Reports

Secondary Calcification of the Planktonic Foraminifer Neogloboquadrina pachyderma as a Climatic Index

Abstract. *Oscillations in the ratio of two principal types of secondary calcification of the test surface in* Neogloboquadrina pachyderma *populations closely parallel paleoclimatic oscillations over the last 6 million years in a deep-sea core drilled in the temperate South Pacific. The nature of secondary calcification in fossil planktonic foraminifera represents a useful index in interpreting Cenozoic climates.*

During late ontogeny, numerous planktonic foraminifera develop a secondary crust of calcite (up to 50 μm thick) on the original, thinner, bilamellar foundation wall (*1, 2*). This secondary calcification is primarily an adult characteristic and takes place below certain critical water depths (*1–4*). Secondary thickening occurs in living *Globorotalia truncatulinoides* (d'Orbigny) at depths below 300 to 500 m (*1*) and some other Recent species of *Globorotalia* at depths below 120 to 700 m (*2*). In *Neogloboquadrina pachyderma* (Ehrenberg) the development of crystalline thickening in Arctic waters occurs below about 200 m (*3*) and is virtually complete at about 300 to 500 m (*4*).

Before now, the potential value of surface ultrastructural variations as paleoceanographic indexes has not been examined, except for variations involving pore density and porosity (*5*). In this report we describe surface ultrastructural variation in *N. pachyderma* populations throughout the late Miocene to Recent sequence (6 million years ago to the present) cored at Deep-Sea Drilling Project (DSDP) Site 284 (40°30.48′S, 167°40.81′E). The site is located to the west of New Zealand in the presently cool, subtropical (temperate) water mass 400 km north of the Subtropical Convergence. Two holes were drilled: 284 continuously cored to a depth of 208 m, and 284A to obtain three 9-m sections lost in 284. Planktonic foraminifera are abundant throughout this relatively shallow-water site (1068 m deep) and show little evidence of dissolution.

A relatively detailed chronology has been established for this section (*6*) by correlation with paleomagnetically dated Late Cenozoic sequences in New Zealand (*7*). The sequence represents 6 million years of almost continuous deposition of calcareous ooze, although much of the Pleistocene is missing in a disconformity. Frequency oscillations in the cool-water foraminifer *N. pachyderma* appear to reliably reflect paleoclimatic change (*6*). Oscillations in the frequency of this species mark particularly cool episodes during the latest Miocene and earliest Pliocene (equivalent to the New Zealand Kapitean–early Opoitian Stages), during the late Pliocene (Waipipian Stage), and briefly during the early Pleistocene (*6*). Warmer episodes occur during the late Tongaporutuan Stage of the late Miocene throughout much of the Opoitian Stage of the Pliocene and at several intervals during the Pleistocene. These paleoclimatic interpretations are closely supported by changes in oxygen isotope ratios (*8*).

Twenty-three samples of *N. pachyderma* were examined from cool and warm intervals (*6*) from the late Miocene to Recent (Fig. 1). The surface ultrastructure of 50 randomly selected specimens of *N. pachyderma* (> 125 μm in diameter) from each sample were examined with a Cambridge S4 scanning electron microscope (SEM). In addition, coiling ratios and percentages of kummerforms and normalforms (*9*) were determined for each sample.

The two principal types of surface ultrastructures in *N. pachyderma* are reticulate and crystalline. In addition, there are variable proportions of an intermediate form. Reticulate forms (*10*) have a microcrystalline surface with distinct pore pits (Fig. 2) surrounded by polygonal ridges of varying heights. The ridges are normally continuous, but are occasionally discontinuous on the

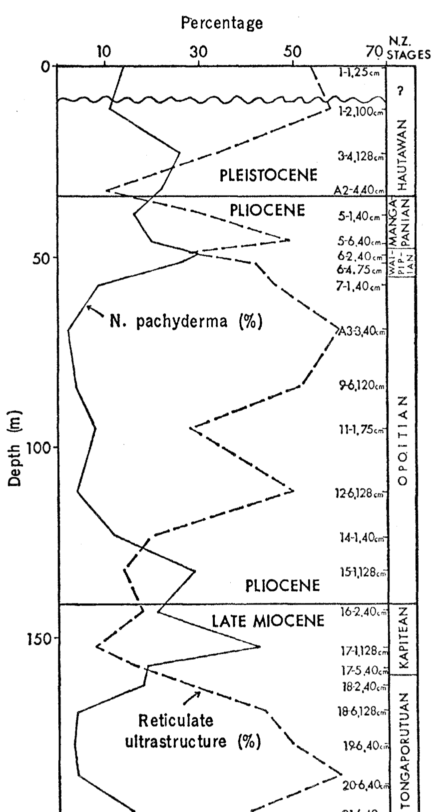

Fig. 1. Percentage fluctuations of *N. pachyderma* (*6*) (solid line) and of reticulate ultrastructural forms of *N. pachyderma* (dashed line) in the late Miocene to Pleistocene sequence recorded at DSDP Site 284 (temperate South Pacific). High frequencies of *N. pachyderma* represent cool intervals; low frequencies represent warm intervals. Characteristics of secondary calcification were determined by SEM examination of 50 specimens in each sample [DSDP sample numbers and levels are shown at the right (*15*)]. Note the generally reciprocal relation between the two parameters. New Zealand (*N.Z.*) late Cenozoic stages are shown at the extreme right (*6*), and the Pleistocene disconformity is indicated by the wavy line near the top of the sequence.

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final chamber, appearing as discrete tubercles. The interpore area is a smooth, microcrystalline surface without any discernible rhombohedral crystals even at ×5000 magnification. Additional test thickening occurs by microcrystalline accumulation on ridges of earlier chambers but even in these specimens the test remains thinner than in individuals with crystalline surface ultrastructure.

The test in crystalline forms (Fig. 2) is covered almost entirely by large euhedral calcite crystals more than 2 μm long. On the final and penultimate chambers the calcite crystals cluster around the pores, while on earlier chambers the rhombohedral crystals develop penetration twins, giving rise to a stellate structure. Crystal faces are normally marked by growth facets. With increased crystallinity on successively earlier chambers, pores become obscured and fewer in number. Tests are more thickened than in reticulate forms. Individuals with crystalline surfaces on all except the final and sometimes the penultimate chambers, which are reticulate, represent intermediate development (*3, 11*). Gradual decrease in crystallinity generally occurs in successively younger chambers, showing that crystalline growth of the test is produced by the foraminifer rather than by any diagenetic process (*1, 12*). Intermediate forms more closely resemble crystalline forms because of crystalline thickening on most chambers.

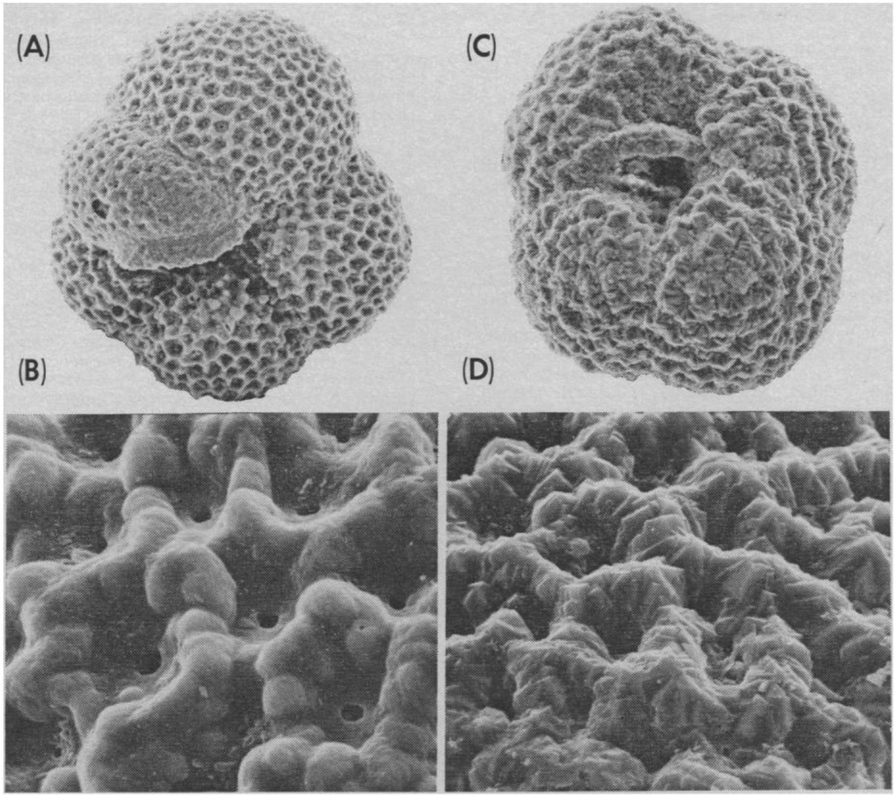

Fig. 2. (A and B) Reticulate form and (C and D) crystalline form of *N. pachyderma*. In the reticulate form note the circular central pores, smooth, microcrystalline wall, and deep, clear pore pits. In the crystalline form, note the calcite rhombohedrons clustering around pores, with interpenetrating crystal twins producing a stellate crust. (A) Dextral specimen, DSDP sample number 284-5-1, 40 cm (×167). (B) Dextral specimen, 284-3-4, 128 cm (× 1373). (C) Dextral specimen, 284-6-2, 40 cm (× 206). (D) Sinistral specimen, 284-17-1, 128 cm (× 1068).

Large fluctuations in the percentage of individuals having reticulate ultrastructure occur throughout the sequence (Fig. 1), and closely parallel paleoceanographic oscillations revealed by changes in the frequency of *N. pachyderma*. Fluctuations in the percentage of reticulate forms are generally reciprocal to fluctuations in the percentage of *N. pachyderma* (*6*) with low percentages occurring during cool episodes when *N. pachyderma* is more abundant (Fig. 2). Conversely, warm episodes are marked by high frequencies of reticulate or low frequencies of crystalline forms. This relation thus represents a valuable additional climatic index. Warm episodes are indicated during the early late Miocene (Tongaporutuan Stage), the middle Pliocene (late Opoitian Stage), and part of the Pleistocene. A severe cooling episode occurs during the latest Miocene and earliest Pliocene (Kapitean–early Opoitian Stages) with less severe coolings during the late Pliocene and earliest Pleistocene. No relation appears to exist between ultrastructure and coiling direction or the percentages of kummerform and normalform individuals. The general lack of dissolution within the planktonic foraminiferal faunas throughout the sequence indicates that the changing ratio of reticulate to crystalline forms is not controlled by selective dissolution.

It has already been demonstrated (*13*) in *Neogloboquadrina* that reticulate ultrastructure represents a primary form of secondary calcification, while crystalline ultrastructure is secondary. Reticulate ultrastructure is initially formed on all individuals of *Neogloboquadrina* (*14*) from polar to equatorial water masses. In certain water masses, most individuals retain this surface with no further substantial alteration, although additional test thickening may result from deposition of microcrystals on interpore ridges. In other water masses, the reticulate ultrastructure in most individuals is covered by further secondary encrustation related to crystalline ultrastructure formation, producing more thickly encrusted tests.

Secondary crystalline thickening in *Neogloboquadrina* is thus related not only to increased water depths but also to regional water-mass changes in the oceans, although this relation is not simple. Oscillations in the dominance of the two ultrastructural types in Site 284 is clearly related to paleoceanographic fluctuations. The nature of crystalline thickening in *Neogloboquadrina* reflects differences in the properties of water masses in which the specimens grew. Little is known about the environmental controls that trigger secondary calcification within planktonic foraminifera and control the nature of this secondary calcification. Physiological experiments on planktonic foraminifera may eventually provide this information. In the meantime, surface ultrastructure in *N. pachyderma* can be utilized in paleoceanographic studies especially because its relation to environment appears to have remained fairly constant through time, while other morphological characteristics, such as the coiling ratio, have undergone change (*6*).

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References and Notes

1. A. W. H. Bé and D. B. Ericson, *Ann. N.Y. Acad. Sci.* **109**, 65 (1963); A. W. H. Bé and L. Lott, *Science* **145**, 823 (1964).
2. W. N. Orr, *Science* **157**, 1554 (1967).
3. A. W. H. Bé, *Contrib. Cushman Found. Foraminiferal Res.* **11**, 64 (1960).
4. E. Boltovskoy, in *The Micropaleontology of Oceans*, B. M. Funnel and W. R. Reidel, Eds. (Cambridge Univ. Press, Cambridge, 1971), p. 277.
5. W. W. Wiles, *Progr. Oceanogr.* **4**, 153 (1967); W. E. Frerichs, M. E. Heiman, L. E. Borgman, A. W. H. Bé, *J. Foraminiferal Res.* **2**, 6 (1972); A. W. H. Bé, *Science* **161**, 881 (1968).
6. J. P. Kennett and P. Vella, in J. P. Kennett, R. E. Houtz *et al.*, *Initial Reports of the Deep-Sea Drilling Project* (Government Printing Office, Washington, D.C., vol. 29, in press).
7. J. P. Kennett, N. D. Watkins, P. Vella, *Science* **171**, 276 (1971); J. P. Kennett and N.D. Watkins, *Geol. Soc. Am. Bull.* **85**, 1385 (1974).
8. N. J. Shackleton and J. P. Kennett, in J. P. Kennett, R. E. Houtz *et al.*, *Initial Reports of the Deep-Sea Drilling Project* (Government Printing Office, Washington, D.C., vol. 29, in press).
9. Coiling ratios changes in *N. pachyderma* have been used extensively for late Cenozoic paleoclimatic interpretations. Kummerform individuals have a final chamber that is generally much smaller than the penultimate chamber; normalform individuals have a final chamber equal in size to or larger than the penultimate chamber.
10. O. L. Bandy, *Micropaleontology* **18**, 294 (1972).
11. K. Hunkins, A. W. H. Bé, N. D. Opdyke, G. Mathieu, in *The Late Cenozoic Glacial Ages*, K. K. Turekian, Ed. (Yale Univ. Press, New Haven, Conn., 1971), p. 215.
12. A. W. H. Bé, *Micropaleontology* **11**, 81 (1965).
13. M. S. Srinivasan and J. P. Kennett, *Am. Assoc. Pet. Geol. Bull.* **1**, 86 (1974); in *Professor Asano Commemoration Volume*, Y. Takayanagi and T. Saito, Eds. (Micropaleontology Press, New York, in press).
14. *Neogloboquadrina* includes the Recent forms *N. pachyderma* (Ehrenberg) and *N. dutertrei* (d'Orbigny) and the fossil forms *N. acostaensis* (Blow), *N. dutertrei subcretacea* (Lomnicki), *N. dutertrei humerosa* (Takayanagi and Saito), and *N. dutertrei* (Berggren).
15. The DSDP sample numbers in Fig. 1 include the core number, section within the core, and centimeters within the section. For example, 1-1, 25 cm means core 1, section 1, 25 cm within section 1. In Fig. 2 legend the DSDP site number is given first.

16. We appreciate technical assistance from D. Scales. Supported by NSF grant GA-35252.

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Ice Crystal Concentration in Cumulus Clouds: Influence of the Drop Spectrum

Abstract. *Secondary ice crystals are thrown off when supercooled cloud drops are captured and freeze on a moving target in a cloud at −5°C. The rate of production of these ice crystals is proportional to the rate of accretion of drops of diameter ≥24 micrometers.*

We reported recently (*1*) on laboratory experiments which showed that when an ice particle grows by the accretion of supercooled cloud drops, copious ice splinters are thrown off if the cloud temperature is about −5°C. We suggested that this phenomenon would probably provide the long-sought explanation for the high concentration of ice crystals found in some cumulus clouds as compared with the concentration of ice nuclei measured in cloud chambers in the vicinity (*2*). We now report on further experiments which demonstrate the influence of drop size distribution on the production of splinters during riming.

We used a cloud chamber with walls of polyethylene sheet, 2 m by 1.2 m by 1.8 m high, enclosed in a cold room. We made a supercooled cloud by injecting steam into the chamber from a boiler with known power input. Rime was grown on a vertical metal rod (*3*), 30 cm long and 0.2 cm in diameter, which moved in a circular path of diameter 30 cm about a vertical axis at a velocity of 2.6 ± 0.1 m/sec, sweeping up supercooled cloud drops in its path. The air temperature at the midpoint of the riming rod was $-4.7° \pm 0.5°$C. Below the riming rod a beam of light traversed the cloud chamber. We counted the number of ice crystals appearing in the beam per minute and derived from this the fallout rate of ice crystals (*4*).

All experiments were continued long enough for a steady state to be reached so that it could be assumed that the rate of fallout of crystals was equal to the rate of production. Because our experiments were carried out at a fixed temperature and target velocity the only known variables affecting the production of splinters were the weight of rime accreted per unit time and the size distribution of the accreted drops.

We investigated the rate of shedding of ice splinters when rime was accreted on the moving rod at widely differing rates (*5*). The liquid water content of the cloud and hence the riming rate could be varied by changing the boiler input power. Figure 1 shows that there is no unequivocal dependence of splinter production on riming rate. Relatively low counts were obtained when the drop sizes (*6*) were deliberately reduced by introducing NaCl nuclei into the cloud from a hot wire, even when the riming rate was very high. Higher counts were obtained when the chamber was flushed with filtered air to reduce the numbers of drop nuclei and give significant concentrations of larger drops.

We have investigated the effect of drop size alone by selecting from the previous experiments a set in which the rate of accretion of rime was constant to within 20 percent. A wide range of drop size distributions was obtained by adding or removing nuclei as described above. The largest drops found in our cloud in any experiment were 36 μm in diameter (sample volume, 5 cm^3).

We plotted the rate of production of secondary ice crystals against the concentrations of drops of diameters larger than 18, 20, 23, and 25 μm present in the chamber. Because drops of these sizes are swept up with almost 100 percent collection efficiency by the riming rod (*7*), the rate of accretion of drops of these sizes can be assumed to be proportional to their concentration. We find a reasonably linear relationship between splinter production rate and drop concentration for all these sizes, the closest correlation applying to drops of diameter >23 μm, for which the results are illustrated in Fig. 2.

From the results of these experiments we suggest that the rate of production of secondary ice crystals is proportional to the number rate at which drops larger than about 23 μm are accreted and is not, in general, a function of the riming rate, that is, the mass rate of accretion of all drops. We see from Fig. 2 that about ten crystals are produced per second for every drop >23 μm in diameter present per cubic centimeter of cloud air. A rod 2 mm in diameter, 30 cm long, and moving at 2.6 m/sec sweeps out a volume of about 1600 cm^3/sec. Thus about 160 drops >23 μm are accreted for every secondary ice crystal that is shed. We showed previously (*1*) that at a temperature of −5°C and a target velocity of 2.7 m/sec, about 350 splinters are produced per milligram of rime accreted. It is now apparent that this result applies only to the particular drop size distribution used in those experiments. Our new work does not affect the validity of the main previous finding (*1*) that the production of secondary ice crystals during riming is virtually confined to the temperature range −3° to −8°C, with a maximum rate at about −5°C.

We now turn to the question of whether we can explain the high concentrations of the crystals found in