

the short-term variations. Further, the He/CO₂ ratios drop dramatically in the 1971 Fissure fumarole prior to or during the summit deflation for all three of the events. We propose the following explanation for this behavior. Under conditions of moderate inflation of the Kilauea summit magma reservoir, the overburden above the chamber is relatively impermeable to most magmatic volatiles. The resistance of the rocks to the release of these gases impedes the flow of CO₂, SO₂, and other large molecular gases more effectively than the flow of He because of the high mobility of He in silicate glasses. This results in a much higher relative ratio of He to CO₂ in the fumarole gases than is actually present in the magma. As the inflating summit reservoir approaches the point of "failure" (that is, the migration of magma), the overburden rock is dilated and incipient fracture systems open, thus releasing considerably more of the volatiles in the magma chamber. The resulting decrease in resistance encountered by the gases reduces the relative advantage of He over the other magmatic volatiles and brings about a net decrease in the He/CO₂ ratio in the fumarole gases.

The cycle present in the Sulphur Bank gases appears to be displaced forward in time relative to that in the 1971 Fissure fumarole gases (the decrease in the He/CO₂ ratio for Sulphur Bank occurs later than that for the 1971 Fissure fumarole). This shift may result from differences in travel time for the gases between the summit magma reservoir and the two surface fumaroles. The 1971 Fissure fumarole is thought to be located almost directly above the summit reservoir, whereas Sulphur Bank is displaced several kilometers to the north.

We conclude that the He/CO₂ ratios observed at the 1971 Fissure fumarole may possibly provide us with a means of predicting impending eruptive activity of Kilauea several weeks prior to the event. With further observations to extend the data base, we may be able to refine this technique sufficiently to forecast the probability of an eruptive event several days beforehand.

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3. The temperature of Sulphur Bank is 97°C (the boiling temperature of water at 1200-m altitude); the temperature measured in the 1971 Fissure fumarole during the period of study was in the range of 140° to 150°C. Sulphur Bank emissions contain only small concentrations of the acid gases (CO₂ ≈ 2 percent, SO₂ ≈ 0.5 percent), whereas the 1971 Fissure fumarole is much richer in the acid gases (CO₂ = 10 percent, SO₂ ≈ 5 percent).
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Application of Carbon Isotope Stratigraphy to Late Miocene Shallow Marine Sediments, New Zealand

Abstract. A distinct (0.5 per mil) carbon-13/carbon-12 isotopic shift in the light direction has been identified in a shallow marine sedimentary sequence of Late Miocene age at Blind River, New Zealand, and correlated with a similar shift in Late Miocene Deep Sea Drilling Project sequences throughout the Indo-Pacific. A dated piston core provides an age for the shift of 6.2 ± 0.1 million years. Correlations based on the carbon isotopic change require a revision of the previously established magnetostratigraphy at Blind River. The carbon shift at Blind River occurs between 6.2 and 6.3 ± 0.1 million years before present. A new chronology provides an age for the evolutionary first appearance datum of *Globorotalia conomiozea* at 6.1 ± 0.1 million years, the beginning of a distinct latest Miocene cooling event associated with the Kapitean stage at 6.2 ± 0.1 million years, and the beginning of a distinct shallowing of water depths at 6.1 ± 0.1 million years. The Miocene-Pliocene boundary as recognized in New Zealand is now dated at 5.3 ± 0.1 million years. Extension of carbon isotope stratigraphy to other shallow Late Miocene sequences should provide an important datum for international correlation of Late Miocene shallow and deep marine sequences.

The stable isotope composition of foraminiferal tests is often used to determine the paleoceanographic and paleoclimatic history of the oceans through the Cenozoic and, to a much lesser extent, the Mesozoic. Recognizable changes in stable isotope composition, shifts or events, also serve as chronostratigraphic markers where biostratigraphic correlation is difficult between locations underlying different water masses (1, 2). Shackleton (3) considered that Quaternary isotopic composition changes are of greater value for stratigraphic correlation than the paleotemperature record they provide. Until recently (4, 5), isotope stratigraphy was mostly restricted to latest Neogene studies and utilized only the oxygen isotope record.

Although changes in the ¹³C/¹²C ratio in foraminifera are little understood, Shackleton and Kennett (2) called for the collection of ¹³C data for coherent patterns to emerge. Since then, Keigwin (5) and workers in the Cenozoic Paleocceanography (CENOP) program (6) have recorded a Late Miocene permanent shift in the ¹³C record of about 0.5 to 0.8 per mil in the light direction. This occurs at approximately 6.5 million years in Deep Sea Drilling Project (DSDP) sites 158 and 310 in the east equatorial and

central north Pacific, respectively. Unpublished work by Shackleton on piston core RC12-66 shows the existence of the carbon isotopic shift in the upper part of magnetic Epoch 6.

Since the carbon isotopic shift was established as a potential criterion for interoceanic correlation and for chronology, its stratigraphic occurrence needed to be tested in a shallow marine sedimentary sequence on land and a logical choice was the Blind River section, New Zealand. The Blind River section is a relatively continuous, freshly exposed land section containing a rich assemblage of benthonic foraminifera for isotopic analysis. Previous paleomagnetic dating (7) suggested that the Blind River section was of the right age to find the carbon isotope shift if it occurs in shallow marine sedimentary sequences.

The Blind River section is also important for two other reasons. First, it contains a well-established evolutionary sequence of globorotalids (*Globorotalia miozea conoidea*, *Globorotalia conomiozea*, *Globorotalia punctulata*), which is important for global correlation of temperate sequences (7-9). Second, it contains an excellent paleoclimatic record including a dramatic Late Miocene cooling and was important in providing a

foundation for our understanding of pre-Quaternary climatic evolution (10, 11).

The Blind River section is a 1200-m section consisting of mudstone, siltstone, and minor sandstone. The base of the sequence consists of coarse-grained sandstone and conglomerate unconformably overlying a basement of indurated graywacke and argillite of Permian-Jurassic age (11). Three New Zealand stages are represented at Blind River. The Late Miocene is represented by the Tongaporutuan and Kapitean stages. The Miocene-Pliocene boundary occurs between the Kapitean and Opoitian stages. Seventeen samples for isotopic analysis were obtained from the micropaleontological samples collected

by Kennett and Watkins (7). The sampling interval in the Tongaporutuan varies from 20 to 80 m, depending on outcrop occurrence. The Kapitean is more intensely sampled than the Tongaporutuan (Fig. 1). Subsamples of *Uvigerina* sp. (about 0.3 to 0.5 mg) were analyzed in a mass spectrometer (12).

There is little variation in the oxygen isotopic record (Fig. 1), but variation is greatest in the Kapitean. The small variation in the oxygen isotopic record at Blind River is unexpected because previous studies on DSDP sequences show significant Late Miocene change (2, 5). Oscillations in the $\delta^{18}\text{O}$ record at Blind River are thus not yet useful for correlation without more detailed work.

A permanent $\delta^{13}\text{C}$ shift of about 0.5 per mil is the most important feature of the stable isotopic record at Blind River (Fig. 1). The shift is from heavy values below 490 m to light values above 613 m, but is not as large a shift (0.8 per mil) as in the deep-sea sequences (5, 6). The shift is not a reversible event, but is a permanent and important change in the paleoceanographic and geochemical state of the oceans. The carbon isotope change may reflect either a global decrease in upwelling rate or a change in abyssal circulation patterns (13, 14). At Blind River the shift occurs over a thickness of at least 130 m, and we are not able to narrow this interval because of breaks in outcrop.

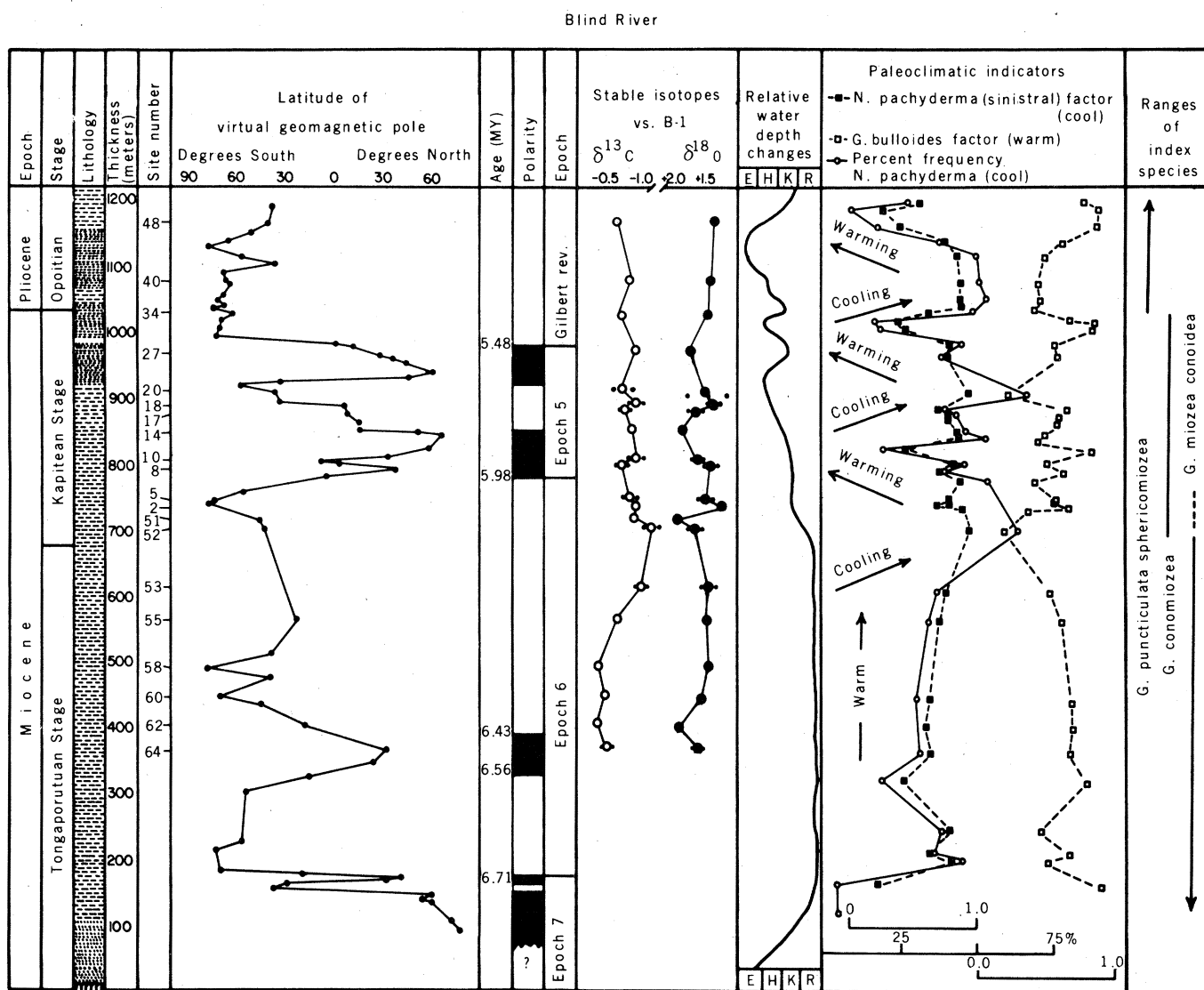


Fig. 1. Paleomagnetic stratigraphy, stratigraphic succession, isotope stratigraphy, relative water depth changes, paleoclimatic history, and ranges of some key planktonic foraminiferal species in the Blind River section, New Zealand. Magnetic polarity in the section was interpreted from the latitude of the virtual magnetic pole: (closed bar) normal polarity, (open bar) reversed polarity. Ages (MY, million years) of polarity boundaries are after MacDougall *et al.* (20). Sediment lithology symbols: (dots) sandstone, (fine dashes) siltstone, (coarse dashes) mudstone. Stable isotopic results (per mil): (○) $\delta^{13}\text{C}$, (●) $\delta^{18}\text{O}$. Relative water depth changes were derived from plotting the benthonic foraminiferal biofacies of each sample (11); depth increases to the right. Biofacies are represented by symbols as follows: (E) *Elphidium*, (H) *Haueslerella*, (K) *Karrerella*, and (R) *Robulus*. Paleoclimatic indicators are relative percentage of frequency of *N. pachyderma* (7), high frequencies indicating cool surface temperatures; *G. bulloides* factor, high loadings indicating warm surface water; and *N. pachyderma* factor, high loadings indicating cool surface water. Thickness is in meters measured from basement.

The latitude of the virtual geomagnetic pole for the Blind River section (7) is presented (Fig. 1). The two short normal-polarity sequences in the upper part of the Kapitean were previously interpreted (7) as being the split Gilbert C event, and the normal section at the base of the section was assigned to magnetic Epoch 5. Ryan *et al.* (15) later suggested that the two normal events were within magnetic Epoch 5 and that the Kapitean stage was coeval with the Messinian stage in the Mediterranean. The carbon isotope shift occurs near the middle of the long reversed interval at Blind River (Fig. 1), which had previously been interpreted as Gilbert epoch (7). The presence of the carbon isotopic shift allows a definitive reinterpretation of this reversed period as Epoch 6 rather than Gilbert. We base our reinterpretation of the magnetostratigraphy at Blind River on the fact that the carbon shift in RC12-66 also occurs in the upper reversed portion of magnetic Epoch 6 (16). We thus place the two normal events of the Kapitean stage in magnetic Epoch 5, and the normal event at ~350 m in magnetic Epoch 6 (Fig. 1). The lowermost normal sequence is interpreted as magnetic Epoch 7 and the upper part of the Blind River section is within Gilbert reversed epoch.

The Blind River paleomagnetic sequence is almost identical to the sequences recorded by Vine (17), Heirtzler *et al.* (18), Talwani *et al.* (19), and MacDougall *et al.* (20) for the Late Miocene and Early Pliocene. The short normal event in magnetic Epoch 6 at Blind River is also present in RC12-66 (21). The reinterpreted magnetostratigraphy shows the Blind River section to range in age from 5.1 to 6.8 million years. The carbon shift is from 6.2 to 6.3 ± 0.1 million years before present (B.P.) (20, 22). It took place within 150,000 years, based on a sedimentation rate of 83 cm per 1000 years through this interval (Fig. 2). There is a decrease in sedimentation rate from 83 cm per 1000 years in the earlier Late Miocene to 41 cm per 1000 years in the latest Miocene to earliest Pliocene (Fig. 1). This change in sedimentation is consistent with previously determined water depth-related biofacies changes based on benthonic foraminifera and lithofacies changes (11) (Fig. 1).

Keigwin (5), using microfossil biostratigraphy, determined that the $\delta^{13}\text{C}$ shifts at DSDP sites 158 and 310 are isochronous. In these two sites the carbon shift falls near the narrow overlap of the radiolarian *Ommatartus penultimus* zone and the nannofossil *Ceratolithus primus* subzone (5). The *Ommatartus penultimus*-*Stichocorys peregrina* radio-

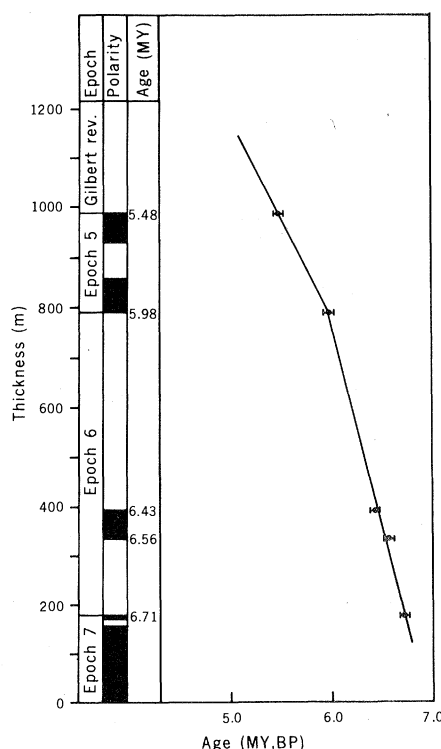


Fig. 2. Sedimentation rate diagram for the Blind River section. Paleomagnetic polarity boundary ages are from MacDougall *et al.* (20). (Closed bar) normal polarity, (open bar) reversed polarity. The slope of the line indicates sedimentation rates of ~83 cm per 1000 years during magnetic Epoch 6 and ~41 cm per 1000 years during magnetic Epoch 5.

larian boundary, which is simultaneous with the first appearance of *Thalassiosira praeconvexa* (23, 24), occurs just below the shift. Both of these siliceous fossil events have been paleomagnetically dated at about 6.3 million years B.P. (23, 24).

In the Blind River section the first evolutionary appearance of the planktonic foraminifera *G. conomiozea* Kennett and the base of the Kapitean stage is at 6.1 ± 0.1 million years and is close to the carbon shift. This is an important datum, particularly in the South Pacific (7-9, 25, 26). The first-appearance datum of *G. conomiozea* in Mediterranean sequences is at 6.5 ± 0.5 million years (27).

The Miocene-Pliocene boundary (Kapitean-Opoitian stage boundary) is placed at the level where the *G. conomiozea* morphotype becomes dominated by the *G. puncticulata sphericomiozea* Walters morphotype (7, 8, 28). This event occurs just above the top of magnetic Epoch 5 at 5.3 ± 0.1 million years B.P. and is close to the ages of 5.2 (15) and 5.0 (29) million years assigned for the same boundary in the Mediterranean region. Supportive evidence for a 5.3 million year age for the Miocene-Pliocene boundary of Blind River is a 5.2 million

year K/Ar date for sediments containing *G. puncticulata sphericomiozea* at the Chatham Islands, New Zealand (30).

A paleoclimatic history at Blind River was determined by Kennett and Watkins (7). On the basis of frequency changes of *Neoglobobulimina pachyderma*, they concluded that particularly cold conditions prevailed during much of the Kapitean and earliest Opoitian times. We also use the changes in frequency of *N. pachyderma* (7) to determine a paleoclimatic history (Fig. 1). The beginning of the latest Miocene cooling is dated at 6.2 ± 0.1 million years B.P. A distinct change in the stability of the paleoclimatic record occurs at this time—from warmer, relatively stable conditions in the Tongaporutuan to greater surface-water temperature oscillations during the Kapitean and earliest Pliocene (Fig. 1).

Of possible significance is the chronological sequence of several important events recorded in the Blind River section, all of which took place within 300,000 years. The dramatic permanent shift in the state of the oceans shown by the $\delta^{13}\text{C}$ record occurs between 6.3 and 6.2 million years B.P. (13, 14). This was followed at 6.2 million years by a sharp drop in surface-water temperatures and at 6.1 million years by the beginning of a distinct shallowing of water depths (11), and then a change in the nature of the benthonic oxygen isotopic record from a relatively constant stable record before 6.05 million years to a more variable signal after (31). The evolution of *G. conomiozea* through this interval is almost certainly related to these various paleoenvironmental stresses.

The cooling in the Kapitean stage may be synchronous with Late Miocene cooling in California (32, 33), increased ice rafting around Antarctica (34-36), and an inferred increase in volume of the Antarctic ice cap (2). For some reason the oxygen isotope record at Blind River shows no such increase in the volume of the Antarctic ice cap, but if it increased in the latest Miocene a glacioeustatic sea-level lowering would result. One possible explanation is that the Blind River section is a relatively shallow marine sedimentary sequence, and a decrease in water depth would, in effect, bring the bottom closer to the surface, thereby causing an increase in water temperature. Such a temperature increase would tend to cancel out any $\delta^{18}\text{O}$ ice volume effect recorded in benthonic foraminifera (37). A shallowing of water depths derived from plotting benthonic foraminiferal biofacies has been recorded at Blind River (10, 11). Shackleton and Kennett (2) estimated that sea level

dropped by 40 m in the latest Miocene. Berggren and Haq (38) estimated a glacioeustatic sea-level lowering of about 70 to 100 m at approximately 5.5 million years. The shallowest water depths recorded at Blind River in the Kapitean occur at about 5.6 million years (Fig. 1). Thus, these antipodal regions record a drop in sea level of about 40 to 70 m at about 5.5 to 5.6 million years. A drop of this magnitude could have effectively isolated the Mediterranean Basin, perhaps in combination with some local tectonic activity (38-41). Evaporitic sequences were thus deposited during the youngest part of the Messinian stage during the well-known Messinian salinity crisis (39). A rise in sea level recorded in Spanish and New Zealand sequences (11, 38) near the Miocene-Pliocene boundary may have been responsible for the subsequent reconnection of the Mediterranean Basin with oceanic waters.

Major paleoenvironmental changes recorded in sedimentary sequences in the South Pacific during the late Miocene may have had an effect on certain events in the Mediterranean region. We support the suggestion of Adams *et al.* (42) that expansion of the Antarctic ice cap and related glacioeustatic sea-level changes were a major factor in the isolation of the Mediterranean Basin during the Messinian.

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Nautilus Movement and Distribution in Palau, Western Caroline Islands

Abstract. Long-term movement of up to 150 kilometers in 332 days by tagged, living *Nautilus*, and postmortem shell drift of 1000 kilometers in 138 days, corroborate and explain the cosmopolitan distribution of many fossil shelled cephalopods.

The well-known worldwide distribution of genera and species of fossil shelled cephalopods is relied on for precise correlation of fossiliferous marine strata. Understanding of the mechanism by which the dispersal of these orga-

nisms was achieved is minimal, largely because they are survived today by only a single genus, *Nautilus*. This relict animal is relatively rare and poorly known, and its inaccessible habitat has limited laboratory and field investigations. Re-

Table 1. *Nautilus* tagged, released, and recaptured in 1977 and 1978 in Palau, Western Caroline Islands. "Distance moved" refers to minimum distance, measured roughly parallel to fringe reef. All animals tabulated were males except for Nos. 227 and 429.

Animal No.	Initial release		Recaptured		Elapsed time (days)	Distance moved (km)	Rate (km/day)
	Date	Site	Date	Site			
190	7-1-77	B	6-13-78	E	347	114	0.33
201	7-1-77	B	7-2-78	C	365	40	0.11
298	7-8-77	D	6-5-78	A	332	150	0.45
316	7-8-77	D	5-31-78	B	327	68	0.21
634	5-12-78	D	7-2-78	C	51	31	0.60
172	6-30-77	D	5-18-78	D	322	0	
198	7-1-77	B	5-26-78	B	329	0	
227	7-1-77	D	5-7-78	D	310	0	
323	7-8-77	D	6-17-78	D	344	0	
340	7-9-77	D	5-18-78	D	313	0	
005	5-27-77	D	1-20-78	D	239	0	
338	7-9-77	D	2-1-78	D	207	0	
429	7-24-77	D	2-1-78	D	192	0	