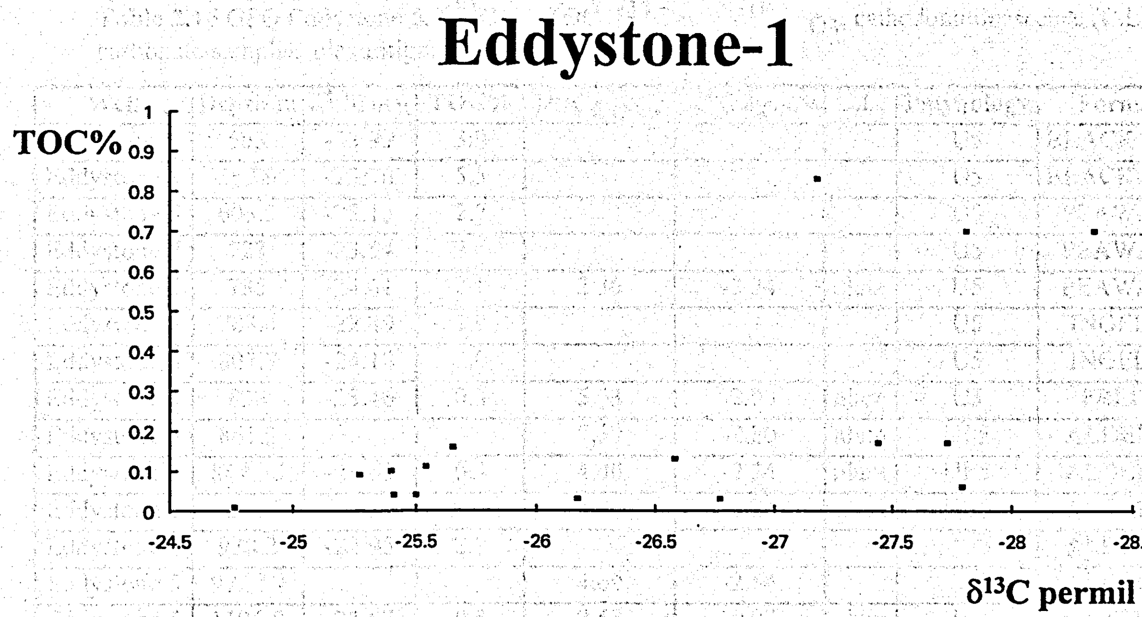

Figure 2.21 TOC vs $\delta^{13}C_{org}$ of the samples from the lower Rewan Formation in Eddystone-1.

Table 2.16 GSQ Eddystone 5. $\delta^{13}C_{org}$, TOC, $\delta^{13}C_{CO3}$, $\delta^{18}O_{CO3}$, cathodoluminescence (C.L.) of carbonate samples, biostratigraphy and formations.

Well	Depth m	δ^{13}Corg	TOC%	$\delta^{13}C_{CO3}$‰	$\delta^{18}O_{CO3}$‰	C.L.	Palynology	Formation
Eddystone 5	563	-23.99	3.0				U5	BLACK ALLEY
Eddystone 5	565.9	-23.76	5.5				U5	BLACK ALLEY
Eddystone 5	603.5	-23.13	2.7				U5	PEAWADDY
Eddystone 5	723	-23.54	2.5				U5	PEAWADDY
Eddystone 5	735	-24.61	2.1	2.36	-3.24	nlum	U5	PEAWADDY
Eddystone 5	783.4	-22.49	1.9				U5	INGELARA
Eddystone 5	807.7	-24.19	2.0				U5	INGELARA
Eddystone 5	833	-23.46	0.3	5.03	-2.03	nlum	U5	FREITAG
Eddystone 5	861.3			7.30	-2.80	nlum	UL5	ALDEBRAN
Eddystone 5	864.35	-25.65	0.3	4.40	-2.34	nlum	UL5	ALDEBRAN
Eddystone 5	864.35			4.34	-1.24	nlum	UL5	ALDEBRAN
Eddystone 5	938.2	-22.95	2.9					ALDEBRAN
Eddystone 5	972.59			4.60	-2.54			ALDEBRAN
Eddystone 5	1196.8	-23.67	0.8	7.55	-0.97	nlum	U4	CATTLE CK
Eddystone 5	1210.6	-23.89	2.4	6.52	-0.73	nlum	U4	CATTLE CK
Eddystone 5	1210.6			5.08	-0.53	nlum	U4	CATTLE CK
Eddystone 5	1219.3			4.38	-2.51	nlum	U4	CATTLE CK
Eddystone 5	1219.3	-23.16	1.2	4.40	-2.26	nlum	U4	CATTLE CK
Eddystone 5	1219.3	-23.16	1.2	4.02	-4.49	**plum**	U4	CATTLE CK
Eddystone 5	1256.2	-23.80	1.1	3.50	-5.20	**plum**	U4	CATTLE CK
Eddystone 5	1302.2	-22.89	1.1	6.10	-1.50	nlum	U4	CATTLE CK
Eddystone 5	1306	-27.13	1.9	5.34	-3.64	nlum	U4	CATTLE CK
Eddystone 5	1306	-27.05	1.8				U4	CATTLE CK
Eddystone 5	1316.2			5.50	-2.65	nlum	U4	CATTLE CK

nlum - nonluminescent; plum - part luminescent.

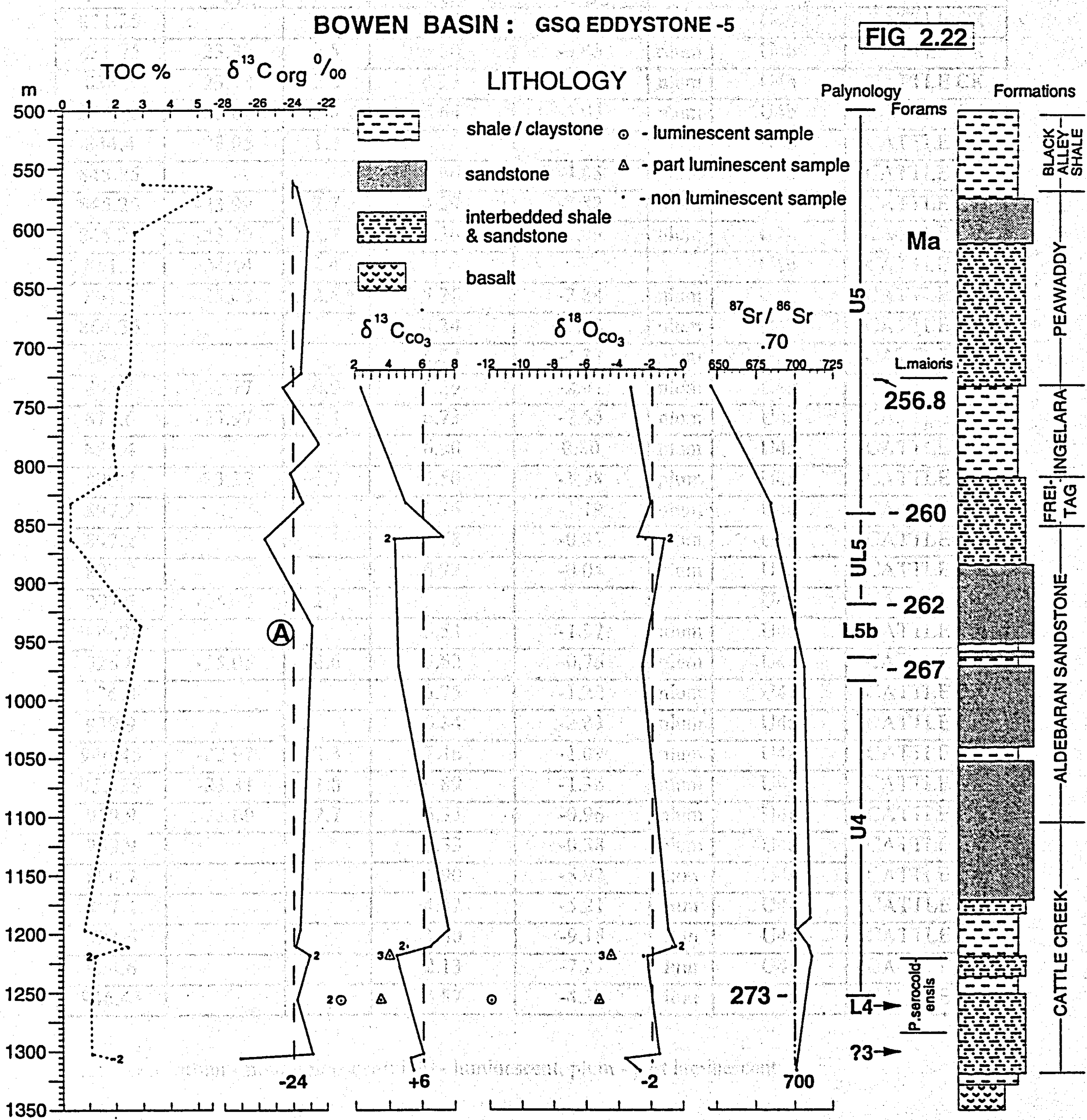

Figure 2.22 Eddystone 5, Bowen Basin, eastern Australia. Total organic carbon (TOC), $\delta^{13}C_{org}$, $\delta^{13}C_{CO3}$, $\delta^{18}O_{CO3}$, $^{87}Sr/^{86}Sr_{CO3}$, palynological zones (Jones, 1986), the top of the Reids Dome Beds are Stage 3b (Veevers, et al., 1995), foraminiferan zones (Palmieri, 1983), brachiopod zones (Briggs pers. comm., 1992), lithological log, and formations (Draper & Green, 1983). Determinations on carbonate samples are from non-luminescent (nlum) brachiopods, except at 1219.3 m which was a partly luminescent (plum) specimen.

Table 2.17 Taroom-10. $\delta^{13}C_{org}$, TOC, $\delta^{13}C_{CO3}$, $\delta^{18}O_{CO3}$, biostratigraphy.

Depth m	$\delta^{13}C_{org}$‰	TOC%	$\delta^{13}C_{CO3}$‰	$\delta^{18}O_{CO3}$‰	C.L.	Palynology	Formation
831.25			2.46	-4.12	plum	U4b	CATTLE CK
831.25	-23.30	2.5	3.50	-3.45	nlum	U4b	CATTLE CK
838.2	-23.98	2.0	4.23	-1.28	nlum	U4b	CATTLE CK
844.28	-23.87	2.8	5.64	-3.03	nlum	U4b	CATTLE CK
844.4	-23.95	1.3			nlum	U4b	CATTLE CK
845.25			4.66	-4.85	plum	U4b	CATTLE CK
845.25	-23.99	2.7	4.29	-2.82	nlum	U4b	CATTLE CK
845.25	-23.99	2.7	4.36	-3.09	nlum	U4b	CATTLE CK
851.2	-24.44	2.4				U4b	CATTLE CK
861.3	-25.08	2.6	7.35	-2.84	nlum	U4b	CATTLE CK
864.35			4.34	-1.24	nlum	U4b	CATTLE CK
864.7			4.24	-4.33	nlum	undetermined	CATTLE CK
868.8	-23.77	0.9	5.29	-2.41	nlum	U4a	CATTLE CK
872.6	-23.97	1.4	6.73	-2.55	nlum	U4a	CATTLE CK
884.4			6.90	0.30	nlum	U4a	CATTLE CK
890.7	-23.37	2.7	5.50	-1.98	plum	U4a	CATTLE CK
897.2			6.96	-1.19	nlum	U4a	CATTLE CK
897.2			7.78	-0.87	nlum	U4a	CATTLE CK
897.2			6.92	-0.04	nlum	U4a	CATTLE CK
907.5	-24.58	2.4				U4a	CATTLE CK
909.75			6.54	-1.37	nlum	U4a	CATTLE CK
926.8	-25.05	0.6	5.62	-0.76	nlum	U4a	CATTLE CK
926.8			5.75	-1.22	nlum	U4a	CATTLE CK
939.9			6.84	-2.03	nlum	U4a	CATTLE CK
946.45	-22.97	2.3	7.46	-1.09	nlum	U4a	CATTLE CK
952.39	-23.31	1.8	6.89	-1.38	nlum	U4a	CATTLE CK
959.9	-23.00	2.7	6.33	-0.96	nlum	U4a	CATTLE CK
959.9			6.33	-0.38	nlum	U4a	CATTLE CK
890.7			1.90	-5.92	lum	U4a	CATTLE CK
897.2			4.42	-5.21	lum	U4a	CATTLE CK
924.6			1.40	-9.18	lum	U4a	CATTLE CK
924.6			2.13	-7.27	lum	U4a	CATTLE CK
946.45			4.87	-4.32	lum	U4a	CATTLE CK

nlum - nonluminescent; lum - luminescent, plum - part luminescent.

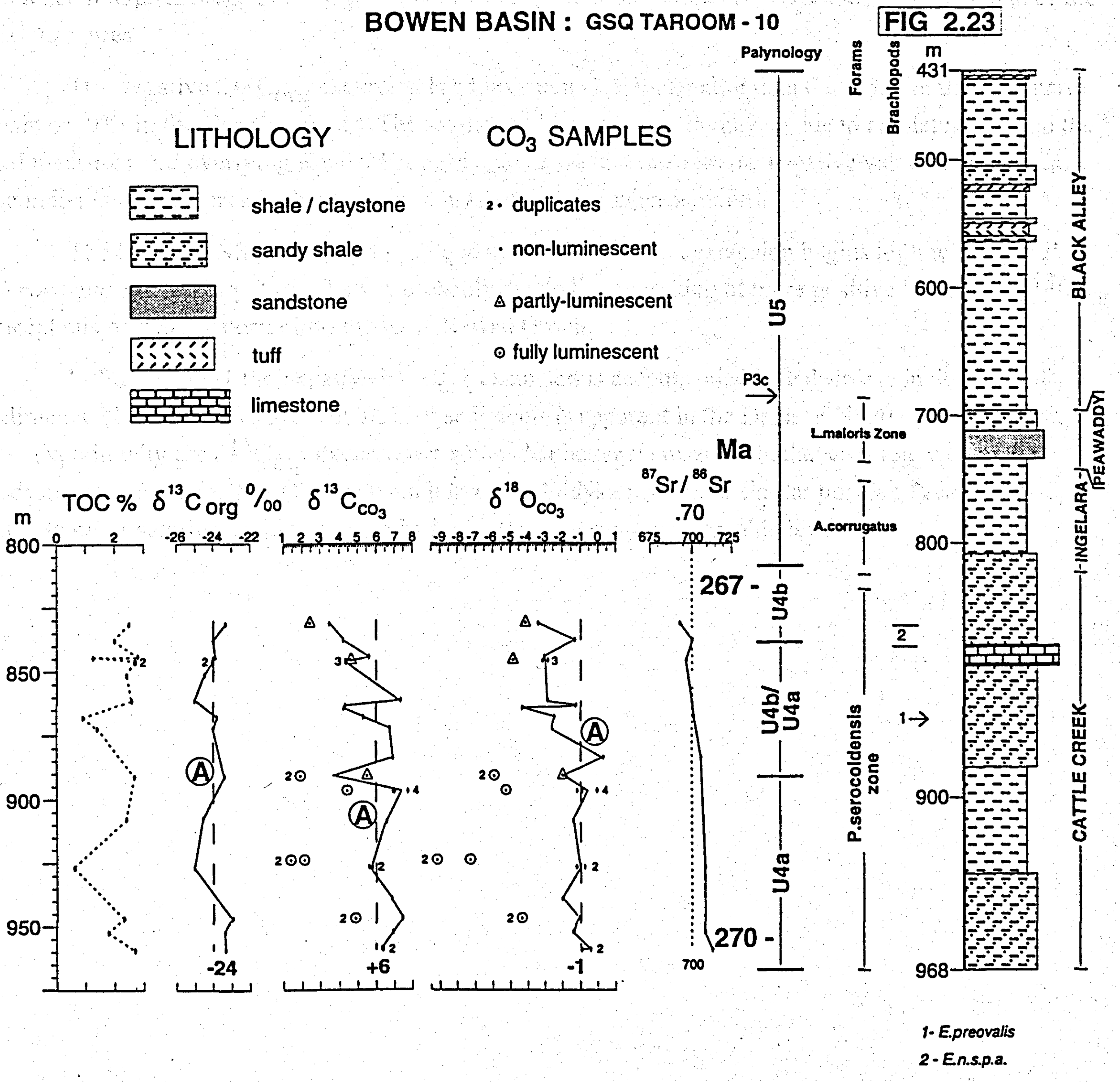

Figure 2.23 Taroom-10, Bowen Basin, eastern Australia. Total organic carbon (TOC), $\delta^{13}C_{org}$, $\delta^{13}C_{CO3}$, $\delta^{18}O_{CO3}$, $^{87}Sr/^{86}Sr_{CO3}$, palynological zones (McKellar, 1978), foraminifera zones (Palmieri, 1983), brachiopod zones (Briggs pers. comm., 1992), lithological log and formations (Draper and Green, 1983).

2.5.5 Bowen Basin synopsis

$\delta^{13}C_{org}$ has more positive values (-22 to -24 ‰) in Upper Stage 4 decreasing (-23 to -25 ‰) up sequence in Upper Stage 5. $\delta^{13}C_{org}$ of the Rewan Formation sediments is more negative than that of the coal measures.

The negative $\delta^{13}C_{org}$ excursion is a maximum -5.5 ‰, smaller than the -10‰ in the Bonaparte Basin or -9‰ in the Canning Basin. The smaller $\delta^{13}C_{org}$ excursion may be due to an hiatus between the coal measures and overlying Rewan Group sediments so that the extreme negative value of the $\delta^{13}C_{org}$ excursion is not preserved; alternatively it may never have been achieved.

The Denison NS20 corehole is unique in that the $\delta^{13}C_{org}$ excursion begins high within the *P. microcorpus* palynology Zone. This is probably due to the reworking of more positive "Permian" $\delta^{13}C_{org}$ amorphous organic material into the basal Rewan Group.

In Eddystone-1 the negative $\delta^{13}C_{org}$ excursion is accompanied by a decrease in the TOC of sediments. No decreasing trend in TOC of sediments is apparent in the Denison NS20 corehole and this may explain why the $\delta^{13}C_{org}$ excursion is somewhat better represented in that corehole than in the Eddystone-1 corehole. The P3c acritarch horizon in Eddystone-1 has a similar positive Permian $\delta^{13}C_{org}$ value to other samples lacking acritarchs from about the same stratigraphic level.

2.6 Sydney Basin

$\delta^{13}C_{org}$ profiles through the nonmarine coal measures and basal Narrabeen Group were made in four coreholes (Fig. 2.24). The position of the Permian-Triassic boundary in the Sydney Basin was traditionally accepted as at the coal measures /Narrabeen Group boundary (David, 1950). However, on the basis of long-range correlation of palynomorphs to the Salt Range, Pakistan the Permian-Triassic boundary was placed at the top of the Munmorah Conglomerate about 200 m above the coal measures/Narrabeen Group boundary (Balme, 1970; Balme and Helby, 1973).

This study of the $\delta^{13}C_{org}$ profiles through the coal measures and basal Narrabeen Group allows a reassessment of the placement of the Permian-Triassic boundary. These $\delta^{13}C_{org}$ profiles cover the interval from the palynological Upper Stage 5 to *Aratrisporites tenuispinosus* Zone (Helby pers. comm., 1993; 1994).

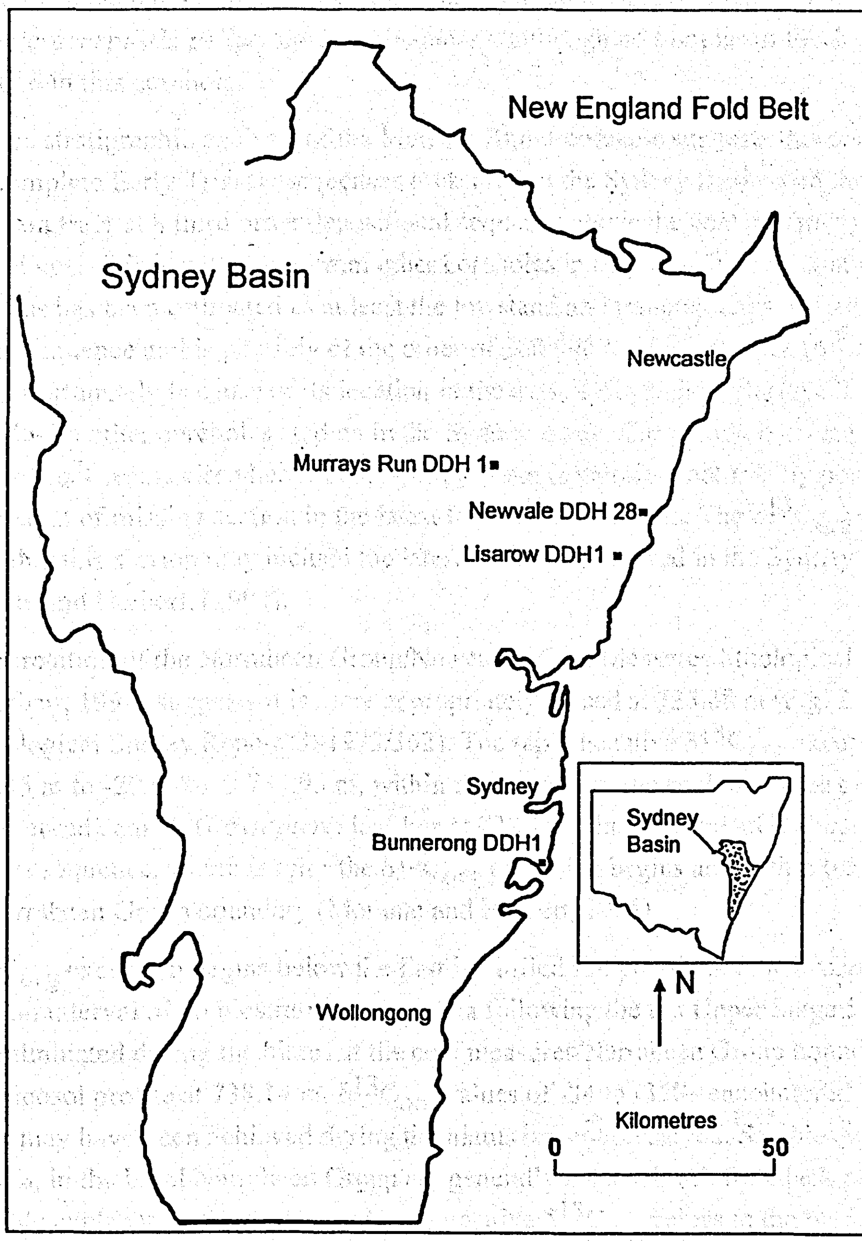

Figure 2.24 Location of Murrays Run DDH 1, Awaba DDH 2, Bunnerong DDH 1, Lisarow DDH 1, and Newvale DDH 28.

2.6.1 DM Murrays Run-1

Murrays Run-1 (Fig. 2.25; Table 2.18) was one of a series of boreholes designed to test the reserves of coking coals in the Cooranbong-Kulnura area in the Newcastle and Tomago Coal Measures. The topmost coal at 758.055 m was originally interpreted as marking the coal measures/Narrabeen Group boundary (Geological Survey Report 1973/362).

The top of this corehole is probably still in the *Aratrisporites tenuispinosus* Zone because the Bald Hill Claystone where this corehole was spudded elsewhere contains the *Dicroidium zuberi* flora in outcrop, thought to be equivalent in range to the *A. tenuispinosus* Zone (Runnegar, 1980, p 417). The *Dicroidium zuberi* flora continues until the overlying Newport Formation time (Retallack, 1980, fig. 21.8, p. 412). The boundary between the *Aratrisporites tenuispinosus* Zone and *P. samoilovichii* zones (Fig. 2.25) is uncertain but has been estimated as half way between limiting samples. The base of the *P. samoilovichii* Zone is picked at the bottom sample. The Munmorah/Tuggerah Formation boundary is picked as the *P. microcorpus/L. pellucidus* Zone boundary, although no samples of the *L. pellucidus* Zone have been identified in this corehole.

A sequence stratigraphic analysis of the Murrays Run-1 corehole suggests this corehole provides one of the most complete Early Triassic sequences preserved in the Sydney Basin with the preservation of the highstand system tract of a third order depositional sequence above the coal measures/Narrabeen Group boundary hiatus. This is not known from other coreholes in the basin. The amount of section missing in the hiatus has been estimated as at least the lowstand and trangressive system tracts of a third order depositional sequence and is possibly of the order of 300 000 to 500 000 years (Morante and Herbert, 1994). Unfortunately because of its location in the axis of a syncline, Murrays Run-1 cannot be directly correlated with other coreholes studied in the Sydney Basin. Correlation between the upper coal in Murrays Run-1 and coal seams elsewhere in the Sydney Basin is therefore not readily possible so determining the extent of missing section in the latest Permian is uncertain. The $\delta^{13}C_{org}$ record does however suggest that this section may include the latest Permian preserved in the Sydney Basin, as detailed in Morante and Herbert, (1994).

A reinterpretation of the Narrabeen Group/Newcastle Coal Measures lithological boundary (Morante and Herbert, 1994) suggests it is more appropriately placed at 738.28 m (Fig. 2.25) rather than at 758 m (NSW Geological Survey Report GS1973/362). The rapid negative $\delta^{13}C_{org}$ excursion is from –25.63‰ at 743.35 m to -29.63‰ at 737.95 m, within the top 5 m of the coal measures sediment but well above the last preserved coal. A *Glossopteris* leaf lies at 738.76 m in the terminal Newcastle Coal Measures 5th order sequence, which is *after* the $\delta^{13}C_{org}$ excursion begins and within 0.5 metres of the coal measures/Narrabeen Group boundary (Morante and Herbert, 1994).

The $\delta^{13}C_{org}$ excursion begins below the first identified sample of the *P. microcorpus* Zone at 733.14 m, above an interval of no biostratigraphical data following the top Upper Stage 5 sample at 739.8 m. It may have culminated during the hiatus at the coal measures/Narrabeen Group boundary which is identified by a paleosol profile at 738.14 m. $\delta^{13}C_{org}$ values of -34 to -35‰ encountered in the West Australian basins may have been achieved during the hiatus but not preserved. Samples with more positive values e.g. > -26‰, in the basal Narrabeen Group are generally paleosols (G. Retallack pers. comm., 1993). One possible explanation for the anomalously positive $\delta^{13}C_{org}$ values in the Narrabeen Group is that the organic matter may have been partially degraded in the paleosol as the organic matter was rapidly recycled and under such conditions it is common for the lighter isotope of carbon to be preferentially removed as a volatile fluid product resulting in a more positive $\delta^{13}C_{org}$ value (Schidlowski, 1988). A dramatic decrease in TOC parallels the $\delta^{13}C_{org}$ excursion.

The determined H/C ratios on extracted kerogen from selected samples from DM Murrays Run-1 have values ranging from 0.58 to 0.78 (Table 2.18). According to Hayes et al. (1983) these H/C ratios are above the threshold value of 0.3 and indicate a high probability that the primary $\delta^{13}C_{org}$ signature in the samples has been preserved. The low N/C (nitrogen/carbon) ratios indicate the organic matter is nonmarine in origin (Wang et al., 1994).

The location of the Permian-Triassic boundary in this corehole is taken to approximate the coal measures/Narrabeen Group boundary despite indications from carbonate sections (Holser et al., 1989; Baud et al., 1989) that the Permian-Triassic boundary lies at the base of the excursion. The terminal 5th order sequence where the excursion is found in Murrays Run-1 is probably representative of negligible sediment in more condensed carbonate sections.

Table 2.18 Murrays Run-1. $\delta^{13}C_{org}$, TOC %, H/C, N/C, and biostratigraphy.

Depth m	$\delta^{13}C_{org}$‰	TOC %	H/C	N/C	sample type	Palynology
54.96	-28.35	3.1			cc	unknown
87.99	-28.76	0.4	0.78	0.02	cc	*A. tenuispinosus*
167.52	-26.84	0.8			cc	*A. tenuispinosus*
193.75	-25.84	0.8	0.68	0.02	cc	*A. tenuispinosus*
214.37	-27.00	0.1			cc	undetermined
218.02	-27.48	0.2			cc	undetermined
298.2	-25.06	0.2			cc	*P. samoilovichii*
354.61	-26.69	0.3			cc	*P. samoilovichii*
381.43	-30.92	0.4			cc	*P. samoilovichii*
406	-30.29	0.4			cc	*P. samoilovichii*
418	-26.13	0.3			cc	*P. samoilovichii*
436.37	-26.62	0.1			cc	*P. samoilovichii*
452.16	-25.18				cc	*P. samoilovichii*
462.67	-25.24	0.1			cc	*P. samoilovichii*
462.67	-25.26	0.1			cc	*P. samoilovichii*
478.1	-24.80	0.4			cc	unknown
482.71	-24.62	0.3			cc	unknown
507.75	-26.74	0.5			cc	unknown
568	-28.23	0.5			cc	unknown
568	-25.62	0.4			cc	unknown
568.65	-23.33	0.1			cc	unknown
591.72	-25.92	<0.1			cc	unknown
615.44	-27.27	0.1			cc	unknown
643.5	-24.90	<0.1			cc	barren
650.37	-26.73	0.2			cc	unknown
663.26	-25.54	0.1			cc	unknown
668.35	-26.94	0.2			cc	unknown
679	-27.06	0.2			cc	*P. microcorpus*
682.65	-27.30	0.1			cc	*P. microcorpus*
709.04	-26.38	<0.1			cc	*P. microcorpus*
710.98	-27.82	0.3			cc	*P. microcorpus*
713.16	-29.98	0.3	0.60	0.03	cc	*P. microcorpus*
715.5	-23.83	<0.1			cc	*P. microcorpus*

Depth m	$\delta^{13}C_{org}$‰	TOC %	H/C	N/C	sample type	Palynology
717.49	-25.44	< 0.1			cc	*P. microcorpus*
721.87	-28.58	0.2	0.65	0.03	cc	*P. microcorpus*
728.1	-24.18	0.6	0.58	0.02	cc	*P. microcorpus*
728.71	-24.11	1.1			cc	*P. microcorpus*
733.1	-27.76	0.5	0.70	0.02	cc	*P. microcorpus*
733.14	-28.84	3.0			cc	*P. microcorpus*
736	-24.89	0.4	0.68	0.03	cc	unknown
737.95	-29.62	2.5			cc	unknown
738.13	-28.46	2.0			cc	unknown
739.15	-27.90	2.0			cc	unknown
739.8	-29.04	2.9			cc	U5
739.8	-29.06	2.9			cc	U5
740.1	-29.38	2.8			cc	U5
740.16	-29.12	2.2			cc	U5
740.4	-26.18	1.3			cc	U5
740.53	-29.62	3.2			cc	U5
740.63	-25.89	0.9			cc	U5
741	-28.22	1.5			cc	U5
741.03	-26.20	1.3			cc	U5
741.18	-25.52	0.8			cc	U5
741.48	-26.28	0.8			cc	U5
741.7	-25.52	1.5			cc	U5
742.12	-27.87	2.3			cc	U5
742.44	-27.93	1.5			cc	U5
742.6	-27.31	1.2			cc	U5
742.64	-26.73	1.1			cc	U5
742.7	-27.62	2.0			cc	U5
742.8	-27.62	2.0			cc	U5
743.1	-26.51	1.4	0.64	0.02	cc	U5
743.35	-25.63	2.0			cc	U5
744.1	-25.55	2.2			cc	U5
744.54	-25.22	1.4			cc	U5
746.94	-25.82	1.7			cc	U5
759.7	-25.99	6.2			cc	U5
767.22	-26.59	5.3			cc	U5
768.98	-24.70	5.4			cc	U5
770.13	-25.16	6.6	0.72	0.02	cc	U5
781.86	-25.13	12.6			cc	U5
796.63	-23.84	8.1	0.64	0.02	cc	unknown
811.56	-24.19	2.3			cc	unknown

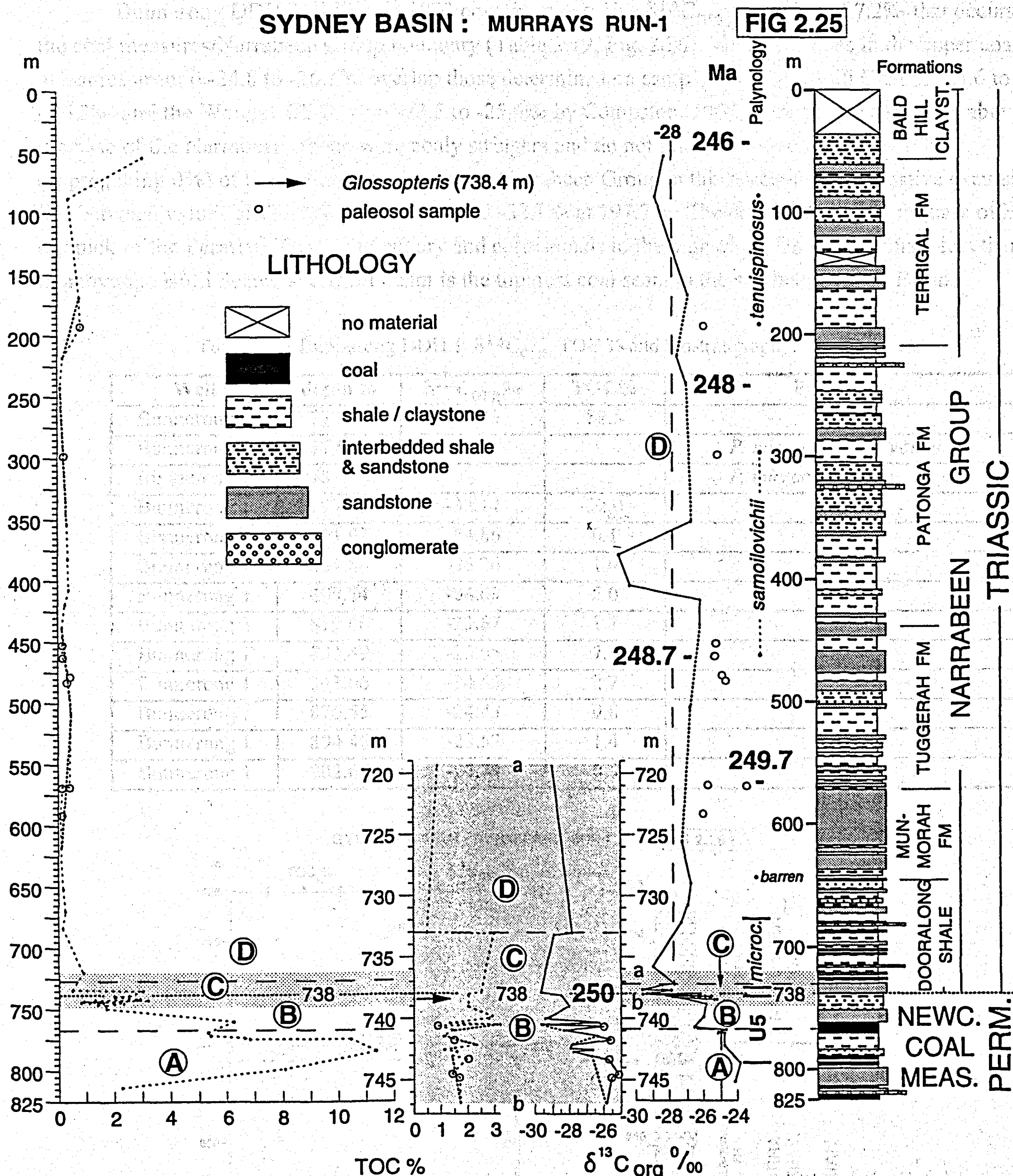

Figure 2.25 Department of Mineral Resources Murrays Run DDH 1, Sydney Basin, eastern Australia. Total organic carbon (TOC) and $\delta^{13}C_{org}$, are expanded about the negative excursion, palynological zones (R.J. Helby pers. comm. 1992, 1994), lithological log, formations (NSW Geological Survey Report GS1973/362). The $\delta^{13}C_{org}$ excursion is between values of -25.8‰ at a depth of 746.94 m and -29.6‰ at 737.95 m. The dotted line at 738 m is my pick of the Permian-Triassic boundary and corresponds to the base of the Dooralong Shale, the basal unit of the Narrabeen Group. The shading indicates the expanded part of the section.

2.6.2 Bunnerong DDH-1

Bunnerong DDH-1, drilled in 1993 contains a negative $\delta^{13}C_{org}$ excursion of 7.2‰ that occurs at the coal measures/Narrabeen Group boundary (Table 2.19; Fig. 2.26). $\delta^{13}C_{org}$ values in the upper coal measures around -24.8 to -26.3‰ overlap those determined on samples from the Bulli Coal of -24.6 to –26.3‰ and the Wongawilli Coal of -23.5 to -25.6‰ by Compston (1960, table 5a). The samples above the base of the Narrabeen Group were coaly stringers and do not reflect the extremely low TOC (approaching 0%) of the sediments of the basal Narrabeen Group in this corehole. The negative excursion lies between values of -24.9‰ at 801.03 m and -32.1‰ at 797.7 m. The dotted line at 801 m (base of B) is my pick of the Permian-Triassic boundary and corresponds to the base of the Dooralong Shale less than 1 m above the Bulli Seam. The Bulli Seam is the topmost coal seam in the southern Sydney Basin.

Table 2.19 Bunnerong DDH 1. $\delta^{13}C_{org}$, TOC % and biostratigraphy.

Well	depth m	$\delta^{13}C_{org}$‰	TOC%	Palynology
Bunnerong 1	732.22	-29.95	82.5	
Bunnerong 1	777.85			*P. microcorpus or younger*
Bunnerong 1	781.30			*P. microcorpus or younger*
Bunnerong 1	797.70	-32.14	22.0	
Bunnerong 1	801.03	-24.86	0.1	
Bunnerong 1	801.80	-26.26	1.0	
Bunnerong 1	809.74	-24.63	5.0	
Bunnerong 1	819.60	-23.87	1.7	
Bunnerong 1	831.49	-25.05	7.9	
Bunnerong 1	843.06	-24.45	2.7	
Bunnerong 1	876.55	-24.43	0.8	
Bunnerong 1	894.45	-23.52	1.4	
Bunnerong 1	902.65	-24.74	0.5	

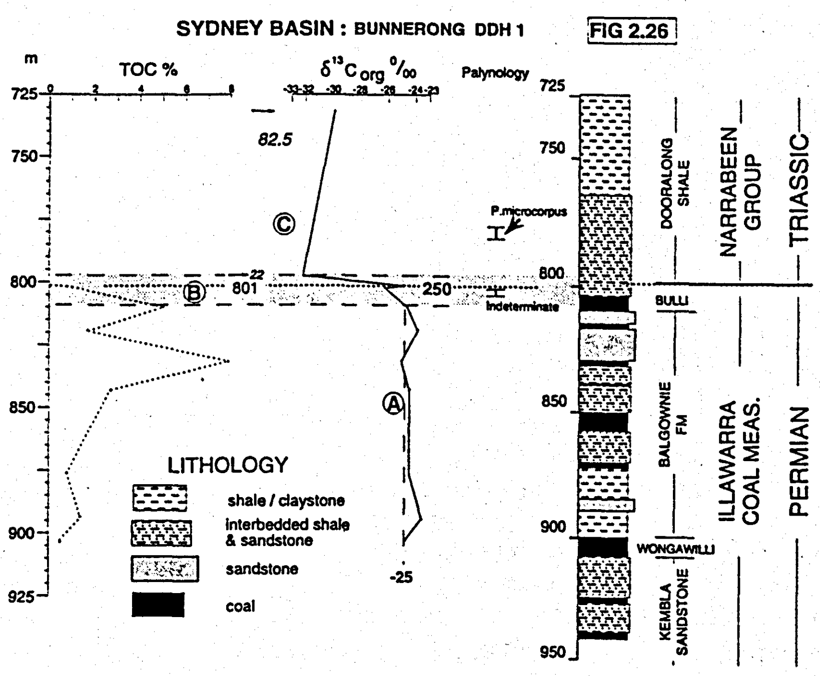

Figure 2.26 Bunnerong DDH 1, Sydney Basin, eastern Australia. Total organic carbon (TOC), $\delta^{13}C_{org}$, palynological zones (R.J. Helby pers. comm., 1994), lithological log, formations (C. Herbert pers. comm., 1994).

2.6.3 Lisarow DDH 1

Lisarow DDH 1, drilled in 1982 (Fig 2.27; Table 2.20) intersected the youngest coal in the Sydney Basin, the Vales Point Seam, of the Newcastle Coal Measures which is known to contain a *Dulhuntyispora* assemblage (=Upper stage 5) (Kemp et al., 1977). The core also intersected a well-developed band of the Awaba Tuff marker bed, dated by Gulson et al. (1990) as 256 ± 4Ma.

A problem encountered in the study of this core in the Narrabeen Group was the location of suitable samples for analysis. Experience from sampling the Murrays Run-1 core showed that paleosols with disrupted bedding tend to have $\delta^{13}C_{org}$ values more positive than samples without disrupted bedding. In Lisarow-1 almost all fine grained sediment horizons above the Vales Point (V.P.) coal are paleosols. These paleosols are well developed after 635.5.5 m on top of, and through, crevasse splays. The oldest mottled green sediments are encountered around 625 m and thereafter the TOC of the samples decreases to levels of below 0.5%. $\delta^{13}C_{org}$ of the paleosol beds ranges from -24 to -25.2‰ and reflect the more positive values expected in paleosols. An oil shale between 647.1 and 647.0 m may represent the terminal Permian in this corehole.

An indication that samples above 646.9 m may have suffered partial degradation of the organic matter and consequent increase in $\delta^{13}C_{org}$ is that the plot of TOC vs $\delta^{13}C_{org}$ shows a weak positive correlation between increasing TOC and decreasing $\delta^{13}C_{org}$ (Fig. 2.28). This encourages an interpretation that paleosol development leads to more positive $\delta^{13}C_{org}$ values that can mask the extent of the negative $\delta^{13}C_{org}$ excursion in nonmarine sediments. Assuming this degradation led to an increase in $\delta^{13}C_{org}$ of around 2‰ (Hayes, 1983), I infer a steady $\delta^{13}C_{org}$ profile through the lower Narrabeen Group sediments in this core hole at around -26.5 to -27‰, typical of other Early Triassic sections in segment D of $\delta^{13}C_{org}$ profiles.

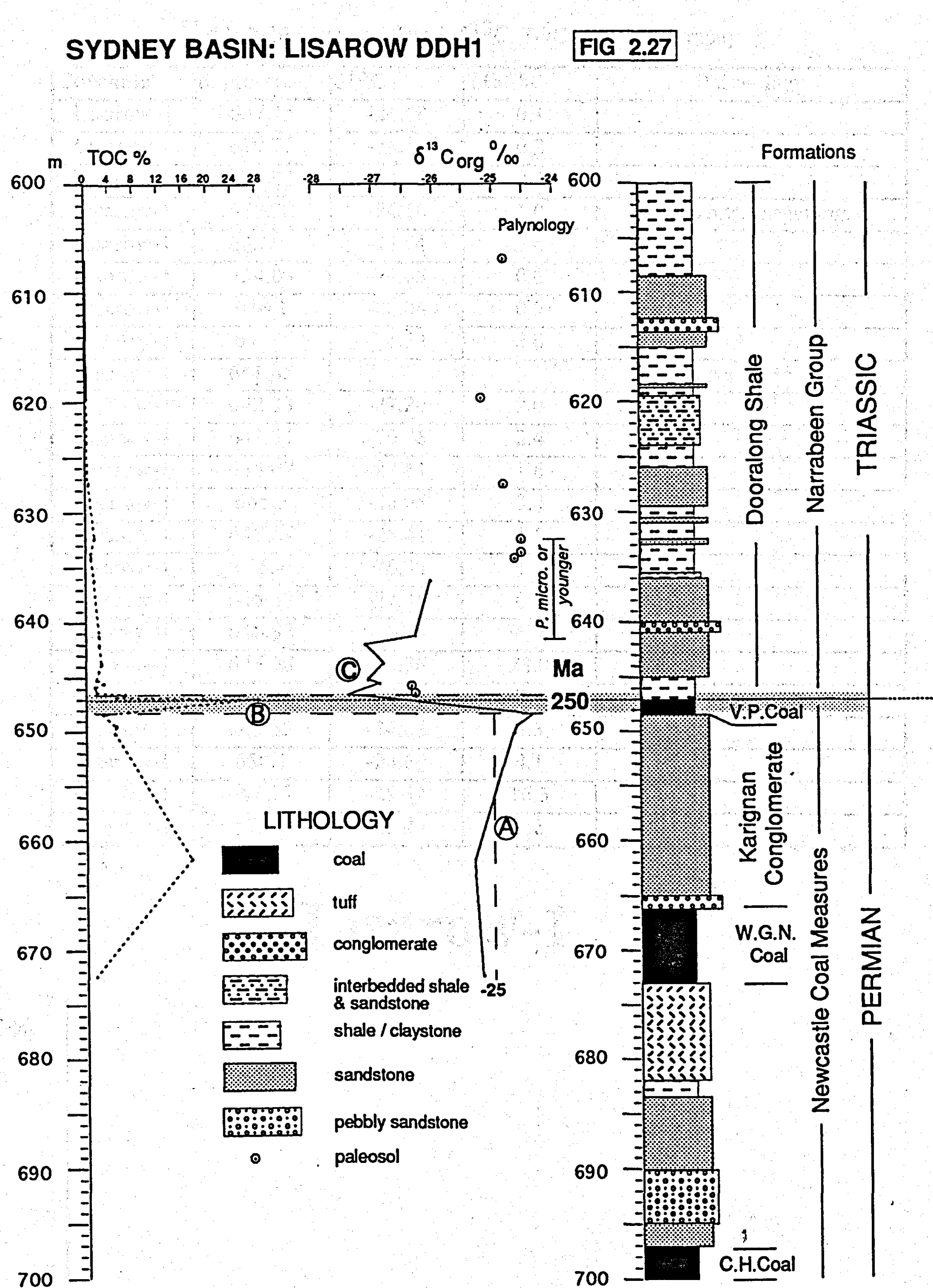

Figure 2.27 Lisarow DDH 1, Sydney Basin, eastern Australia. Total organic carbon (TOC), $\delta^{13}C_{org}$, palynological zones (R.J. Helby pers. comm. 1994), lithological log (Electricity Commission of NSW, 1992), formations (C. Herbert, pers. comm., 1994). The negative $\delta^{13}C_{org}$ excursion lies between values of -24.5‰ at 648.36 m and -27.5‰ at 646.67 m. The dotted line at 647 m is my pick of the Permian-Triassic boundary which equals the base of the Dooralong Shale (Narrabeen Group). $\delta^{13}C_{org}$ for paleosols above 635 m (ringed) is displaced 1 to 2‰ to more positive values from values interpreted as primary, e.g., those at the base of the Dooralong Shale.

Table 2.20 Lisarow DDH 1. $\delta^{13}C$, TOC%, biostratigraphy.

Corehole	depth m	$\delta^{13}C$	TOC%	Palynology
Lisarow-1	607.15	-24.78	0.1	
Lisarow-1	619.75	-25.18	0.2	
Lisarow-1	627.42	-24.87	0.3	
Lisarow-1	632.36	-24.56	1.0	*P. microcorpus/younger*
Lisarow-1	633.99	-24.54	0.6	
Lisarow-1	634.09	-24.65	0.6	
Lisarow-1	636.1	-26.06	0.9	
Lisarow-1	641.2	-26.34	2.0	
Lisarow-1	641.85			*P. microcorpus/younger*
Lisarow-1	642.33	-27.20	2.0	
Lisarow-1	643.71	-26.76	2.4	
Lisarow-1	645.07	-27.11	1.6	
Lisarow-1	645.5	-26.95	3.0	
Lisarow-1	645.67	-26.41	1.6	
Lisarow-1	646.1	-26.38	1.9	
Lisarow-1	646.67	-27.45	6.4	
Lisarow-1	646.88	-26.74	4.8	
Lisarow-1	646.98	-26.76	28.0	
Lisarow-1	648.36	-24.46	3.0	
Lisarow-1	649.52	-24.68	4.5	
Lisarow-1	650.1	-24.69	4.1	
Lisarow-1	661.77	-25.32	16.5	
Lisarow-1	673.3	-25.23	1.2	

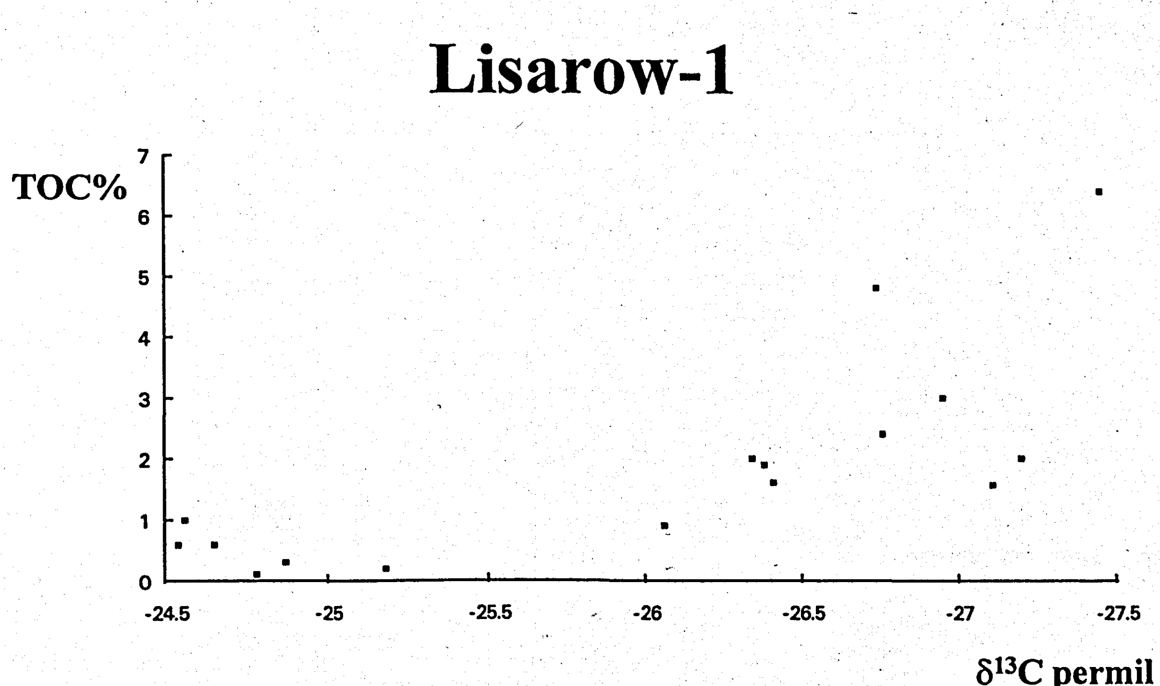

Figure. 2.28 TOC vs $\delta^{13}C_{org}$ for the lower Narrabeen Group samples in Lisarow-1.

2.6.4 Awaba DDH 2

Awaba DDH 2, drilled in 1984, spudded into the Newcastle Coal Measures (Fig. 2.29; Table 2.21). The $\delta^{13}C_{org}$ profile is remarkably stable within the range -23.3 to -25.8‰ during the long period of positive $\delta^{13}C_{org}$ values during the Permian.

An age of Upper Stage 5 between 106.5 and 795 m is indicated by the miospore *Microreticulatisporites bitriangularus*. Sediments above 106.5 m were not studied for palynology and the only sample studied below 795 m at 840.1 m was barren (McMinn, 1984). The base of this corehole is interpreted to approximate the base of Upper Stage 5.

The environment of deposition can be divided into two parts at 351 m: upper delta plain with higher $\delta^{13}C_{org}$ above, and lower delta plain or marginal marine indicated by acritarchs (McMinn, 1984) with lower $\delta^{13}C_{org}$ below.

Two ties can be made between Awaba-2 and Lisarow-1:

1) the Great Northern coal in Lisarow-1 is equivalent to the Wangawilli/Great Northern (WGN) coal in Awaba-2, and

2) the Awaba Tuff below the WGN in Lisarow-1 is equivalent to the Awaba Tuff in Awaba-2.

Lisarow-1 was deposited at the edge of a conglomerate section whereas Awaba-2 was more central and hence has a much thicker section. This suggests the top 170 m of section from the top of Awaba-2 is equal to the interval 643-673 m in Lisarow-1. The Vales Point seam, the youngest coal in the Sydney Basin is at 648.5 m in Lisarow-1. The coreholes therefore provide a complete $\delta^{13}C_{org}$ profile through the recognised latest Permian preserved in the Sydney Basin, unavailable from a single corehole.

Table 2.21 Awaba DDH 2. $\delta^{13}C$, TOC, biostratigraphy.

Corehole	Depth (m)	$\delta^{13}C_{org}$‰	TOC%	Palynology
Awaba 2	39.8	-25.40	1.6	undetermined
Awaba 2	49	-24.49	9.2	undetermined
Awaba 2	104	-23.70	1.3	undetermined
Awaba 2	127.85	-24.79	4.8	U5
Awaba 2	140.95	-23.78	2.2	U5
Awaba 2	189.1	-23.36	0.7	U5
Awaba 2	207.6	-23.95	1.8	U5
Awaba 2	225.3	-23.96	2.4	U5
Awaba 2	253.1	-23.44	0.9	U5
Awaba 2	279.28	-23.99	3.6	U5
Awaba 2	296.6	-23.94	2.0	U5
Awaba 2	322.8	-24.00	2.4	U5
Awaba 2	413	-25.01	3.2	U5
Awaba 2	415.2	-24.11	2.1	U5
Awaba 2	416.5	-24.46	2.2	U5
Awaba 2	418.5	-24.36	1.3	U5
Awaba 2	439.2	-24.11	3.5	U5
Awaba 2	466.1	-24.74	6.2	U5
Awaba 2	487.6	-24.53	3.4	U5
Awaba 2	516.8	-24.65	2.6	U5
Awaba 2	525.75	-24.48	3.8	U5
Awaba 2	542.88	-24.89	2.7	U5
Awaba 2	551.5	-24.83	2.6	U5
Awaba 2	583.75	-25.22	2.3	U5
Awaba 2	583.75	-25.19	2.7	U5
Awaba 2	595.00	-24.90	1.6	U5
Awaba 2	602.89	-24.47	1.8	U5
Awaba 2	613.3	-24.62	2.4	U5
Awaba 2	649.8	-25.02	2.7	U5
Awaba 2	667.58	-24.82	2.4	U5
Awaba 2	683.2	-25.03	1.9	U5
Awaba 2	719.2	-24.60	2.8	U5
Awaba 2	719.2	-24.58	3.4	U5
Awaba 2	727.2	-25.23	5.6	U5
Awaba 2	739	-24.50	2.8	U5
Awaba 2	769.6	-25.086	3.7	U5
Awaba 2	778.2	-24.14	3.4	U5
Awaba 2	796.45	-24.75	8.6	undetermined
Awaba 2	806.7	-25.83	17.5	undetermined
Awaba 2	817.6	-23.96	2.2	undetermined
Awaba 2	820.6	-24.06	4.1	undetermined
Awaba 2	820.6	-24.08	3.9	undetermined

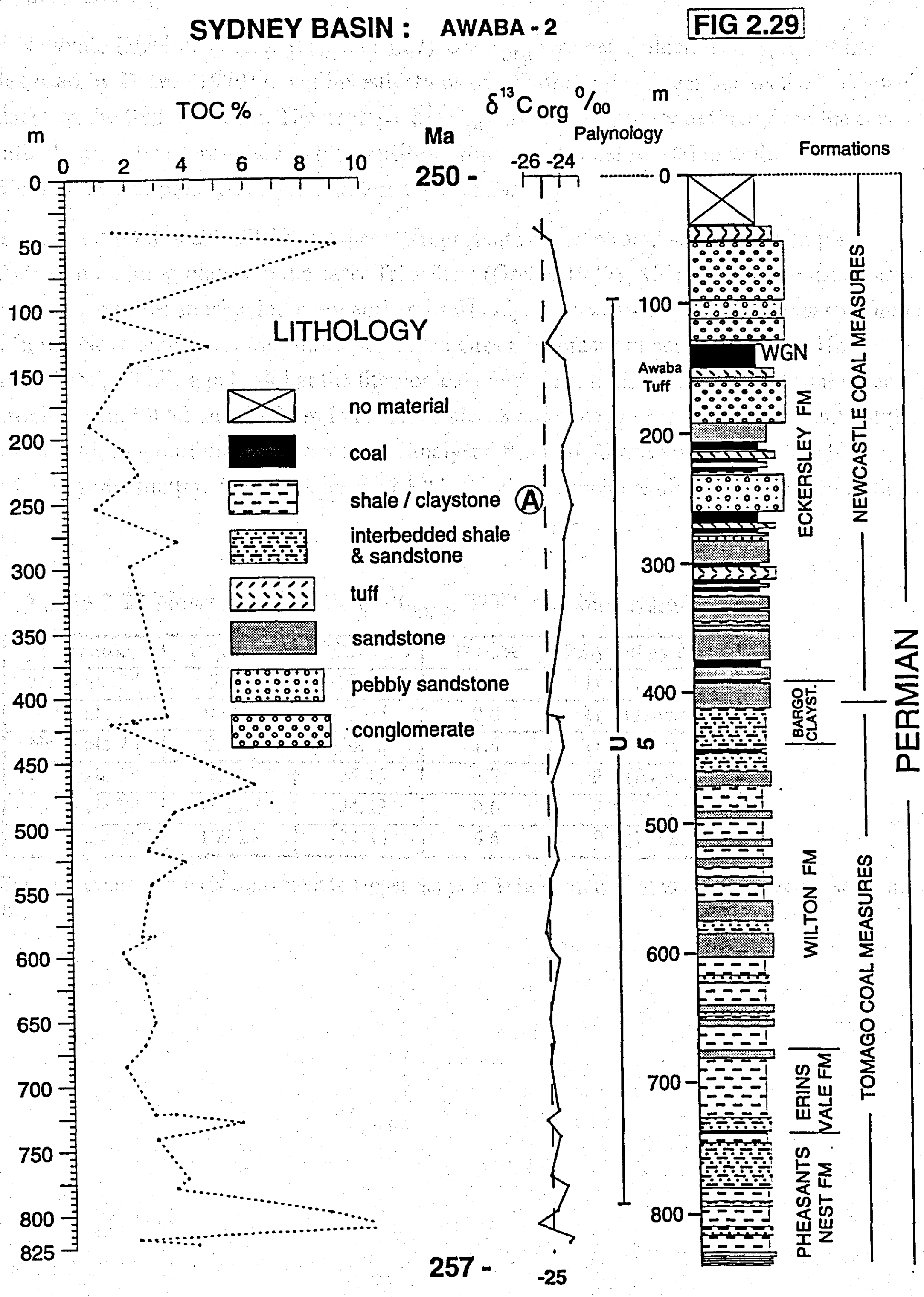

Figure 2.29 Awaba DDH 2, Sydney Basin, eastern Australia. Total organic carbon (TOC), $\delta^{13}C_{org}$, palynological zones (McMinn, 1984), lithological log, and formations (C. Herbert pers. comm., 1994; Bradley et al., 1985, p. 149). Note that this drillhole spudded beneath the Newcastle Coal Measures/Narrabeen Group boundary. The base of Awaba-2 corehole is picked as the base of U5 and estimated at 257 Ma. The top of the corehole (uncored) is estimated to equal the top of the coal measures (250 Ma).

2.6.5 DM Newvale DDH-28

In DM Newvale DDH-28 (Fig. 2.30; Table 2.22), $\delta^{13}C_{org}$ was determined from splits of the original samples used by Grebe (1970) in her investigations of palynofloral changes across the "Permian-Triassic boundary" in the Sydney Basin. The negative $\delta^{13}C_{org}$ excursion, poorly defined from the few dark shales available, may be represented in the transition from samples below 106 m with $\delta^{13}C_{org}$ greater than -25‰ to the samples above 90.52 m less than -25‰.

The samples at 90.88 m and 90.52 m appear to represent an exceptional situation, with plant debris recognisable on bedding planes in the early Tr1a Zone (Grebe, 1970), which elsewhere lacks plant fossils, and the presence of the marine indicator acritarchs *Micrhystridium* sp and *Veryhachium* sp (Grebe, 1970, table 2). In the Newcastle Coal Measures/Narrabeen Group boundary at nearby Wybung Head (Retallack, pers. comm., 1993), a paleosol at the lithological contact contains illitic clay and coal breccia. Because the samples from 90.52 and 90.88 m in the Newvale-28 corehole are probably equivalents of the Wybung Head paleosol, much of the organic material analysed from 90.88 and 90.52 m is probably reworked Permian organic matter. This explains the $\delta^{13}C_{org}$ values which are similar to those from the coal measures.

Table 2.22 Newvale DDH 28 $\delta^{13}C_{org}$, TOC, and biostratigraphy.

Corehole	Depth m	$\delta^{13}C_{org}$‰	TOC%	Palynology Zone
Newvale 28	76.2	-27.21	0.3	Tr 1a (Evans)
Newvale 28	90.52	-25.65	0.8	Tr 1a (Evans)
Newvale 28	90.88	-24.42	1.6	Tr 1a (Evans)
Newvale 28	91.74	-25.45	6.7	P 4 (Evans)
Newvale 28	106.67	-24.29	0.6	P 4 (Evans)
Newvale 28	107.28	-24.56	6.6	P 4 (Evans)

P4 palynology Zone of Evans (1966) is equivalent to Upper Stage 5; Tr1a is equivalent to the *P. microcorpus* Zone (Helby et al., 1987).

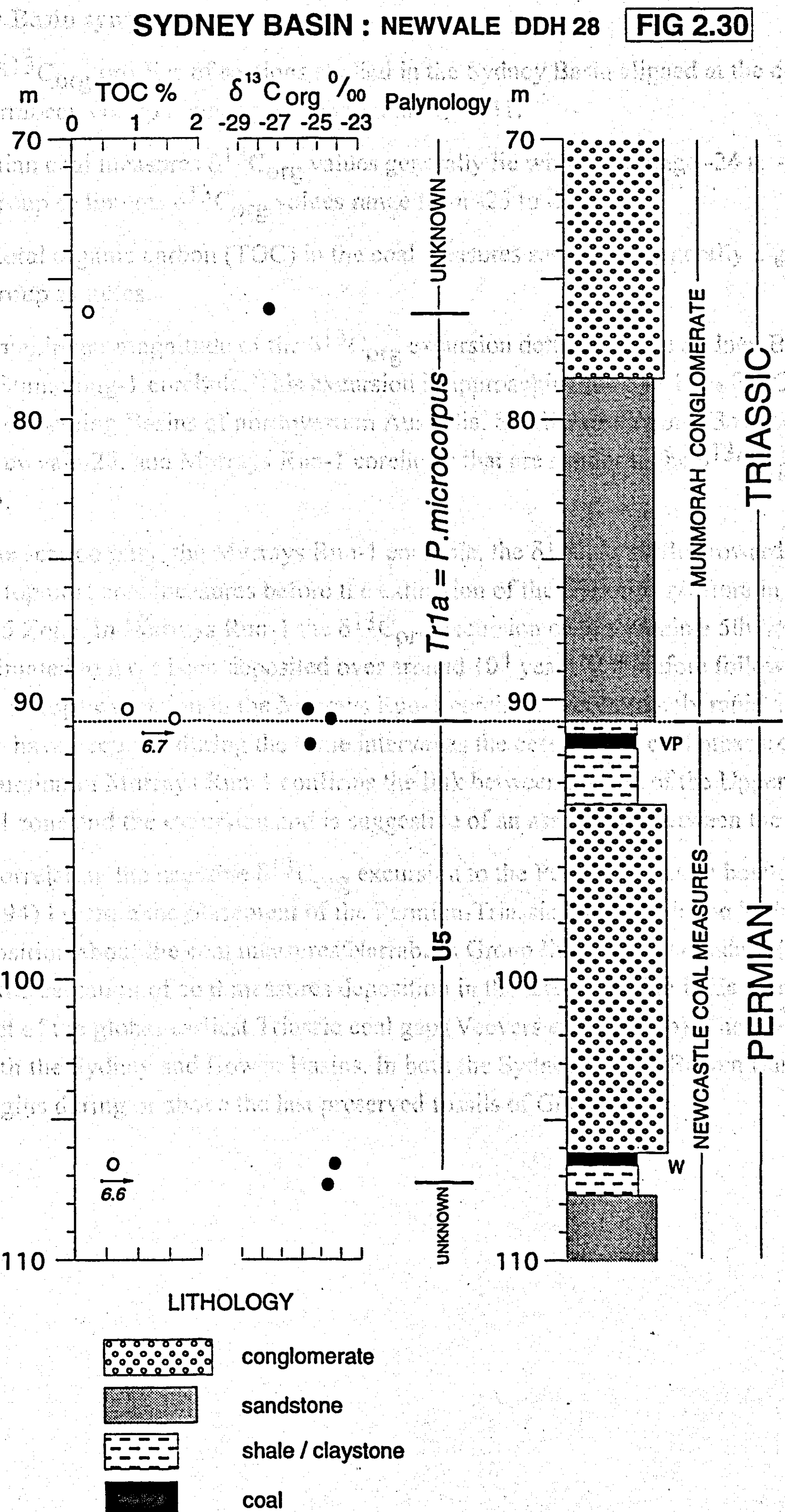

Fig.2.30 Newvale DDH 28, Sydney Basin, eastern Australia. Total organic carbon (TOC), $\delta^{13}C_{org}$, palynological zones (Grebe, 1970), lithological log (Uren, 1980, fig. 9.2), and formations (Grebe, 1970). The negative $\delta^{13}C_{org}$ excursion poorly defined due to the low sampling ferquency lies between -24.3‰ at 106.67 m and -27.2‰ at 76.2 m. The dotted line at 90.85 m is my pick of the Permian-Triassic boundary which corresponds to the base of the Munmorah Conglomerate and the first determined sample of the Tr1a (= *P. microcorpus*) Zone.

2.6.6 Sydney Basin synopsis

The $\delta^{13}C_{org}$ profiles of sections studied in the Sydney Basin aligned at the coal measures/Narrabeen Group boundary are shown in Fig. 2.31.

Permian coal measures $\delta^{13}C_{org}$ values generally lie within the range -24 to -25‰ whereas Narrabeen Group sediments $\delta^{13}C_{org}$ values range from -25 to -31.5‰.

The total organic carbon (TOC) in the coal measures samples is generally higher than in Narrabeen Group samples.

The maximum magnitude of the $\delta^{13}C_{org}$ excursion detected in the Sydney Basin section was 7.3‰ in the Bunnerong-1 corehole. This excursion is approaching the 8 to 10‰ $\delta^{13}C_{org}$ excursions in the Bonaparte and Canning Basins of northwestern Australia. Smaller excursions (3 to 5‰) are found in the Lisarow-1, Newvale-28, and Murrays Run-1 coreholes that are similar to the $\delta^{13}C_{org}$ excursions in the Bowen Basin.

In one section only, the Murrays Run-1 corehole, the $\delta^{13}C_{org}$ shifted toward more negative values in the topmost coal measures before the extinction of the *Glossopteris* flora in sediments from Upper Stage 5 Zone. In Murrays Run-1 the $\delta^{13}C_{org}$ excursion occurs within a 5th order sedimentary sequence estimated to have been deposited over around 10^4 years. It therefore follows that on a geological scale the fast isotope excursion in the Murrays Run-1 corehole was extremely rapid and could be considered to have occurred during the same interval as the cessation of coal measures deposition. The $\delta^{13}C_{org}$ excursion in Murrays Run-1 confirms the link between the end of the Upper Stage 5 palynological zone and the excursion and is suggestive of an association between the two events.

By correlating the negative $\delta^{13}C_{org}$ excursion to the Permian-Triassic boundary (Newell, 1994, Yin et al., 1994) I restore the placement of the Permian-Triassic boundary in the Sydney Basin to the traditional position about the coal measures/Narrabeen Group lithological boundary (David, 1950). It follows that the cessation of coal measures deposition in the latest Permian in Eastern Australia coincides with the onset of the global earliest Triassic coal gap (Veevers et al., 1994b). The $\delta^{13}C_{org}$ excursion is similar in both the Sydney and Bowen Basins. In both the Sydney and the Bowen Basins, the $\delta^{13}C_{org}$ excursion begins during or above the last preserved fossils of *Glossopteris.*

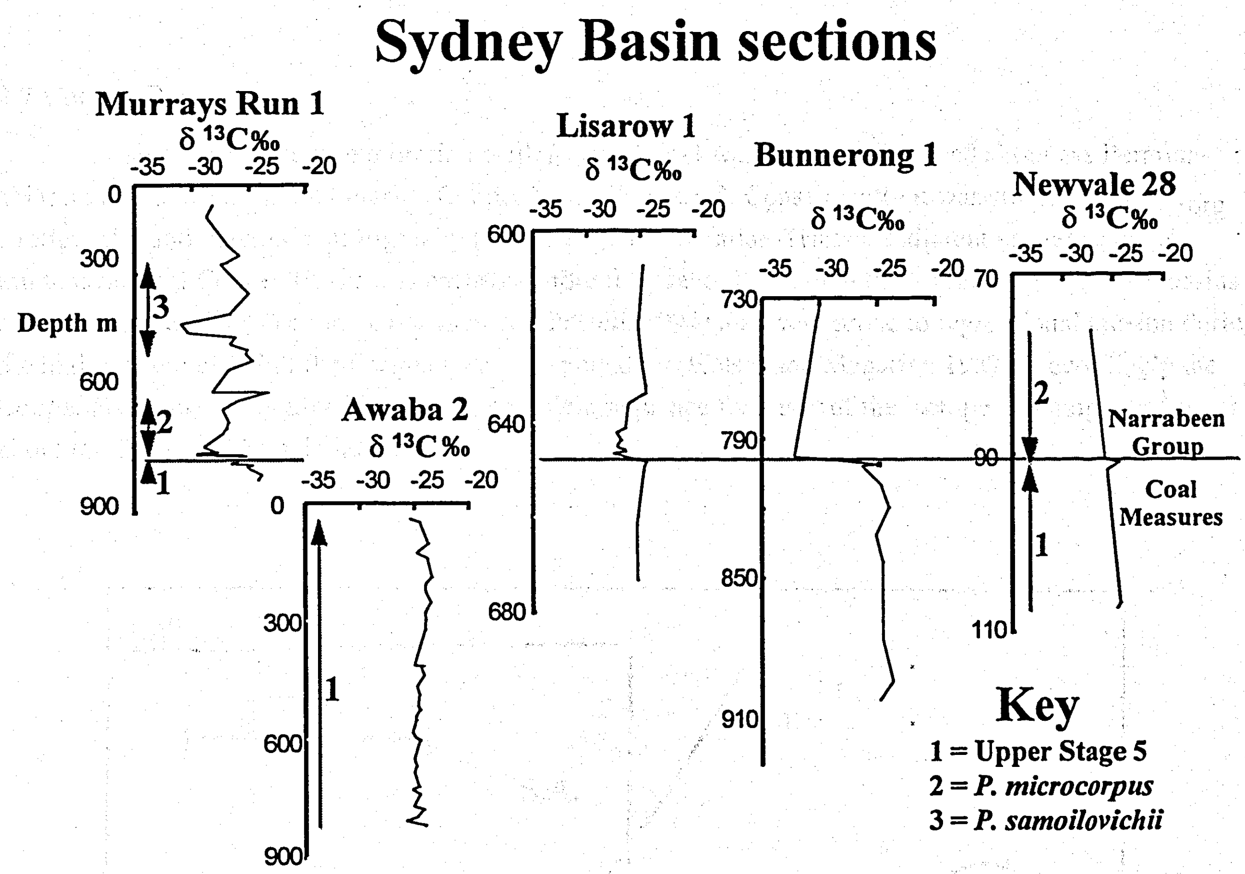

Figure 2.31 Sydney Basin $\delta^{13}C_{org}$ profiles plotted and aligned at the Coal Measures/Narrabeen Group lithostratigraphic boundary showing the palynology zones. Note that the depth scale in each core hole is not relative.

2.7 Cooper Basin

A single petroleum exploration well, Merrimelia-3 was almost fully cored about the Permian-Triassic boundary in the nonmarine Cooper Basin (Fig. 2.32). Consequently it was studied for $\delta^{13}C_{org}$ stratigraphy and magnetic stratigraphy (Chapter 5). The Permian-Triassic sediment sequence in the intracontinental Cooper Basin was probably more fully recorded than in the foreland sedimentary basins of eastern Australia (Veevers, Conaghan and Powell, 1994) that were prone to regressional erosion during the major sealevel fall at the Permian-Triassic boundary (Holser and Magaritz, 1987). Accordingly the Cooper Basin probably provides a more complete sequence for study of the isotope and magnetic record about the Permian-Triassic boundary.

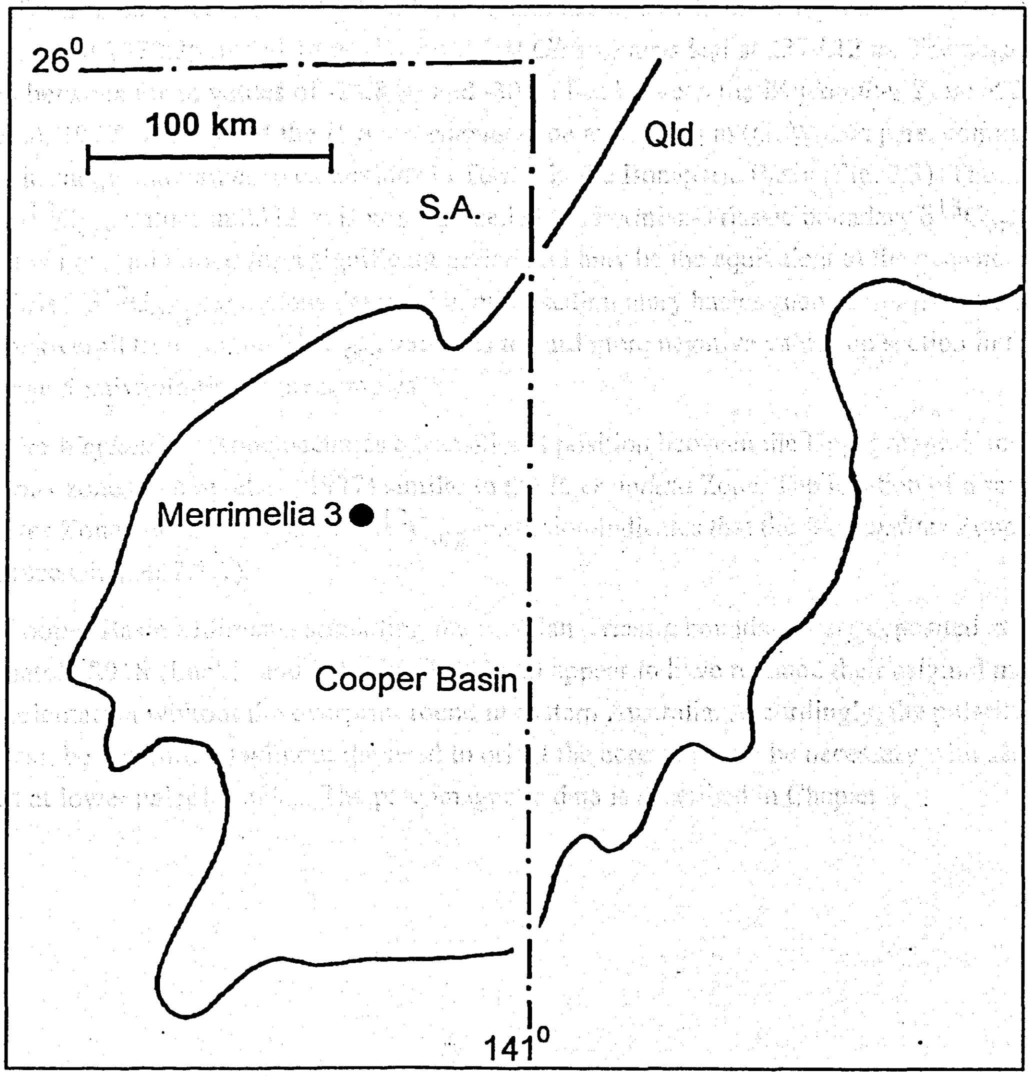

Figure 2.32 Location of Merrimelia 3.

2.7.1. Merrimelia-3

Merrimelia-3 (Fig. 2.33; Table 2.23), drilled by Delhi-Santos Petroleum in 1965, was fully cored in the lower part of the Triassic Nappamerri Formation and Late Permian sediments, based on palynological correlation (G. Woods pers. comm., 1993; Table 2.24). A magnetic-polarity transition coincides within metres with a -6‰ $\delta^{13}C_{org}$ excursion (Fig. 2.33; Chapter 5).

More positive $\delta^{13}C_{org}$ values above 2355 m (Fig. 2.33, circled data points) correspond to sediment with an increasing proportion of detrital graphite (M. Smyth pers. comm., 1993). Samples deeper than 2355 m lack detrital graphite. Whole-rock analysis of graphite-rich samples gives unreliable $\delta^{13}C_{org}$ results because detrital graphite may have a more positive $\delta^{13}C$ value due to loss of ^{13}C-depleted volatile products during metamorphism.

The interpretation of the most likely primary $\delta^{13}C_{org}$ curve is shown by the dotted line (Fig. 2.33) which links values from samples without graphite. The dotted line at 2362 m is my pick of the Permian-Triassic boundary. The $\delta^{13}C$-isotope excursion starts at 2362 m, approximately 10 m above the top coal seam at 2372.25 m and 14 m above the last *Glossopteris* leaf at 2377.12 m. The negative $\delta^{13}C_{org}$ excursion between mean values of -24.8 ‰ and -30 ‰ lies between the *Weylandites* Zone at 2373.17 m (Kemp et al. 1977, p. 191) and the *P. microcorpus* Zone at 2357.93 m (G. Woods pers. comm. 1993). This is similar in range and values to excursions in Tern-3 in the Bonaparte Basin (Fig. 2.3). The shift to more negative $\delta^{13}C_{org}$ values at 2372 m is not regarded at the Permian-Triassic boundary $\delta^{13}C_{org}$ excursion because it is not maintained for a significant period and may be the equivalent to the occasional more negative brief $\delta^{13}C_{org}$ excursions detected in other sedimentary basins such as in Fishburn-1, Bonaparte Basin. The overall trend in the $\delta^{13}C_{org}$ values is toward more negative values up section in the younger Upper Stage 5 palynological zone samples

The *Weylandites* Zone occupies a transitional position between the Upper Stage 5 and *P. microcorpus* zones (Kemp et al., 1977) similar to the *P. crenulata* Zone. The location of a sample from the *Weylandites* Zone below the negative $\delta^{13}C_{org}$ excursion indicates that the *Weylandites* Zone is latest Permian (see Chapter 2.1.1).

Cooper Basin sediments straddling the Permian-Triassic boundary were deposited at approximately 80° S (Lackie and Schmidt, 1993) and appear to have retained their original magnetic-polarity orientation without the overprint found in eastern Australia. Accordingly, the polarity of the core material can be determined without the need to orient the core as would be necessary with sediment deposited at lower paleolatitudes. The paleomagnetic data is described in Chapter 5.

Table 2.23 Merrimelia-3. $\delta^{13}C_{org}$, TOC, and notes on samples.

depth m	$\delta^{13}C_{org}$‰	TOC %	sample type	Notes
2318.6	-27.44	0.1	cc	
2320.3	-24.37	< 0.1	cc	* siderite
2327.6	-26.65	< 0.1	cc	* siderite
2329.25	-24.21	< 0.1	cc	*
2330.8	-23.94	< 0.1	cc	*
2334.55	-24.45	< 0.1	cc	*
2339.86	-25.16	0.1	cc	*
2340.87	-23.52	0.1	cc	* siderite
2342.7	-28.42	0.2	cc	plant frags
2347.32	-24.77	< 0.1	cc	*
2349	-25.55	0.3	cc	* siderite
2350.5	-25.52	0.1	cc	*
2352.86	-24.83	< 0.1	cc	* siderite
2354.95	-29.29	0.3	cc	
2356	-29.72	0.5	cc	
2357	-30.23	0.5	cc	
2357.97	-28.78	0.4	cc	plant frags
2359	-30.02	0.6	cc	plant frags
2360.35	-27.61	0.3	cc	bedding
2361.5	-24.54	< 0.1	cc	bedding
2363.63	-27.14	1.1	cc	plant frags
2365.02	-26.11	0.2	cc	plant frags
2366	-25.53	0.4	cc	
2366.95	-25.76	0.3	cc	plant frags
2369	-25.70	0.4	cc	bedding
2370.12	-25.88	0.6	cc	
2371.62	-27.31	0.3	cc	bedding
2372	-27.67	0.8	cc	bedding
2377.32	-25.53	7.8	cc	*Glossopteris*
2382.35	-23.52	2.5	cc	plant frags
2384.65	-23.13	2.0	cc	plant frags
2387.1	-23.43	2.7	cc	plant frags
2403	-24.20	2.3	cc	plant frags
2408.6	-23.59	3.0	cc	plant frags

*** sample contains a high proportion of detrital graphite compared to primary organic matter from fluorescence microscopy of polished blocks; "plant frags" indicates fossil plant fragments visible.**

Table 2.24 Merrimelia -3 palynology (G. Woods, pers. comm., 1993), *Weylandites* from Kemp et al. (1977, p. 191).

Depth feet	Depth metres	Core	Biostratigraphy
6335	1930.9	1	PJ3
7082	2158	2	Jurassic
7082	2158.59	2	PJ3
7321	2231.44	3	barren
7460	2273.81	4	barren
7473	2277.77	4	barren
7636	2327.45	7	barren
7648	2331.11	7	E. Triassic
7667	2336.9	7	barren
7708	2349.4	8	barren
7729	2355.8	8	barren
7736	2357.93	10	*P. microcorpus*
7736	2357.93	10	PP6-PT1
7742	2359.76	10	?E. Triassic
7786	2373.17	10	Tr1a/*Weylandites*
7788.5	2373.94	10	PP5
7795	2375.92	10	Upper stage 5
7809.3	2380.27	10	barren
7833.1	2387.57	11	PP5
7835.1	2388.14	11	?PP5
7840.3	2389.72	11	?PP5
7843	2390.55	11	PP5
7847.1	2391.8	11	?PP5
7855.8	2394.45	11	?PP5
7868	2398.17	12	PP2.2
7873.6	2399.87	12	PP2
7874	2400	11	PP2
7886.75	2403.88	12	Indeterminate
8094	2467.05	15	PP1

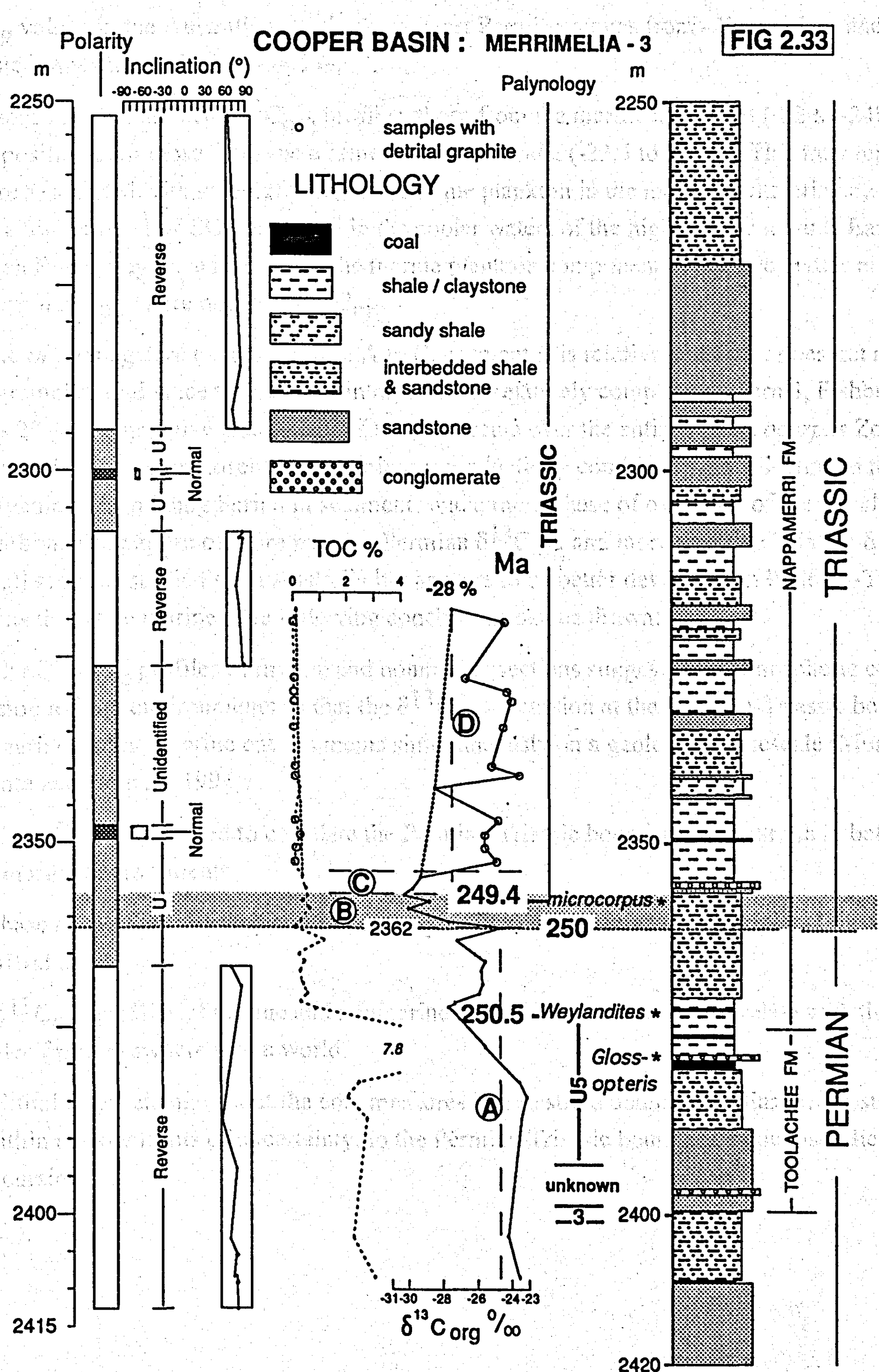

Figure 2.33 Merrimelia-3, Cooper Basin, central Australia. Magnetic polarity, total organic carbon (TOC), $\delta^{13}C_{org}$, palynological zones from G. Woods pers. comm. (1993), Paten, (1966), Kemp et al.(1977, p. 191), lithological log and formations (Delhi Australia Petroleum Ltd, 1965). The $\delta^{13}C_{org}$ samples represented as open circles are those determined to have a high proportion of graphite relative to organic matter.

2.8 Synopsis of all Australian $\delta^{13}C_{org}$ data

$\delta^{13}C_{org}$ values in the Australian late Early to latest Permian ranges from -22 to -25‰, and within the Early Triassic ranges from -26.5 to -34.5‰.

In segment A of the studied $\delta^{13}C_{org}$ profiles, those from the marine northwest (-22 to -24‰) are generally more positive than those from the marine eastern Australia (-23.5 to -25‰). This may represent a primary feature associated with paleolatitude, as in marine plankton in the modern Antarctic ocean (Rau et al., 1989). The higher level of CO_2 dissolved in the cooler waters of the higher polar latitude Eastern Australian Bowen Basin may have resulted in the marine plankton component of organic matter preserved in those sediments having a more negative $\delta^{13}C_{org}$.

The zone of the negative excursion from A to C, segment B is relatively short. It does not appear to have been extremely rapid since the sections interpreted as relatively complete — Tern 3, Fishburn 1, and Denison NS 20 — the negative excursion in $\delta^{13}C_{org}$ occurs over the entire *P. microcorpus* Zone. This interval probably represents extremely low primary productivity combined with a decline in the proportion of organic carbon being buried in sediments and a rapid phase of oxidation of previously stored ^{13}C-depleted carbon. The pattern of more positive Permian $\delta^{13}C_{org}$ and more negative Triassic $\delta^{13}C_{org}$ is consistent in all sections studied from Australia but appears to be better developed in Permian-Triassic boundary sections that were marine. The following conclusions can be drawn:

1) Similar $\delta^{13}C_{org}$ profiles of marine and nonmarine sections suggests that atmospheric carbon dioxide is common to both environments so that the $\delta^{13}C_{org}$ excursion at the Permian-Triassic boundary occurs in both marine and nonmarine environments simultaneously on a geological timescale (Morante et al., 1994; Morante and Herbert, 1994).

2) $\delta^{13}C$ profiles can be used to correlate the Permian-Triassic boundary in Australia in both nonmarine and marine environments.

3) The base of the *Protohaploxypinus microcorpus* Zone approximates the Permian-Triassic boundary in Australia.

4)The $\delta^{13}C_{org}$ profiles of marine and nonmarine sections from Australia correlate with the $\delta^{13}C_{CO_3}$ profiles from elsewhere in the world.

5) The lithological change about the coal measures/barren strata boundary in Eastern Australia corresponds, within narrow limits of uncertainty, to the Permian-Triassic boundary, which is indicated by the $\delta^{13}C_{org}$ excursion.

APPENDIX 2.1

$\delta^{13}C_{org}$ PROFILES ABOUT THE PERMIAN-TRIASSIC BOUNDARY? FROM NEW ZEALAND AND SOUTH AFRICA

New Zealand: Popotonoa Fm, Southland

Dr J.I. Raine supplied samples from the Popotonoa Formation (Fig. 2.34) collected in a traverse along the Awakia Stream. The age of the Popotonoa Formation is indicated by *Aratrisporites* (J.I. Raine pers. comm., 1992) and that suggests an Early Triassic age for at least part of the sequence. This age is supported by the generally negative and "Triassic-like" $\delta^{13}C_{org}$ values for all samples except the lowermost sample at 137 m which has a more positive "Permian-like" $\delta^{13}C_{org}$ value (Fig. 2.35, Table 2.25).

Accordingly the Popotonoa Formation may contain the Permian-Triassic boundary however the limited sampling cannot clearly define the negative $\delta^{13}C_{org}$ excursion.

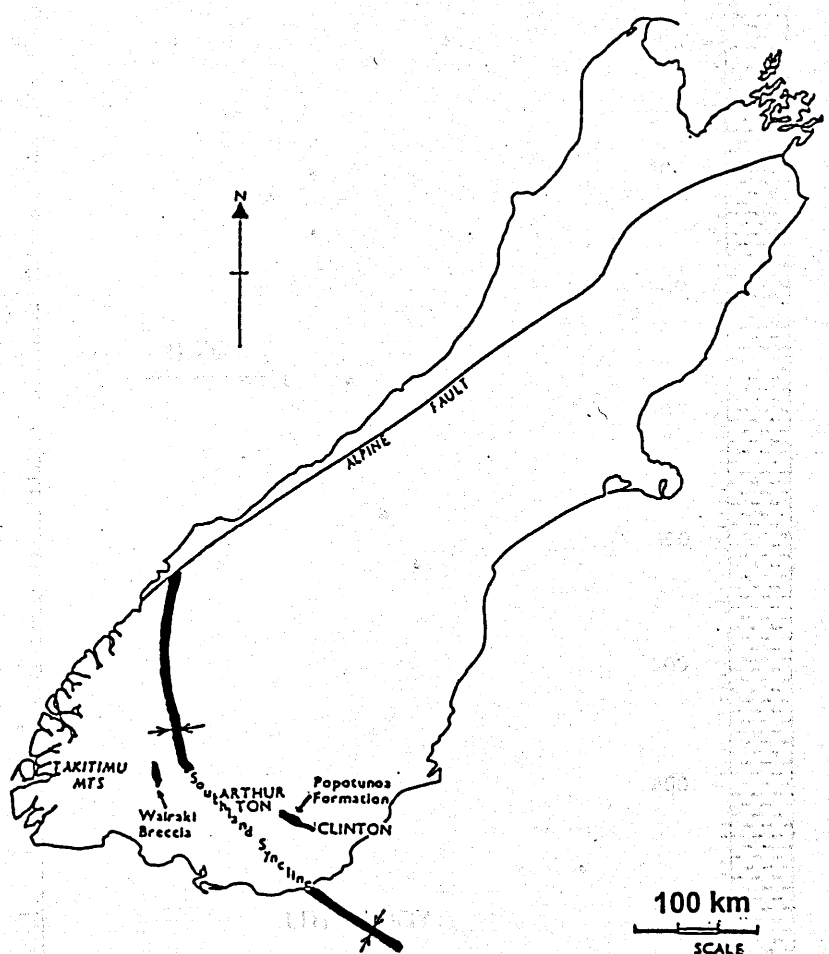

Figure 2.34 Location of the Popotonoa section, Southland (Bishop, 1965).

Table 2.25 Popotonoa Fm $\delta^{13}C_{org}$, TOC %.

Section	Section m	$\delta^{13}C_{org}$‰	TOC%
G46	800	-26.9	0.3
G46	693.3	-28.8	0.2
G46	647.5	-28.8	0.2
G46	526	-28.4	0.7
G46	496	-28.2	0.2
G46	419	-27.8	0.2
G46	381	-27.4	0.3
G46	137	-25.0	0.2

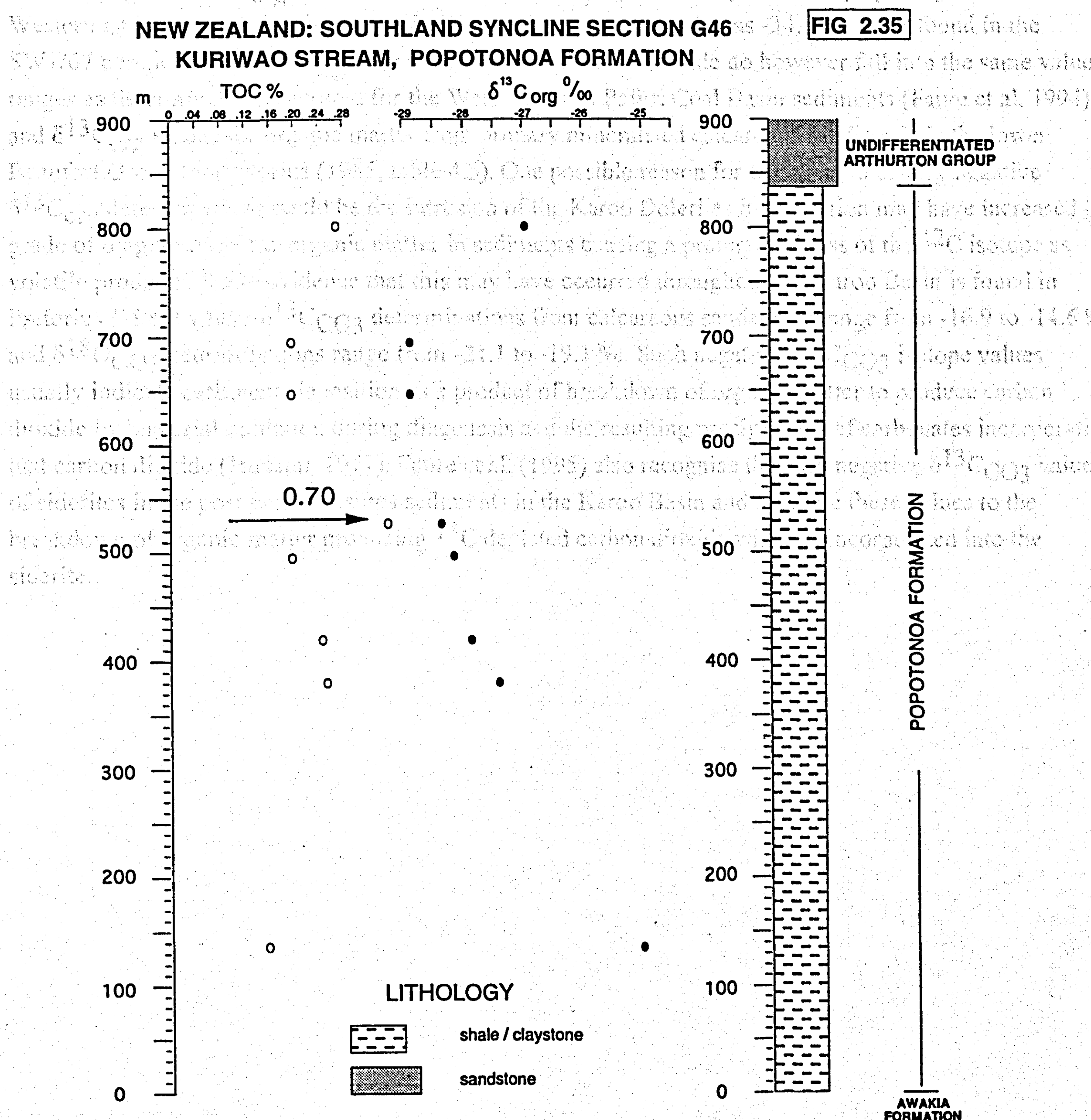

Figure 2.35 Popotonoa Fm: $\delta^{13}C_{org}$, TOC, lithology and stratigraphy (Bishop, 1965).

South Africa, SW1/67, Karoo Basin

Dr D. Cole, Geological Survey of South Africa, identified the SW1/67 corehole as the best section in the Karoo Basin for a $\delta^{13}C_{org}$ stratigraphy study across the Permian-Triassic boundary because it was least affected by the Karoo Dolerite. The SW1/67 corehole, Karoo Basin was drilled in 1967-68 in the easternmost Cape province in the district of Swartberg (latitude 30° 09' 15" S, longitude 29° 16' 00" E). This preliminary study of the $\delta^{13}C_{org}$ profile was unsuccessful in clearly identifying the $\delta^{13}C_{org}$ excursion to more negative values in the Karoo Basin. Attempts to identify the Upper Stage 5/*P. microcorpus* Zone boundary within the SW1/67 corehole have also failed. The $\delta^{13}C_{org}$ values in the section (Fig. 2.36) vary between -22 to -24.9 ‰ however no consistent pattern is apparent and the palynology preparations containing identifiable specimens (Fig. 2.36 Table 2.26.) indicate that the interval of more negative $\delta^{13}C_{org}$ values found in the *P. microcorpus* and *L. pellucidus* palynological zones in Western and Eastern Australia where $\delta^{13}C_{org}$ values are as negative as -34.5 ‰ is not found in the SW1/67 corehole. The $\delta^{13}C_{org}$ determinations that have been made do however fall into the same value ranges as determinations reported for the Waterberg and Pafuri Coal Basin sediments (Faure et al, 1994) and $\delta^{13}C_{org}$ values for organic matter from primary mineralised calcareous sandstones in the lower Beaufort Group by Pretorius (1985, table 4.3). One possible reason for the absence of very negative $\delta^{13}C_{org}$ determinations could be the intrusion of the Karoo Dolerites in the region may have increased the grade of diagenesis of the organic matter in sediments causing a preferential loss of the ^{12}C isotope as volatile products. Some evidence that this may have occurred throughout the Karoo Basin is found in Pretorius (1985) where $\delta^{13}C_{CO3}$ determinations from calcareous sandstones range from -16.9 to -14.6 ‰ and $\delta^{18}O_{CO3}$ determinations range from -21.1 to -19.1 ‰. Such negative $\delta^{13}C_{CO3}$ isotope values usually indicate carbonate deposition as a product of breakdown of organic matter to produce carbon dioxide by bacterial oxidation during diagenesis and the resulting precipitation of carbonates incorporating that carbon dioxide (Hudson, 1977). Faure et al. (1995) also recognise the very negative $\delta^{13}C_{CO3}$ values of siderites in the post coal measures sediments in the Karoo Basin and attribute these values to the breakdown of organic matter producing ^{13}C depleted carbon dioxide which is incorporated into the siderite.

Table 2.26 SW1/67, $\delta^{13}C$, TOC %, and biostratigraphy (Helby pers. comm., 1994).

Well	DEPTH m	$\delta^{13}C_{org}$‰	TOC%	Palynology Zone
SW1/67	42.6	-23.38	< 0.1	
SW1/67	51.31	-23.42	0.1	
SW1/67	64.08	-24.24	< 0.1	
SW1/67	68.9	-24.22	< 0.1	
SW1/67	124.46	-24.02	< 0.1	
SW1/67	150.38	-23.70	0.3	
SW1/67	186.43	-23.27	0.4	
SW1/67	188.21	-23.27	0.3	
SW1/67	214.06	-23.81	< 0.1	
SW1/67	220.36	-24.11	0.3	*L. pellucidus*
SW1/67	224.98	-23.80	0.2	
SW1/67	230.52	-23.28	0.3	
SW1/67	237.86	-23.16	0.1	*L. pellucidus*/younger
SW1/67	240.6	-24.11	0.5	*P. microcorpus*
SW1/67	250.48	-24.89	0.2	Barren
SW1/67	257.85	-23.10	< 0.1	
SW1/67	263.23	-23.06	< 0.1	Barren
SW1/67	289.95	-24.19	< 0.1	
SW1/67	301.43	-23.65	< 0.1	
SW1/67	305.85	-22.83	< 0.1	
SW1/67	310.86	-24.93	0.2	Barren
SW1/67	324.80	-23.51	0.1	
SW1/67	363.20	-23.64	< 0.1	
SW1/67	382.92	-22.71	0.1	
SW1/67	403.56	-22.09	0.1	
SW1/67	420.68	-22.24	0.2	
SW1/67	426.85	-22.90	0.2	

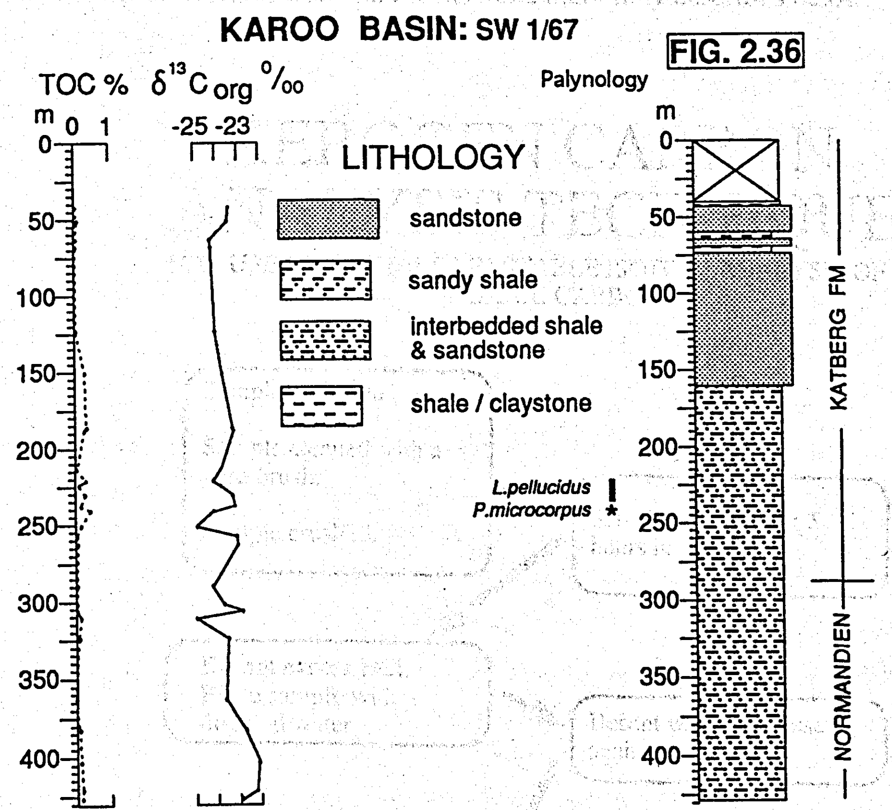

Figure 2.36 SW 1/67, Karoo Basin, South Africa. TOC, $\delta^{13}C_{org}$, palynological zones (R. J. Helby pers. com., 1994), lithological log and formations (D. Cole pers. comm., 1993).

APPENDIX 2.2

Organic carbon analysis technique used on whole rock shales and siltstones.

Preparation of the organic carbon for analysis largely followed the methods of Magaritz et al. (1992). The method used is summarised in Fig 2.37 and more fully described below.

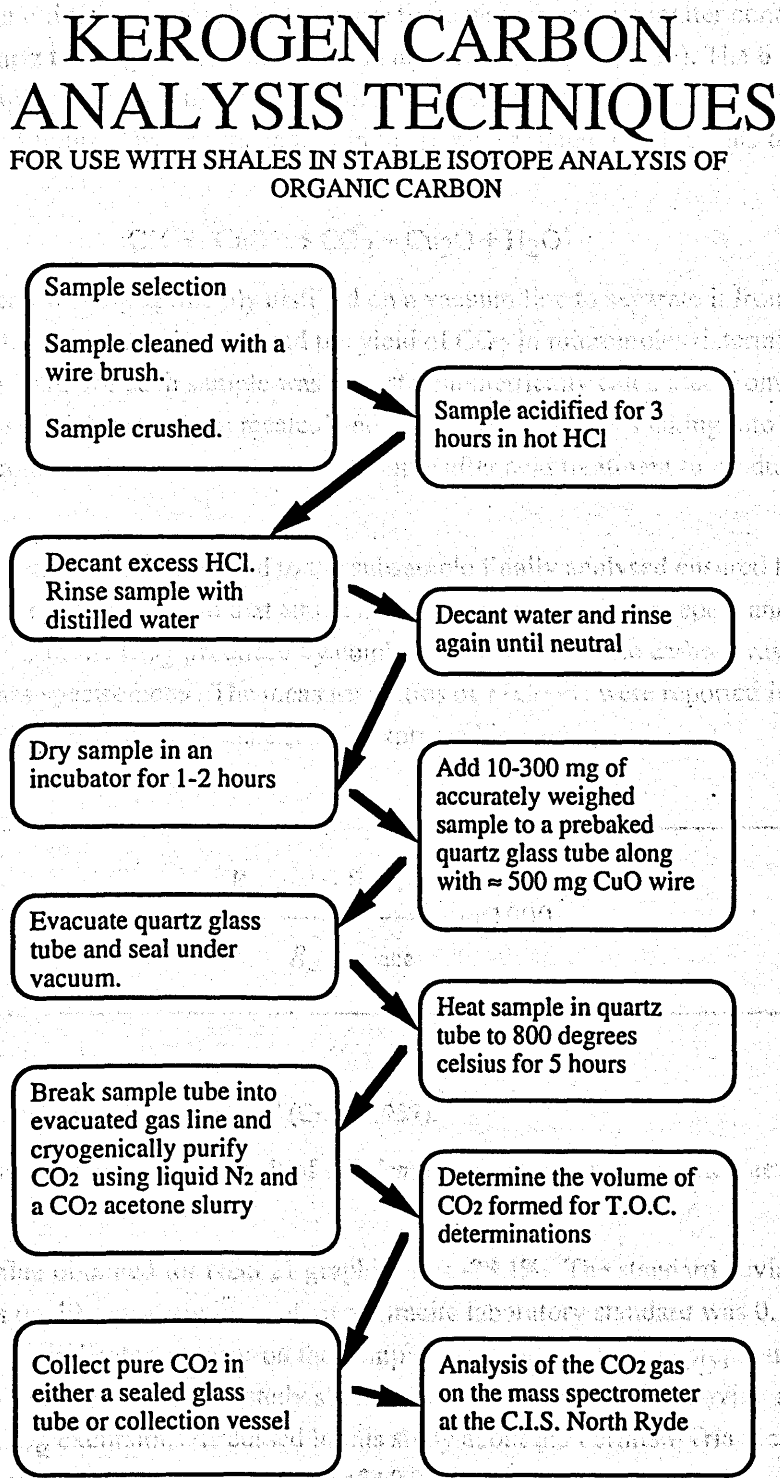

Figure 2.37 Organic carbon processing technique.

Crushed cleaned shale or fine grained siltstone samples of 1-2 grams were weighed before being treated with heated hydrochloric acid at 80° C for 3 hours to react carbonate. Samples were then washed with distilled water 3 to 4 times or until neutral allowing time for samples to settle between decantings. After the final decanting of water the samples were dried in an incubator at 70° C. Samples were then reweighed to calculate the amount of material that had either reacted with the acid (carbonates) or had dissolved into the acid solution. This enabled a correction factor to be applied when calculating the total organic carbon % (TOC) of the samples. Acid-treated sub-samples of 50-100 mg and cupric oxide (prebaked at 800° C in an oxidising atmosphere to ensure there was no organic matter contamination) were placed in 6 mm quartz tubes (prebaked at 800° C in an oxidising atmosphere). The 6 mm quartz tubes containing the sample and cupric oxide (CuO) mix were evacuated and sealed before furnace combustion at 800°C for 5 hours. The organic matter in the sample reacted with the CuO to form CO_2 gas and Cu_2O.

$$CH + CuO \Rightarrow CO_2 + Cu_2O + H_2O$$

The CO_2 produced was cryogenically distilled on a vacuum line to separate it from any other gases produced or liberated in the combustion and the yield of CO_2 in micromoles determined on a calibrated manometer. A TOC for each sample was then stoichometrically calculated from the carbonate free combustion sample size. This was then recalculated on a whole rock basis taking into account the original sample weight compared to the weight of the sample after acid treatment to produce a "whole rock" TOC.

The large initial sample size compared to the subsample finally analysed ensured that any contamination effects were minimised and that ample material was available for repeat analyses. The measured ratio of $^{13}C/^{12}C$ in the CO_2 produced by combustion of the organic carbon was determined on a Finnigan MAT 252 mass spectrometer. The measured ratios of $^{13}C/^{12}C$ were reported in the standard format of $\delta^{13}C$ relative to a standard carbonate (PDB) expressed in parts permil (‰).

$$\delta = \frac{R\ \text{sample} - R\ \text{reference}}{R\ \text{reference}} * 1000$$

in which R is the ratio $^{13}C^{16}O_2/^{12}C^{16}O_2$ for $\delta^{13}C$ (Craig, 1957).

PDB standard is calcium carbonate from a shell of a *Belemnitica americana* from the Pee Dee Formation in South Carolina, U.S.A.

The $\delta^{13}C_{org}$ value obtained for NBS 21 graphite was -28.1‰. The standard deviation of the $\delta^{13}C_{org}$ determinations on 49 repeat analyses of an anthracite laboratory standard was 0.13‰ (Fig. 2.38; Table 2.27). This therefore indicates an error on the complete method used in the preparation of samples for $\delta^{13}C_{org}$. All samples referred to in this study should therefore be accepted as having an error of ±0.26‰ (2 σ). All $\delta^{13}C_{org}$ excursions discussed in this study about the Permian-Triassic boundary are an order of magnitude larger than the determined error of ±0.26‰.

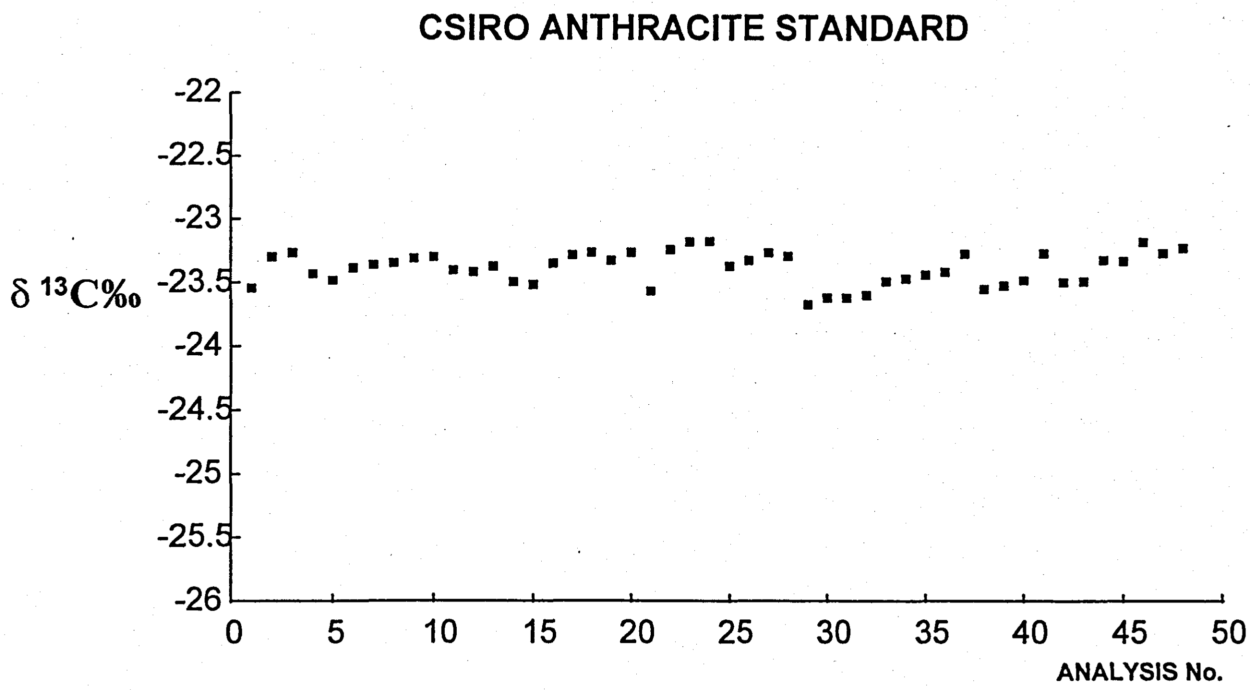

Figure 2. 38 $\delta^{13}C_{org}$ of the standard CSIRO anthracite samples processed with rock samples in this study.

Table 2. 27 CSIRO anthracite standard analyses.

Sample type.	$\delta^{13}C‰$	Sample type.	$\delta^{13}C‰$
CSIRO Anthracite	-23.54	CSIRO Anthracite	-23.37
CSIRO Anthracite	-23.30	CSIRO Anthracite	-23.33
CSIRO Anthracite	-23.26	CSIRO Anthracite	-23.26
CSIRO Anthracite	-23.43	CSIRO Anthracite	-23.29
CSIRO Anthracite	-23.48	CSIRO Anthracite	-23.67
CSIRO Anthracite	-23.38	CSIRO Anthracite	-23.62
CSIRO Anthracite	-23.36	CSIRO Anthracite	-23.62
CSIRO Anthracite	-23.34	CSIRO Anthracite	-23.60
CSIRO Anthracite	-23.31	CSIRO Anthracite	-23.49
CSIRO Anthracite	-23.30	CSIRO Anthracite	-23.47
CSIRO Anthracite	-23.40	CSIRO Anthracite	-23.44
CSIRO Anthracite	-23.42	CSIRO Anthracite	-23.41
CSIRO Anthracite	-23.37	CSIRO Anthracite	-23.27
CSIRO Anthracite	-23.88	CSIRO Anthracite	-23.55
CSIRO Anthracite	-23.50	CSIRO Anthracite	-23.52
CSIRO Anthracite	-23.52	CSIRO Anthracite	-23.48
CSIRO Anthracite	-23.35	CSIRO Anthracite	-23.27
CSIRO Anthracite	-23.28	CSIRO Anthracite	-23.49
CSIRO Anthracite	-23.27	CSIRO Anthracite	-23.49
CSIRO Anthracite	-23.33	CSIRO Anthracite	-23.32
CSIRO Anthracite	-23.27	CSIRO Anthracite	-23.33
CSIRO Anthracite	-23.57	CSIRO Anthracite	-23.18
CSIRO Anthracite	-23.24	CSIRO Anthracite	-23.27
CSIRO Anthracite	-23.18	CSIRO Anthracite	-23.23
CSIRO Anthracite	-23.18		

APPENDIX 2.3

Isotopic analysis of Sm/Nd (samarium/neodymium)

Chemical Preparation.

Shale samples of around 200 mg were roasted at 600ºC for 5 hours in order to oxidise any organic matter that might fractionate Sm from Nd. Following this, roasted samples of around 170 mg were dissolved in 2ml of triple distilled HF in open Krogh-type hydrothermal bombs for 4 hours. Ten drops of concentrated HNO_3 were then added and the mixture allowed to stand overnight before evaporating at 150°C and then baking at 210°C. Samples were cooled then an additional 2ml of HF added. Sealed bombs were heated for five days at 180°C. Samples were decanted into teflon beakers and 0.2 ml of $HClO_4$ added. Samples were evaporated at 150°C then fumed at 210°C and allowed to cool. Samples were placed into the pressure vessels with 3 ml of 6 M HCl and heated at 180°C overnight to transform all components into chlorides. Dissolved samples were diluted to 10 ml and the sample split 4:6 with the smaller sample spiked for isotope dilution determination of the elemental concentrations. The spike solution was accurately weighed and added to the solutions before drying in preparation for column-separation treatment.

Column-separation treatment

Dried samples were dissolved in 2 ml of 2.5 ml HCl, left standing overnight then centrifuged to remove undissolved residues. The solution was carefully decanted using a Pasteur Pippette to ensure no undissolved residue was included in the sample to be run through the ion exchange columns. Samples were loaded on to the cation exchange resin columns (7 ml volume AG50WX8 200-400 mesh resin) then rinsed down with 1 ml of 2.5 M HCl three times. A 12.5 ml aliqout of 2.5 M HCl was used to wash the sample to remove Fe, Mg, and most other unwanted components. The Rb was collected with 7.5 ml of 2.5 M HCl before flushing the columns with 9ml of 2.5M HCl. Sr was then collected with 10 ml of 2.5 M HCl. The Rare Earth Element (REE) fraction was then collected with 18 ml of 6 M HCl then evaporated down at 150°C and dried at 80°C and the columns were then washed using 25 ml of 6 M HCl and conditioned using 30 ml of 2.5 M HCl.

Separation of the Rare Earth fractions to Nd and Sm was accomplished by first taking an aliquot of 0.22M HCl then dissolving the REE in 3 drops of the aliquot. The three drops of sample were then added to the HDEHP coated Bio Beads (Korsch and Gulson, 1986) cation exchange columns and washed with part of the preserved aliquot four times before the remainder of the 9 ml aliquot was added to the columns. The column was eluted with 0.22 M HCl before the Nd was collected with 6 ml of 0.22M HCl which was dried at 120°C. The column was then flushed with 4ml of 0.45M HCl before collecting the Sm with 5 ml of 0.45 M HCl. The sample was then dried at 120°C. The columns were flushed with 20 ml of 6 M HCl and conditioned with 10 ml of 0.22M HCl.

Mass Spectrometry

The samples of Sm or Nd were loaded onto zone refined Re triple filaments (used as double filaments since only one side of the filament was loaded with samples) and the elemental concentrations determined by isotope dilution were measured on a VG 354 Sector thermal ionisation mass spectrometer fitted with 7 collectors. Procedural blanks are negligible and require no correction to the measured isotope ratio.

3 STRONTIUM ISOTOPE SEAWATER CURVE IN THE LATE PERMIAN OF AUSTRALIA

The Permian saw two prominent global geochemical events: the negative $\delta^{13}C$ excursion at the paleontologically determined Permian-Triassic boundary described previously, and a dramatic fall in $^{87}Sr/^{86}Sr$ in seawater carbonates reaching a minimum about the Guadalupian/Ochoan stage boundary, followed by a rapid $^{87}Sr/^{86}Sr$ rise approaching the Permian-Triassic boundary (Fig. 3.1). New data from Australia identify these geochemical events and permit the firm correlation of the Australian biostratigraphical scale to the international geological timescale.

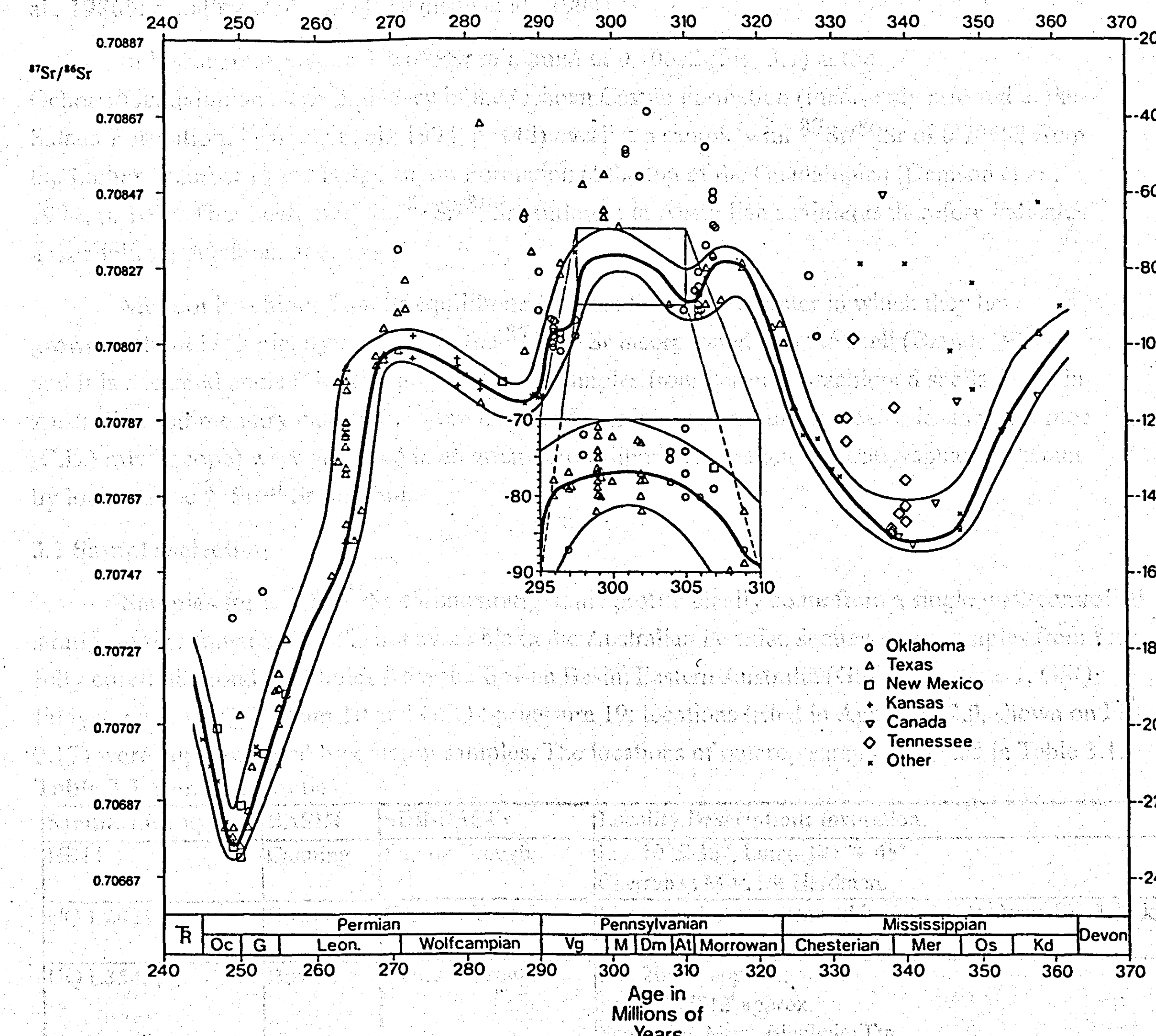

Figure. 3.1 $^{87}Sr/^{86}Sr$ seawater curve for the Mississippian-Triassic after Denison et al. (1994).