Coral Record of Equatorial Sea-Surface Temperatures During the Penultimate Deglaciation at Huon Peninsula

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Uplifted coral terraces at Huon Peninsula, Papua New Guinea, preserve a record of sea level, sea-surface temperature, and salinity from the penultimate deglaciation. Remnants have been found of a shallow-water reef that formed during a pause, similar to the Younger Dryas, in the penultimate deglaciation at 130,000 ± 2000 years ago, when sea level was 60 to 80 meters lower than it is today. *Porites* coral, which grew during this period, has oxygen isotopic values and strontium/calcium ratios that indicate that sea-surface temperatures were much cooler (22° ± 2°C) than either Last Interglacial or present-day tropical temperatures (29° ± 1°C). These observations provide further evidence for a major cooling of the equatorial western Pacific followed by an extremely rapid rise in sea level during the latter stages of Termination II.

The equatorial western Pacific Ocean is the major source of heat and water vapor to the atmosphere and plays a key role in modulating the global response to climate change (*1*). Despite the importance of this region, the response of the tropical oceans during glacial to interglacial transitions remains uncertain. During the Last Glacial Maximum (LGM), Sr/Ca ratios in corals from Barbados (*2*), and the Indian (*3*) and western Pacific oceans (*4*), imply that tropical oceans were up to ~6°C cooler than at present. Terrestrial records of temperature inferred from snow lines (*5*) and ice cores from tropical mountains (*6*) are also generally consistent with such cooling. In contrast, oxygen isotope studies of planktonic foraminifera (*7*) as well as alkenones (*8*) show a change in glacial SSTs of a few degrees at most. In order to better understand the discrepancy between these records, we examine ocean temperature changes during the transition from the penultimate glaciation to the Last Interglacial, known as Termination II (marine isotope stages 6/5e). Sea-surface temperatures (SSTs) are reported from combined Sr/Ca ratios and $\delta^{18}O$ values in corals collected from the uplifted terraces of Huon Peninsula that grew during Termination II and are compared with those from modern and Last Interglacial corals.

The uplifted Pleistocene coral terraces of the Huon Peninsula (*9*) are situated along the northeastern coast of Papua New Guinea. As a result of the combined effects of rapid uplift together with oscillations in sea level, younger coral terraces generally occur at successively lower heights, draped over older terraces. The Last Interglacial coral terrace [Reef VII, 135 to 118 thousand years ago (ka)], is a prominent feature that formed when sea level was at or slightly above present-day heights. It is now at an altitude of ~200 m above Sialum (*9*), corresponding to an uplift rate of ~1.6 m per 1000 years. In a serendipitous discovery, corals that grew during the Termination II have been found in the floor of a cave that is located ~90 m below the main crest of the Last Interglacial Reef VII, close to the contact between the younger Reefs VIb and V (Fig. 1). Here, a well-preserved massive *Porites* coral and a number of smaller coral heads (*Favites*, *Goniastrea*) are present, some of which are still in their original growth positions. The matrix includes broken branches of *Acropora* and facies (*10*) consistent with shallow water (<20 m). The results of U-series dating of these corals using both mass spectrometric and alpha-counting methods (*10*) indicate that the corals grew around 130 ± 2 ka, during either a temporary fall or a pause in the rise of sea level. This locality, named "Aladdin's Cave" is thus interpreted as providing a window through Reef VIb into a lower, in situ section of the Last Interglacial Reef VII, at a time when sea level was significantly lower than at present. Allowing for uncertainties of up to 20 m in the depth range that corals can grow, the chronological (*10*) and stratigraphic constraints indicate that between 132 to 128 ka, sea level was from ~60 m and possibly as much as 80 m lower than present-day heights.

Oxygen isotopic compositions (*11*) and Sr/Ca ratios (*12*) of the aragonitic skeleton of *Porites* corals provide a proxy for SSTs. Over glacial-interglacial cycles, the main uncertainty in the application of these seawater paleothermometers is the variation of $\delta^{18}O$ in the oceans due to changing ice volumes, local precipitation or runoff events, the long-term uniformity of Sr/Ca ratios of seawater (*13*), and the effects of coral diagenesis. To evaluate the veracity of both the Sr/Ca and $\delta^{18}O$ methods, we compared *Porites* corals collected from Aladdin's Cave with those from the

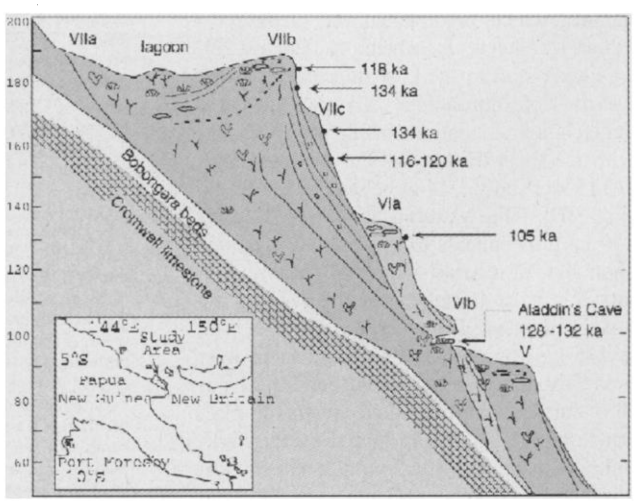

Fig. 1. Stratigraphic section of the raised coral terraces of the Huon Peninsula (*9*). Because of tectonic uplift, the Last Interglacial Reef VII now occurs at the top of the section. Age constraints are from U-Th dating of corals (*10*). The Aladdin's Cave location occurs near the contact of Reef VIb and Reef V and provides a window into a lower section of Reef VII, during the penultimate deglaciation, at 130 ± 2 ka. The difference in height between the crest of Reef VII and Aladdin's Cave of implies an increase in sea level of 60 to 80 m over a period of <2000 years, at ~129 ka. The dashed line shows a disconformity exposed near Sialum. Inset shows the location of the Huon Peninsula in Papua New Guinea.

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Last Interglacial Reef VIIa, as well as modern *Porites* collected from the Sialum lagoon and the Walingai fringing reefs ~30 km southeast of Sialum. The modern corals have Sr/Ca ratios ranging from 0.0088 to 0.0090 (Fig. 2), the same as the Last Interglacial coral collected from the back of Reef VIIa (Fig. 1), corresponding to a temperature range of 27° to 30°C (Fig. 3) (*13*). The close correspondence between the Last Interglacial and modern corals indicates that at the earlier time, conditions were generally similar to the present and that the Sr/Ca ratio of seawater was unchanged during the Last Interglacial period. Oxygen isotopic compositions show a similar pattern, except that the modern Walingai coral has a larger range of more negative $\delta^{18}O$ values, consistent with lower salinity due to freshwater inputs with low $\delta^{18}O$ (<–7 per mil) from a nearby stream.

The Aladdin's Cave coral has markedly higher $\delta^{18}O$ (–3.2 per mil) values and Sr/Ca (0.00935) ratios, corresponding to SSTs of 22° ± 2°C (*13*). This is ~6° ± 2°C cooler than either the modern or Last Interglacial corals and, for example, is similar to the minimum winter temperatures found in corals (*14*) from the central Great Barrier Reef of Australia at ~18°S latitude (Fig. 4). Although only a 10-year snapshot of SST is represented here, the seasonal range of ~±0.6°C for the Aladdin's Cave coral is the same as that obtained for both the Last Interglacial Reef VIIa (±0.5°C) and modern corals from Sialum (±0.5°C), indicating a similar seasonality. River runoff results in more negative $\delta^{18}O$ values, which is in the opposite sense to the more positive $\delta^{18}O$ composition observed in the Aladdin's Cave coral (Fig. 4). The difference in $\delta^{18}O$ between the Aladdin's Cave ($\delta^{18}O$ = –3.2 ± 0.4 per mil) and Last Interglacial coral ($\delta^{18}O$ = –4.8 ± 0.4 per mil) is ~1.6 per mil. A ~6°C change in SST accounts for a shift in the oxygen isotopic composition of ≥1.08 per mil [for a change in $\delta^{18}O$ of ≥–0.18 per mil/°C (*11*)], leaving a residual $\delta^{18}O$ of ≤0.5 ± 0.2 per mil due to ice volume effects. For comparison, the shift in $\delta^{18}O$ attributed to ice volume during the LGM, when average sea level was ~125 m lower, is 1.2 to 1.3 per mil (*15*) to 0.8 to 1.0 per mil (*16*). The Aladdin's Cave estimate for sea level at 60 to 80 m is consistent with the lower estimate of Schrag *et al.* (*16*). In summary, this set of self-consistent results provides evidence for SSTs in the equatorial western Pacific that were ~6° ± 2°C cooler during the penultimate deglaciation, when sea levels were ~70 ± 10 m lower than today.

The question of whether the tropics underwent significant cooling during the LGM is now extended back to the penultimate glaciation. The problem arises in large part from the limited amplitude in $\delta^{18}O$ as well as similarities in assemblage distributions of tropical foraminifera between glacial-interglacial periods (*7*). In contrast to our data, the oxygen isotopic composition of planktonic foraminifera for marine isotopes stages 6/5e from the high-resolution Sulu Sea core 769 (*17*) implies a more gradual cooling of the tropical oceans (Fig. 5). Furthermore, the difference in $\delta^{18}O$ for stages 6/5e in core 769 is 1.6 per mil (*17*)—too small to include both the ice volume effect (*15, 16*) and a temperature difference of ~6°C. One major difficulty in interpreting foraminifera oxygen isotope shifts is that in addition to ice volume and SST, $\delta^{18}O$ is also sensitive to ocean salinity (*18*). In the tropical oceans, there are commonly large variations in sea-surface salinity (*19*), which (as shown in Fig. 3) can seriously perturb the $\delta^{18}O$ values. In corals, these ef-

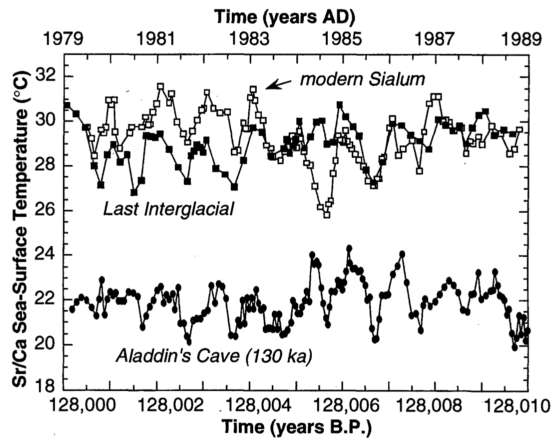

Fig. 3. Plot of SSTs calculated from Sr/Ca ratios using the calibration of 1000(Sr/Ca) = 10.7 – 0.062*T* derived using in situ measured SSTs. The lower time axis applies to the Aladdin's Cave coral and illustrates the approximately fortnightly resolution in SST over a 10-year period at 130 ± 2 ka, with temperatures of ~22° ± 2°C compared to 28° to 30°C for the modern and Last Interglacial corals. The chronology for the modern corals (open symbols) is given by the upper time axis. The cool temperatures of the Aladdin's Cave coral provide compelling evidence for substantial cooling of the equatorial western Pacific during the penultimate deglaciation.

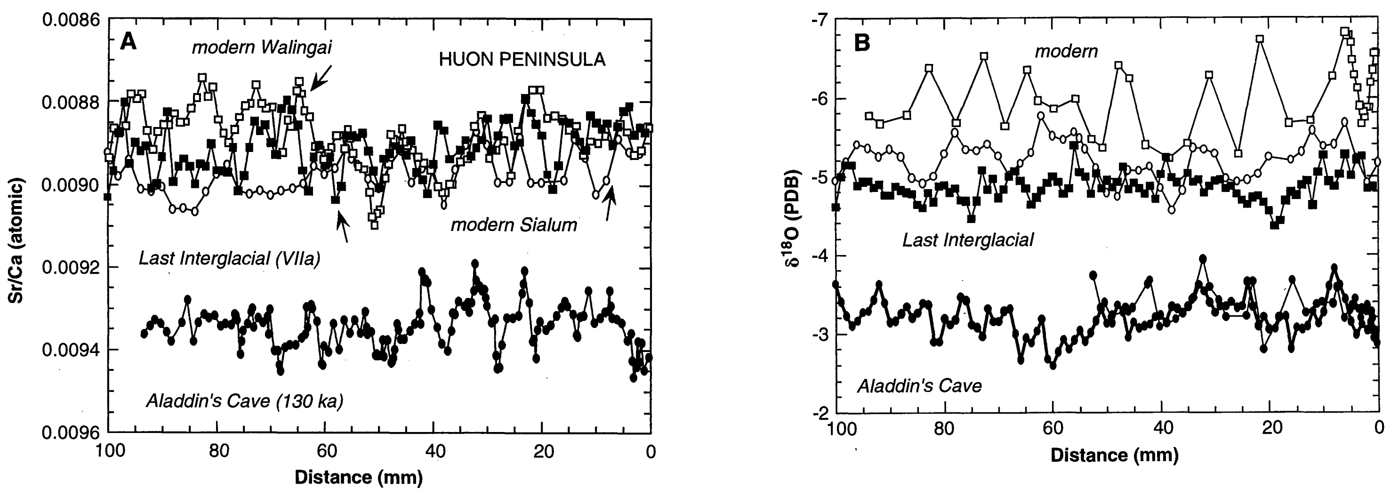

Fig. 2. Plots of (**A**) Sr/Ca ratios and (**B**) $\delta^{18}O$ values for modern (open symbols), Last Interglacial (solid squares), and penultimate deglaciation (solid circles) *Porites* corals from the Huon Peninsula. Coral sections were sampled along major growth axes at intervals of 0.25 and 1 mm over a distance of 8 to 10 cm. Ratios of Sr/Ca were determined by high-precision isotope dilution methods (*12*), and the oxygen isotopic compositions were measured at both the Australian National University and Edinburgh University laboratories (*11*) using automated phosphoric acid baths. The modern and Last Interglacial corals have essentially identical Sr/Ca ratios, indicating the same range of SSTs (28° to 30°C). The more negative $\delta^{18}O$ values for the modern Walingai coral (open squares) is due to river runoff. The Aladdin's Cave coral has both higher Sr/Ca ratios and $\delta^{18}O$ values consistent with substantially cooler (6°C) ocean temperatures.

fects can be decoupled using combined Sr/Ca and $\delta^{18}O$ systematics (*14*), but in foraminifera, it has not yet been possible to apply the Sr/Ca paleothermometer.

Our data provide evidence that the penultimate glaciation was severe and is consistent with other studies (*2, 4*) that show that during the LGM equatorial oceans cooled by at least ~6° ± 2°C. Such dramatic changes should have influenced ocean-atmosphere convection on a global scale. Simulations using an atmospheric general circulation model (*20*), with insolation and CO_2 levels appropriate for the LGM, and maintenance of near-modern ocean heat transport, have shown a 5° to 6°C cooling in tropical SSTs. This suggests (*20*) a much greater climate sensitivity (>1°C W^{-1} m^{-2}) than previous (0.5°C W^{-1} m^{-2}) estimates indicate (*21*). The extremely rapid rise in sea level at ~129 ka indicated by the coral data may thus be a consequence of an Earth with climate sensitivity larger than previously thought (*21*), in response to greater insolation of the Northern Hemisphere (*22*) during the Last Interglacial (~485 W m^{-2}) compared to the Holocene maximum (~470 W m^{-2}). A related question is the influence of such dramatic temperature differences on the ocean-atmosphere interactions responsible for the interannual El Niño–Southern Oscillation (ENSO). Recent modeling (*23*) has shown that intensified trade winds and the resulting increased equatorial upwelling together with equatorward flow of cold water will produce a relatively large decrease in SST of up to 6°C in the western tropical Pacific. The sensitivity of the tropical western Pacific during periods of global cooling now seems to be well established, and although a symmetric response to global warming may be unlikely (*20*), this region will continue to play a key role in Earth's climate system.

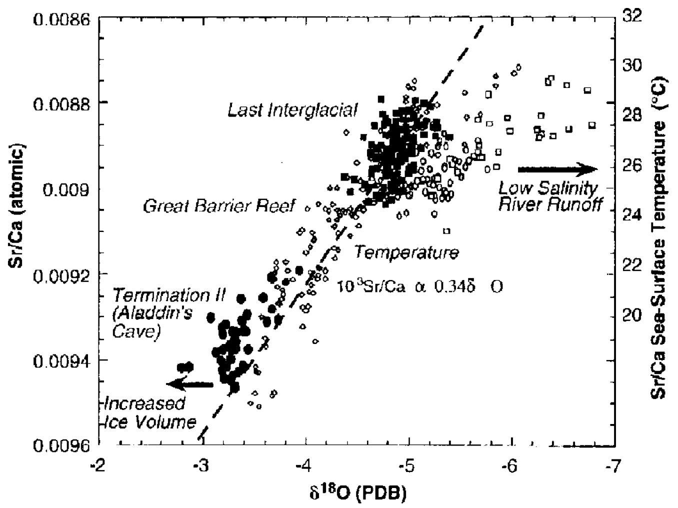

Fig. 4. Combined Sr/Ca and $\delta^{18}O$ systematics for Huon Peninsula corals. The modern coral (*14*) from the central Great Barrier Reef in Australia has a seasonal temperature range from ~22° to 28°C and shows the temperature relationship between the oxygen and Sr/Ca systems of 10^3Sr/Ca α $0.34\delta^{18}O$, which is consistent with $\delta^{18}O$ α $-0.18T$ (*11*) and 10^3Sr/Ca α $-0.062T$ (*13*). Using this relationship, $\delta^{18}O$ shifts due to either low-salinity river runoff (more negative $\delta^{18}O$) or increased ice volumes can be readily distinguished. The Aladdin's Cave coral exhibits both lower temperatures (6°C cooler) together with an ~0.5 per mil positive shift in $\delta^{18}O$, the latter being consistent with the ice volume effect for sea level at ~80 m below present-day heights.

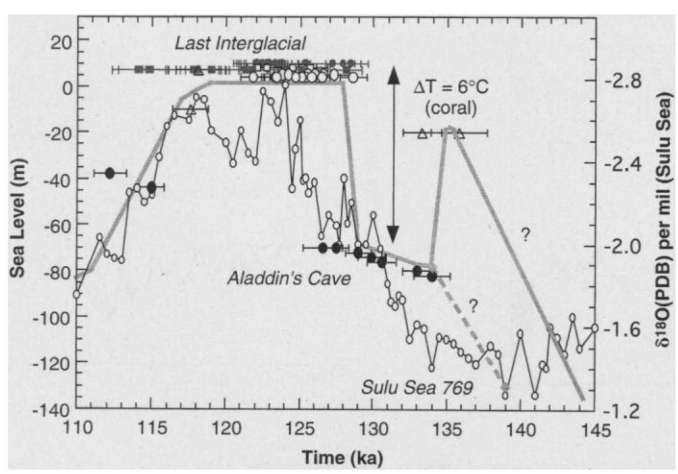

Fig. 5. Sea-level heights derived from U-series dating of corals together with planktonic foraminifera $\delta^{18}O$ variations for the Sulu Sea site 769 (*17*) for the period prior to and including the Last Interglacial. The SPECMAP chronology for the Sula Sea core 769 (*17*) is in good agreement with the independent coral chronology. The Huon Peninsula Aladdin's Cave datum at −80 m is shown as solid circles. The oscillation in sea level together with the cooler (−6°C) SSTs in the period from 132 to 128 ka indicates that the Aladdin's Cave corals grew during a cooling episode similar to the Younger Dryas. The U-series ages of corals from Aladdin's Cave (*10*) together with those from other stable Last Interglacial sites (*24*) require a rapid (~80 m) increase in sea level at ~129 ± 1 ka immediately before the onset of the Last Interglacial. The dashed line shows an alternate sea level curve for 135 ka and older if the 135-ka ages (*10*) from the Huon Peninsula are ignored.

References and Notes

1. S. G. H. Philander, *El Niño, La Niña, and the Southern Oscillation* (Academic Press, San Diego, CA, 1990).
2. T. P. Guilderson, R. G. Fairbanks, J. L. Rubenstone, *Science* **263**, 663 (1994).
3. M. Colonna *et al.*, *Quat. Res.* **46**, 335 (1996).
4. J. W. Beck *et al.*, *Nature* **385**, 705 (1997); M. T. McCulloch *et al.*, *Earth Planet. Sci. Lett.* **138**, 169 (1996).
5. P. Webster and N. Streten, *Quat. Res.* **10**, 279 (1978); D. Rind and D. Peteet, *ibid.* **24**, 1 (1985).
6. L. G. Thompson *et al.*, *Science* **269**, 46 (1995).
7. W. Broecker *et al.*, *Quat. Res.* **26**, 121-25-64 (1986); R. Thunell *et al.*, *ibid.* **41**, 255 (1994).
8. F. G. Prahl *et al.*, *Paleoceanography* **4**, 495 (1989); N. Ohkouchi *et al.*, *Geophys. Res. Lett.* **21**, 2207 (1994).
9. J. Chappell, *Geol. Soc. Am. Bull.* **85**, 553 (1974).
10. T. M. Esat, M. T. McCulloch, J. Chappell, B. Pillans, A. Omura, *Science* **283**, 197 (1999); M. Stein *et al.*, *Geochim. Cosmochim. Acta* **57**, 2541 (1993).
11. T. McConnaughey *et al.*, *Geochim. Cosmochim. Acta* **53**, 151 (1989); A. W. Tudhope *et al.*, *Earth Planet. Sci. Lett.* **136**, 575 (1995); M. K. Gagan *et al.*, *ibid.* **121**, 549 (1994); J. E. Cole, R. G. Fairbanks, G. T. Shen, *Science* **260**, 1790 (1993).
12. J. W. Beck *et al.*, *Science* **257**, 644 (1992); S. De Villiers *et al.*, *Geochim. Cosmochim. Acta* **58**, 197 (1994); C. Alibert and M. T. McCulloch, *Paleoceanography* **12**, 345 (1997).
13. In this study, the temperaure relationship of 1000(Sr/Ca) = 10.7 − 0.062*T* was applied. The gradient of 0.062 is consistent with that of Beck *et al.* (*4*) and Alibert and McCulloch (*12*). The intercept value of 10.7 is derived from the modern coral calibration using in situ measured and satellite SSTs and is similar to recent calibration [M. K. Gagan *et al.*, *Science* **279**, 1014 (1998)]. An uncertainty of ±2°C in the Sr/Ca temperature estimates includes uncertainties due to calibration, water depth, and possibly small changes in the Sr/Ca ratio of glacial seawater [H. M. Stoll and D. P. Schrag, *Geochim. Cosmochim. Acta* **62**, 1107 (1998)].
14. M. T. McCulloch *et al.*, *Geochim. Cosmochim. Acta* **58**, 2747 (1994).
15. R. G. Fairbanks, *Nature* **342**, 637 (1989).
16. D. P. Schrag, G. Hampt, D. W. Murray, *Science* **272**, 1930 (1997).
17. B. K. Linsley, *Nature* **380**, 234 (1996).
18. W. S. Broecker, *Paleoceanography* **4**, 207 (1989); F. L. Norton *et al.*, *ibid.* **12**, 15 (1997).
19. S. Levitus *et al.*, *World Ocean Atlas: Nutrients.* NOAA Atlas NESDIS 3 (U.S. Department of Commerce, Washington, DC, 1994).
20. R. S. Webb *et al.*, *Nature* **385**, 695 (1997).
21. J. Hansen *et al.*, *Explor. Res.* **9**, 142 (1993).
22. A. L. Berger, *Quat. Res.* **9**, 139 (1978).
23. A. B. G. Bush and S. G. H. Philander, *Science* **279**, 1341 (1998).
24. L. R. Edwards, J. H. Chen, G. J. Wasserburg, *Earth Planet. Sci. Lett.* **81**, 175 (1986); R. L. Edwards, J. H. Chen, T.-L. Ku, G. J. Wasserburg, *Science* **236**, 1547 (1987); C. Stirling *et al.*, *Earth Planet. Sci. Lett.* **135**, 115 (1995); C. D. Gallup, R. L. Edwards, R. G. Johnson, *Science* **263**, 796 (1994); B. J. Szabo, K. R. Ludwig, D. R. Muhs, K. R. Simmons, *ibid.* **266**, 93 (1994); J. H. Chen *et al.*, *Geol. Soc. Am. Bull.* **103**, 82 (1991); Z. R. Zhu *et al.*, *Earth Planet. Sci. Lett.* **118**, 281 (1993); B. Hamelin *et al.*, *ibid.* **106**, 169 (1991); E. Bard *et al.*, *Nature* **346**, 456 (1990).

25. We are grateful to anonymous reviewers for helpful comments. The logistical support kindly provided by G. Busch is gratefully appreciated.

11 August 1998; accepted 24 November 1998