"The high tide of the warm Pliocene: Implications of 20-25 m peak global sea level for Antarctic deglaciation"

Kenneth G. Miller, James D. Wright, James V. Browning, Andrew Kulpecz, Michelle Kominz, Tim R. Naish, Yair Rosenthal, Benjamin S. Cramer, W.R. Peltier, Sindia Sosdian

New Zealand Age Control. We tune eustatic Pliocene estimates for sea-level highstands and lowstands from the Rangitikei section sedimentary cycles with the benthic foraminiferal $\delta^{18}O$ record (*26*) by calibrating interglacial minima and glacial maxima in the $\delta^{18}O$ stack with our eustatic estimates. We calibrate the eustatic estimate from New Zealand to present day by assuming similar sea levels during MIC G1 and 99 when $\delta^{18}O$ values were equivalent to modern values and present peak eustatic estimates for all interglacials on the $\delta^{18}O$ stack between 3.2 and 2.7 Ma (Fig. 3).

Oxygen isotopic assumptions. Benthic foraminiferal $\delta^{18}O$ values constrain sea level to ~22±13 m by end-member assumptions of 50:50 and 80:20 ice volume:temperature and mean $\delta^{18}O$ values of ice sheets of -30 to -50‰. We used a 66:37 apportionment (Figs. 1, 2), consistent with Pleistocene glacial-interglacial changes (Fairbanks, 1989), and illustrate the 50:50 and 8:20 end members (Fig. DR1). The Pleistocene ice-volume calibrations of 0.11±0.1‰/10m Ice sheet values bracketed by end member compositions of -30 to -50‰ for large ice sheets (Lhomme et al., 2005), which yields end-member ice-volume/sea-level calibrations of 0.076‰/10 m and 0.126‰/10m, respectively. We used a calibration of 0.1‰/10 m, corresponding to a mean ice composition of -40‰, bracketing $\delta^{18}O$ values of -35‰ for Greenland ice and to -42‰ for West Antarctic ice (Lhomme et al., 2005) and consistent with model predictions for a warmer world (DeConto and Pollard, 2003). Errors for oxygen isotope based sea-level estimates are based on a temperature error of 1.1°C or 0.25‰, a $\delta^{18}O_{benthic}$ error of 0.1-0.2‰, for an total error of 0.26-0.27‰ error in $\delta^{18}O_{seawater}$ or approximately ±13 m in sea level assuming a calibration of 0.1‰/10m sea-level/ $\delta^{18}O_{seawater}$.

Uncertainty analysis:

We calculate the best estimate of peak sea level at each highstand as the mean of individual sea level estimates. To calculate the uncertainty on these best estimates we first calculate the pooled standard deviation as an empirical estimate of the uncertainty associated with individual sea level estimates (see Figure S2). The pooled standard deviation is calculated as:

$$s = \sqrt{\frac{\sum_{i=1}^{m}\left[\sum_{j=1}^{n_i}\left(SL_j - \overline{SL_i}\right)^2\right]}{\sum_{i=1}^{m}\left(n_i - 1\right)}},$$

where SL_j are individual sea level estimates, n_i and $\overline{SL_i}$ are the number and mean of individual sea level estimates at each highstand, and m is the number of highstands. Using this estimate of the standard deviation for each individual sea level estimate, we calculate the standard errors,

$$SE_{\overline{SL_i}} = \frac{s}{\sqrt{n_i}},$$

where $SE_{\overline{SL_i}}$ is the standard error on the mean of individual sea level estimates at each highstand. The standard error is used to define a normal probability distribution which defines the 68%, 90%, and 95% confidence intervals surrounding our best estimates of peak sea level. (Table DR2)

We calculate s=8.6 m, based on the available peak sea level estimates. This is considerably lower than the assumed errors associated with the Mg/Ca-based estimates, similar to the assumed errors for New Zealand and Virginia estimates, and slightly higher than the assumed errors for Enewetak atoll and the scaled $\delta^{18}O$ method (Table DR1). Based on examination of Figure DR2, we suggest that this is an underestimate of the uncertainty for the Sosdian and Rosenthal (2009) Mg/Ca-based record, but it is not obviously inappropriate for the other records and we believe it is a better estimate of the true uncertainty in sea level estimates than the assumed errors associated with each estimate.

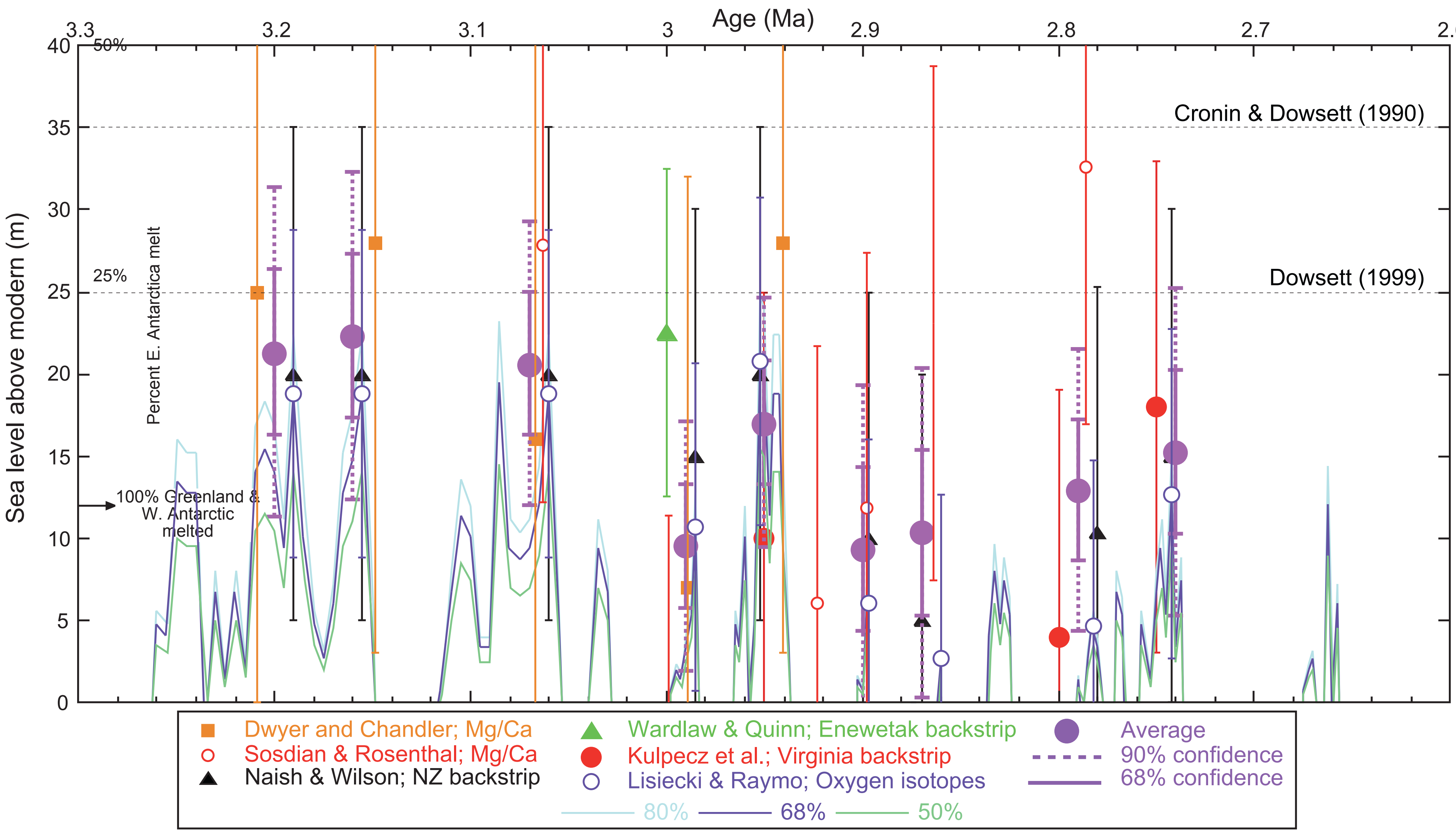
Calculation of confidence intervals from the standard error assumes that the uncertainties are normally distributed. This is a reasonable assumption for the data (Figure DR3), but we could also calculate the confidence intervals using a bootstrap approach and the actual distribution of residuals (Figures DR2 and DR3). We have confirmed that such bootstrap uncertainties are ~25% lower than our result from assuming a normal distribution. Another alternative approach would be to calculate the weighted mean as the best estimate of peak sea level and the weighted standard deviation to obtain the uncertainty estimates, using the assumed errors associated with each method of sea level estimation as weights. This alternative results in uncertainties similar to, but generally lower than, our calculations based on the pooled standard deviation. Our uncertainty estimates are therefore conservative by comparison with these two alternatives.

Figure captions

Fig. DR1. Error in sea level estimates, showing average values for each measurement (Table DR1) and 2 sigma errors (Table DR2). Purple circles are the medians for the various peaks with 1 sigma standard deviation (solid) and 90% confidence interval (dashed). Scale on left shows equivalent loss of ice assuming 7 m stored in Greenland, 5 in West Antarctica, and 54 in East Antarctica. Light blue curve is the $\delta^{18}O$ record scaled to sea level from Fig. 1. Light blue shaded region illustrates the "likely" range for peak sea level. Dashed horizontal line indicates previous estimates for Dowsett and Cronin (1990) and Dowsett et al. (1999).

Fig. DR2. Top: Individual peak sea level estimates from Table DR1 with the mean for each highstand from Table DR2; highstands are highlighted as pink bars. Bottom: The same data with the mean subtracted from individual estimates (residuals) so that the data are centered around 0. The pooled standard deviation is a measure of the dispersion in this centered data. Horizontal lines show 0±1 s.d. (±8.6 m; Table DR2). Data furthest from the mean are all from Sosdian and Rosenthal (2009), suggesting that 8.6 m is an undestimate of the standard deviation in this data. No other dataset is obviously over- or under-dispersed relative to the pooled standard deviation. Note that the large uncertainty in age for the Enewetak estimate would allow it to be included in the 2.95 Ma highstand instead, where it would fall within 1 s.d. of the mean.

Fig. DR3. Histogram of residual sea level values (from the bottom panel in Fig. DR2) compared with a normal probability density function with standard deviation of 8.6 m. A narrower probability distribution might provide a better fit to the histogram, indicating that the confidence intervals based on assuming a normal distribution are likely conservative. We have confirmed this using bootstrap statistics calculated with the actual distribution of sea level residuals.



Miller et al. Fig. DR1

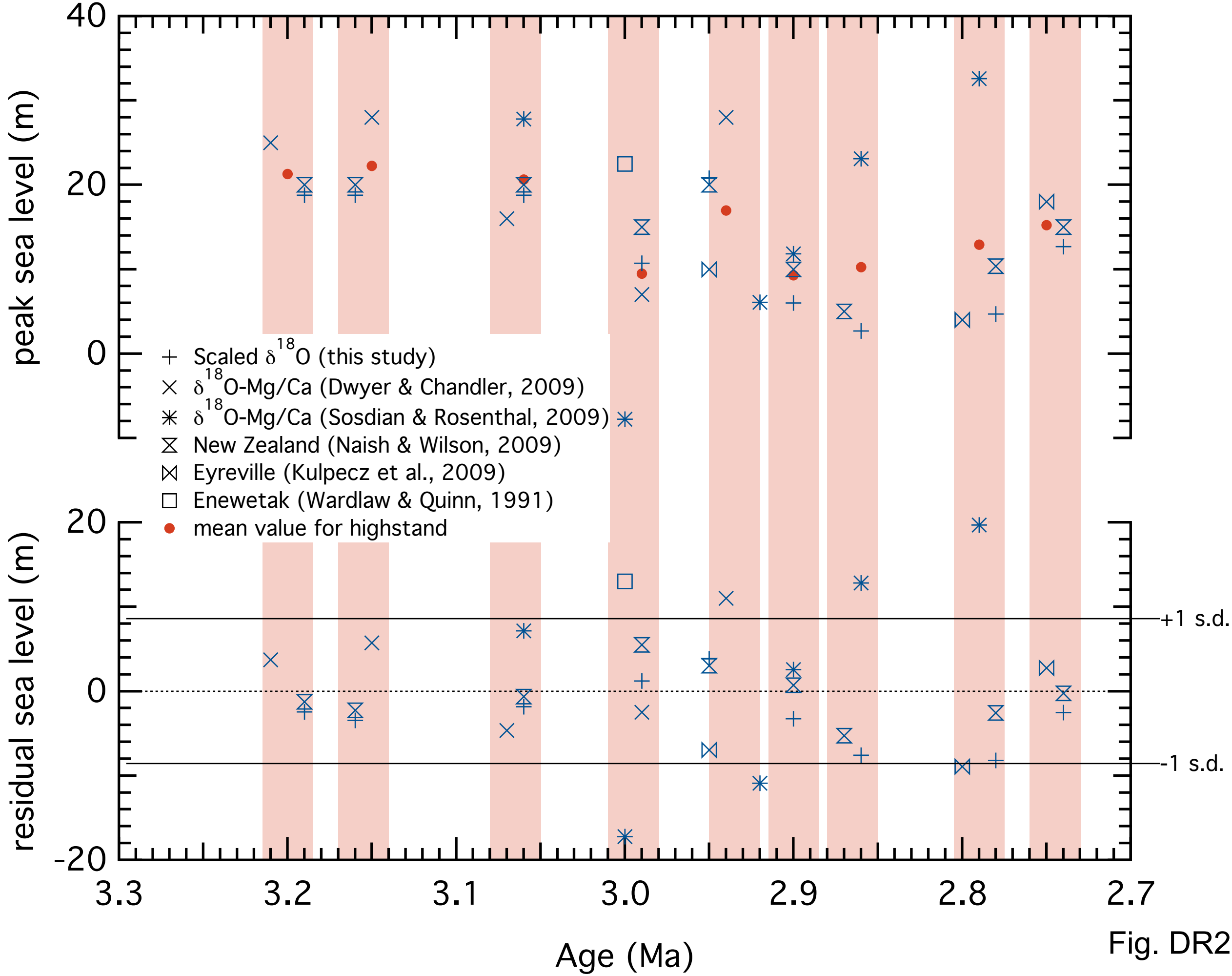
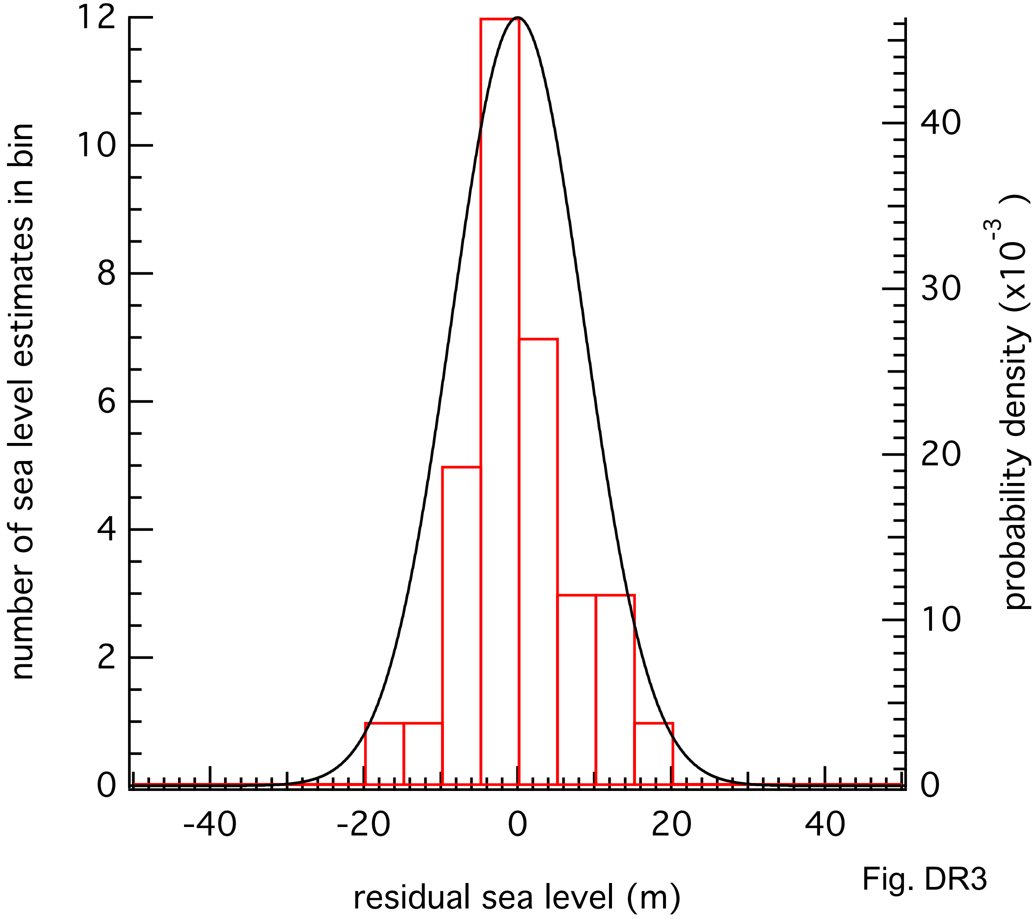

40
20
0
-20
peak sea level (m)
residual sea level (m)
Scaled δ18O (this study)
δ18O-Mg/Ca (Dwyer & Chandler, 2009)
δ18O-Mg/Ca (Sosdian & Rosenthal, 2009)
New Zealand (Naish & Wilson, 2009)
Eyreville (Kulpecz et al., 2009)
Enewetak (Wardlaw & Quinn, 1991)
mean value for highstand
+1 s.d.
-1 s.d.
3.3
3.2
3.1
3.0
2.9
2.8
2.7
Age (Ma)

Fig. DR2



12
10
8
6
4
2
0
number of sea level estimates in bin
40
30
20
10
0
probability density (x10^{-3})
-40
-20
0
20
40
residual sea level (m)

Fig. DR3

Sea level highstand	Age (Ma)	Sea Level high (m)	Uncertainty*
3.20 Ma			
$\delta^{18}O$-Mg/Ca (Dwyer & Chandler, 2009)	3.21	25	25
New Zealand (Naish & Wilson, 2009)	3.19	20	15
Scaled $\delta^{18}O$ (this study)	3.19	18.8	10
Average	3.20	21.27	
3.16 Ma			
$\delta^{18}O$-Mg/Ca (Dwyer & Chandler, 2009)	3.15	28	25
New Zealand (Naish & Wilson, 2009)	3.16	20	15
Scaled $\delta^{18}O$ (this study)	3.16	18.8	10
Average	3.15	22.27	
3.07 Ma			
$\delta^{18}O$-Mg/Ca (Dwyer & Chandler, 2009)	3.07	16	25
$\delta^{18}O$-Mg/Ca (Sosdian & Rosenthal, 2009)	3.06	27.8	15.6 †
New Zealand (Naish & Wilson, 2009)	3.06	20	15
Scaled $\delta^{18}O$ (this study)	3.06	18.8	10
Average	3.06	20.65	
2.99 Ma			
$\delta^{18}O$-Mg/Ca (Dwyer & Chandler, 2009)	2.99	7	25
New Zealand (Naish & Wilson, 2009)	2.99	15	15
$\delta^{18}O$-Mg/Ca (Sosdian & Rosenthal, 2009)	3.00	-7.8	19.1 †
Scaled $\delta^{18}O$ (this study)	2.99	10.7	10
Enewetak (Wardlaw & Quinn, 1991)	3.00	22.5	10
Average	2.99	9.48	
2.95 Ma			
$\delta^{18}O$-Mg/Ca (Dwyer & Chandler, 2009)	2.94	28	25
$\delta^{18}O$-Mg/Ca (Sosdian & Rosenthal, 2009)	2.92	6.1	15.6 †
New Zealand (Naish & Wilson, 2009)	2.95	20	15
Scaled $\delta^{18}O$ (this study)	2.95	20.8	10
Eyreville (Kulpecz et al., 2009)	2.95	10	15
Average	2.94	16.98	
2.90 Ma			
$\delta^{18}O$-Mg/Ca (Sosdian & Rosenthal, 2009)	2.90	11.8	15.6 †
New Zealand (Naish & Wilson, 2009)	2.90	10	15
Scaled $\delta^{18}O$ (this study)	2.90	6	10
Average	2.90	9.27	
2.87 Ma			
$\delta^{18}O$-Mg/Ca (Sosdian & Rosenthal, 2009)	2.86	23.1	15.6 †
New Zealand (Naish & Wilson, 2009)	2.87	5	15
Scaled $\delta^{18}O$ (this study)	2.86	2.7	10
Average	2.86	10.27	

2.79 Ma			
$\delta^{18}O$-Mg/Ca (Sosdian & Rosenthal, 2009)	2.79	32.6	15.6 †
New Zealand (Naish & Wilson, 2009)	2.78	10.36	15
Scaled $\delta^{18}O$ (this study)	2.78	4.7	10
Eyreville (Kulpecz et al., 2009)	2.80	4	15
Average	2.79	12.92	
2.74 Ma			
New Zealand (Naish & Wilson, 2009)	2.74	15	15
Scaled $\delta^{18}O$ (this study)	2.74	12.7	10
Eyreville (Kulpecz et al., 2009)	2.75	18	15
Average	2.75	15.23	

*Stated uncertainty for $\delta^{18}O$-Mg/Ca methods are estimates of 1 s.d. error. For all other methods, stated uncertainty is based on assessment of the "extremely likely" range, and can be thought of as the 95% confidence interval.

†The single point error in Sosdian and Rosenthal (2009) sea level is estimated as 27 m (1 s.d.), but the sea level highs listed here are averages so the uncertainty is reduced by a factor of $1/\sqrt{N}$): 15.6 m for 3 point averages and 19.1 m for 2 point averages.

Table DR1. Sea level peaks

SL highstand	N	Mean Sea Level	standard deviation of highstand estimates	Pooled standard deviation	Standard error on mean	68% confidence interval	90% confidence interval	95% confidence interval
3.20 Ma	3	21.3	3.3	8.6	5.0	21.3 ± 5.0	21.3 ± 8.2	21.3 ± 9.8
3.16 Ma	3	22.3	5.0	8.6	5.0	22.3 ± 5.0	22.3 ± 8.2	22.3 ± 9.8
3.07 Ma	4	20.6	5.1	8.6	4.3	20.6 ± 4.3	20.6 ± 7.1	20.6 ± 8.4
2.99 Ma	5	9.5	11.2	8.6	3.8	9.5 ± 3.8	9.5 ± 6.3	9.5 ± 7.4
2.95 Ma	5	17.0	8.8	8.6	3.8	17.0 ± 3.8	17.0 ± 6.3	17.0 ± 7.4
2.90 Ma	3	9.3	3.0	8.6	5.0	9.3 ± 5.0	9.3 ± 8.2	9.3 ± 9.8
2.87 Ma	3	10.3	11.2	8.6	5.0	10.3 ± 5.0	10.3 ± 8.2	10.3 ± 9.8
2.79 Ma	4	12.9	13.4	8.6	4.3	12.9 ± 4.3	12.9 ± 7.1	12.9 ± 8.4
2.74 Ma	3	15.2	2.7	8.6	5.0	15.2 ± 5.0	15.2 ± 8.2	15.2 ± 9.8

Table DR2. Error analysis