Pleistocene-Recent Boundary and Wisconsin Glacial Biostratigraphy in the Northern Indian Ocean

Abstract. *Two faunal criteria define the Pleistocene-Recent boundary in the Andaman Sea and the Bay of Bengal: there is a marked decrease in the relative abundance of the* Globigerina rubescens *complex and a significant increase in the radiolarian number in sediments of the Recent epoch. The stratigraphic significance of the faunal criteria is supported by a carbon-14 date (8775 years before the present) obtained from foraminiferal tests in sediment at the faunal boundary, and previous publications on the stratigraphic significance of the radiolarian number in the eastern Pacific Ocean. The* Globigerina rubescens *complex, with greater relative abundances indicative of glacial substages, is an accurate indicator of cold and warm climatic intervals of the Wisconsin glacial stage.*

The nature and position of the Pleistocene-Recent boundary and the recognition of cool and warm intervals within the Pleistocene have received much attention in recent years. Widely differing chronologies of the Pleistocene based on different analytical methods have been described by Ericson, Ewing, and Wollin (*1*) and Emiliani (*2*). The Pleistocene chronology of Ericson *et al.* (*1*) is based upon changes in the abundance of *Globorotalia menardii* and appears applicable only to the Atlantic Ocean and the southern Indian Ocean (*3*). Ericson and Wollin (*4*) indicate for the Pacific Ocean, for example, that "it is difficult to discern any zonation at all and what faint zonation may be present is opposite in phase with the zonation of the Atlantic." The Pleistocene chronology of Emiliani is based on isotopic determinations of temperature in deep-sea cores from the Caribbean Sea and, in part, on ratios of warm-water and cold-water planktonic species.

A study of piston and trigger cores from the Andaman Sea and eastern Bay of Bengal (Table 1) has not resulted in recognition of the Pleistocene-Recent boundary based on either the faunal parameters of Ericson *et al.* (*1*) or the ratios-of-planktonics method of Emiliani (*2*). Instead, the Pleistocene-Recent boundary is identified by the following faunal criteria.

Table 1. Locations of samples in the Indian Ocean.

Station	Latitude	Longitude	Depth (m)
A-2	11°01.0	93°42.0	2562
P-19	9°21.3	93°56.2	3175
P-20	10°09.4	91°06.9	3415
P-23	9°54.1	93°44.7	3240
P-24	10°58.7	93°42.0	2522
P-25	9°47.6	93°55.7	3778
P-26	12°48.6	93°57.3	2152

1) The Pleistocene-Recent boundary is indicated best by a marked increase in the abundance of radiolarians in Recent sediments. The radiolarian number increases by many orders of magnitude with the advent of the Recent; two peaks of abundance (8000 years B.P. and 5000 years B.P.) are characteristic, with the more recent peak being the greatest.

2) The *Globigerina rubescens* complex, which is composed of the species *Globigerina rubescens* and *Globigerinoides tenellus,* significantly decreases in relative abundance in Recent sediments. The two species have been combined in the frequency counts because of difficulty in differentiating smaller individuals, and variations in abundance of larger specimens are directly proportional.

Several lines of evidence support the faunal criteria used here to define the Pleistocene-Recent boundary. Foremost is a radiometric date obtained from core P-19 by which foraminiferal tests from a 38-cm section of core immediately below the faunal boundary are dated at 8775 ± 145 carbon-14 years B.P. (*5*). This date is younger than published dates, that is, 11,000 years B.P. (*6*), 11,000 years B.P. (*1*), and 12,000 years B.P. (*7*).

Examples of extreme differences in radiometric dates reported by authors for the Pleistocene-Recent boundary include 7000 years B.P. from a core taken in the tropical eastern Pacific Ocean (*8*) and 16,500 years B.P. from a core taken in the Caribbean Sea (*2*). Thus, the date from the Andaman Sea falls well within the range of published dates.

Further supporting evidence is given by the studies of Bandy (*9*) and Nayuda (*7*), who report increased abundances of radiolarians in Recent sediments of the eastern Pacific Ocean, which agree with the radiolarian trends in cores from the Andaman Sea and the Bay of Bengal.

Finally, the climatic trends, as shown by the *Globigerina rubescens* complex, agree in general with the climatic trends interpreted from the stratigraphic distribution of *Globorotalia menardii* by Ericson *et al.* (*1*) and agree remarkably well with the isotopic temperature curve of Emiliani (*2*) (Fig. 1).

Below the Pleistocene-Recent boundary, radiolarians are essentially lacking in the cores examined. The *Globigerina rubescens* complex, however, changes markedly in relative abundance with depth in the cores. These fluctuations appear to reflect climatic changes within the Pleistocene, with intervals of greater abundance being indicative of glacial times, and intervals of reduced abundance being indicative of the interstadials. In general the relative abundance curve for the *Globigerina rubescens* complex, the abundance curve for *Globorotalia menardii* as published by Ericson *et al.* (*1*), and the temperature curve of Emiliani (*2*) are in very good agreement (Fig. 1). Extrapolated dates, based on an assumed constant rate of sedimentation, are superimposed upon the relative abundance curve of the *Globigerina rubescens* complex. Radiometric dates of Ericson *et al.* (*1*) are indicated for the glacial substage and interstadial boundaries of the *Globorotalia menardii* abundance curve, as are the dates assigned to the isotopic temperature curve by Emiliani. An interstadial within the main Wisconsin glacial substage of Ericson *et al.* (*1*) is the only discrepancy between the three curves. Ericson *et al.* (*1*) have not recorded an interstadial within their main Wisconsin glacial substage, whereas the isotopic temperature curve of Emiliani (*2*) and the relative abundance curve of the *Globigerina rubescens* complex indicate a mild interval at this stratigraphic position. Emiliani dates the

Table 2. Suggested division of the Wisconsin glacial stage.

Subdivision	Age (years B.P.)
Late Wisconsin glacial substage	11,000 to 22,500
Late Wisconsin interstadial	22,500 to 42,000
Middle Wisconsin glacial substage	42,000 to 65,000
Early Wisconsin interstadial	65,000 to 95,000
Early Wisconsin glacial substage	95,000 to 115,000

warm interval as occurring between 46,000 and 25,000 years B.P. Five cores from the Andaman Sea and one core from the Bay of Bengal penetrated the interstadial; extrapolated dates (in years before the present) for the end of the interstadial are as follows:

Core P-26	19,000	Andaman Sea
Core P-24	20,000	Andaman Sea
Core P-20	21,000	Bay of Bengal
Core P-25	22,000	Andaman Sea
Core A-2	23,000	Andaman Sea
Core P-23	31,000	Andaman Sea

From these cores the average date obtained for the end of the interstadial is 22,500 years B.P., which agrees with the date obtained from Emiliani's temperature curve. Core P-23 is the only core containing sediments of the entire Wisconsin glacial, and the extrapolated date for the beginning of the interstadial is 42,000 years B.P.

Additional evidence supporting the presence of an interstadial at this stratigraphic position can be found in radiometric dates from deep-sea sediment cores and from the glacial sequences of Europe. Hough (*10*) reports a warm interval at this same relative stratigraphic position in a core from the Ross Sea. Radiometric dates indicate the warm interval extended from 40,000 years B.P. to 29,500 years B.P.

The stratigraphic position of the Paudorf interstadial of Europe, for which (on the basis of carbon-14 dates and correlation with Pleistocene stratigraphy of the Netherlands) Hammen *et al.* (*11*) suggest an age of 39,000 to 27,000 years B.P., is in general agreement with the stratigraphic position of the warm intervals noted by Emiliani, Hough, and myself. Recently, Schott (*12*) identified two interstadials within the Wisconsin glacial in sediment cores from the Atlantic Ocean. The cores studied by Schott have not been radiometrically dated, but the presence of two interstadials suggests a correlation with the climatic sequence noted in the Andaman Sea and the Bay of Bengal.

The similarity of climatic trends in five widely separated deep-sea and continental areas suggests a five-part division of the Wisconsin glacial stage instead of the usually accepted three-part division favored by Emiliani (*2*), Ericson *et al.* (*1*), and Flint (*13*). The division suggested is shown in Table 2.

Extrapolated dates, based on an assumed constant rate of sedimentation for the Quaternary in the Andaman Sea and the Bay of Bengal, are used to define the boundaries of the late Wisconsin interstadial. All other dates are those of Ericson *et al.* (*1*).

Emiliani considers what is here designated as the early Wisconsin interstadial to represent the Sangamon interglacial and favors a shorter Pleistocene chronology than do Ericson *et al.* (*1*). Recent studies extending the duration of the Pleistocene to three million years, for example, those of Obradovich (*14*) and Evernden *et al.* (*15*), suggest that the Pleistocene chronology of Emiliani is of too short a duration and that the interpretation of Ericson *et al.* (*1*) of a Wisconsin glacial extending from 115,000 to 11,000 years B.P. is reasonable.

The *Globigerina rubescens* complex seems to represent an important tool for deep-sea stratigraphy of the Indian and Pacific oceans, but the two species comprising the complex have not generally been recognized in Recent sediments by other authors. Consequently, except for the work of Parker (*16*) and Bé and Hamlin (*17*) few distributional data are available for these species. Parker notes that *Globigerina rubescens* generally is found north of latitude 35°S in the Pacific Ocean and *Globigerinoides tenellus* generally north of latitude 30°S. Bé and Hamlin (*17*) recorded *Globigerina rubescens* in plankton tows from the Atlantic Ocean between latitudes 25°N and 40°N. These sparse distributional data suggest that *Globigerina rubescens* and *Globigerinoides tenellus* are subtropical species. The greater relative abundances of these species in sediments of the

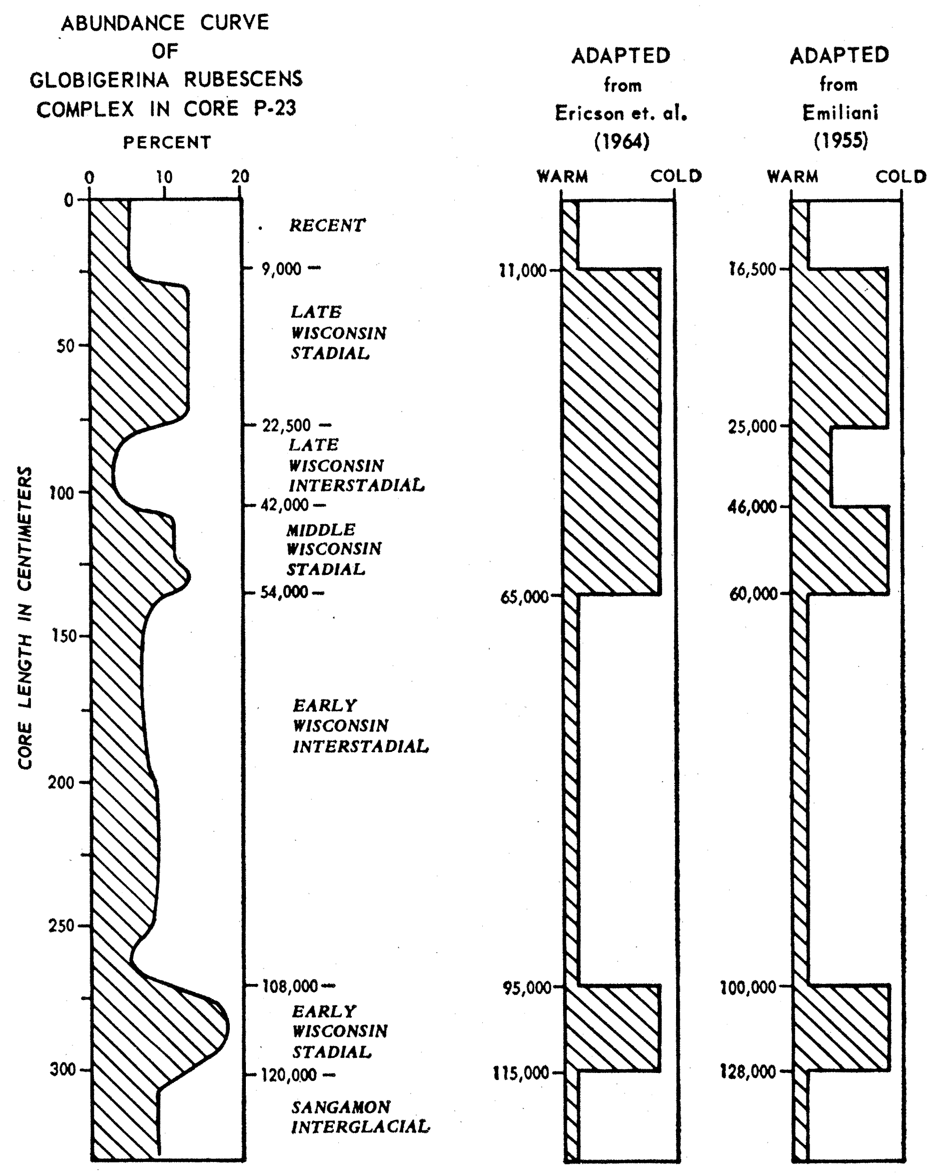

Fig. 1. Climatic fluctuations during the Wisconsin Glacial as indicated by (1) *Globigerina rubescens* complex, (2) isotopic temperature, and (3) change in relative abundance of *Globorotalia menardii.*

glacial substages, therefore, may be due to a shift of the geographic distributions toward the equator during the cooler glacial substages.

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References and Notes

1. D. B. Ericson, M. Ewing, G. Wollin, *Science* **146**, 723 (1964).
2. C. Emiliani, *J. Geol.* **63**, 538 (1955).
3. J. R. Conolly, *Nature* **214**, 873 (1967).
4. D. B. Ericson and G. Wollin, *The Deep and the Past* (Knopf, New York, 1964), p. 255.
5. Geochron date BX0680.
6. O. L. Bandy, *J. Paleontol.* **34**, 671 (1960).
7. Y. R. Nayudu, *Science* **146**, 515 (1964).
8. J. L. Hough, *J. Geol.* **61**, 252 (1953).
9. O. L. Bandy, in *Progress in Oceanography*, M. Sears, Ed. (Pergamon, New York, 1967), vol. 4.
10. J. L. Hough, *J. Geol.* **58**, 254 (1950).
11. T. van der Hammen, G. C. Maarleveld, J. C. Vogel, W. H. Zagwijn, *Geol. Mijnbouw* **46**, 79 (1967).
12. W. Schott, *Swed. Deep-Sea Rept.* **7**, 360 (1966).
13. R. F. Flint, *Glacial and Pleistocene Geology* (Wiley, New York, 1957), p. 386.
14. J. D. Obradovich, *Bull. Am. Assoc. Petrol. Geologists* **49**, 1087 (1965).
15. J. F. Evernden, D. E. Savage, G. H. Curtis, G. T. James, *Am. J. Sci.* **262**, 145 (1964).
16. F. L. Parker, *Micropaleontology* **8**, 219 (1962).
17. A. W. H. Bé and W. H. Hamlin, *ibid.* **13**, 87 (1967).
18. This study was supported by NSF grant GP-2530. I thank Dr. O. L. Bandy of the University of Southern California for suggestions and constructive criticism during the progress of this study.

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Sphene: Uranium-Lead Ages

Abstract. *Uranium-lead ages were measured on 14 samples of sphene from rocks aged from 1000 to 2750 × 10⁶ years. All samples gave concordant or nearly concordant ages, the maximum difference between the* Pb^{206}*-*U^{238} *and* Pb^{207}*-*Pb^{206} *ages being 10 percent. Sphene has more concordant ages than has the coexisting zircon in each of seven rocks in which they were compared. Sphene sometimes has greater ages than does coexisting biotite, although in two metamorphic rocks, in which metamorphism was sufficiently intense to cause redistribution of radiogenic strontium-87 between various mineral phases, sphene dates the time of metamorphism rather than of original crystallization of the rocks.*

Determinations of ages of minerals by the uranium-lead method are uniquely valuable because two isotopes of uranium, U^{238} and U^{235}, decay at different rates into two isotopes of lead, Pb^{206} and Pb^{207}, giving two age values from the isotopic ratios of uranium and lead. In addition, the ratio of radiogenic Pb^{207} to radiogenic Pb^{206} defines a third age value, although just two of the three values are independent. When the three age values agree, the ages are said to be concordant.

Concordant ages are strong evidence that no isotopic disturbance has occurred and that the calculated age reflects the true time of crystallization of the mineral. In practice, the isotopic-lead ages rarely agree within the limits set by analytical errors (± 1 to 2 percent). One of the most favorable minerals is uraninite, which commonly exhibits a discordance of 10 percent or less (*1*). Since uraninite is too rare to serve generally for study of geologic problems, most uranium-lead ages are determined for the mineral zircon, a common accessory mineral in various rocks. Generally the ages of zircons are discordant. In only a few instances have the differences between the Pb^{206}-U^{238} and Pb^{207}-Pb^{206} ages been less than 10 percent; usually they amount to 20 to 30 percent and may exceed even 50 percent.

Experimental studies (*2*) as well as investigations of many zircon suites (*3–6*) show that loss of lead is probably the most important cause of discordance, but much disagreement persists as to the nature of the processes causing the loss. The amount of lead lost from zircon can sometimes be related to the uranium content of the sample: that is to say, the Pb/U ratios decrease as the concentration of uranium increases (*3–5*). Because the crystal structure of zircon is slowly destroyed by α-particle and recoil-nucleus bombardment, leading to the metamict state, it is conceivable that radiation damage may cause loss of lead.

Several factors indicate the potential utility of sphene, another widely distributed accessory mineral. Sphene occurs with zircon in many rocks, providing a second independent uranium system for measurement of age; it contains 5 to 10 times less uranium than does zircon, so that the rate of radiation damage is proportionately lower. Finally, the stability of sphene toward metamorphic processes should differ from that of zircon.

The existing determinations of age for sphene mostly agree within 10 percent and can be considered nearly concordant (*7*). Nearly concordant ages for sphene are reported by Oosthyzen and Burger (*7*) from a rock whose zircon ages are quite discordant. To test further the suitability of sphene for dating purposes we selected samples from rocks on which results of isotopic studies were available, including in most instances age data for zircons.

Great care was taken in purification of mineral separates. In addition to the usual separations based on density and magnetic susceptibilities, all samples were hand-picked to reduce impurities to abundances of 0.1 percent. All separates were cleaned in warm (50°C) 8*M* nitric acid for 30 minutes before analysis. The uranium and lead concentrations (Table 1) were determined by stable-isotope dilution techniques closely following those described (*8*). The concentrations are believed to be accurate within 1 percent; the isotopic ratios for lead are known within 1 percent (*9*). Thus the uranium-lead and the Pb^{207}-Pb^{206} ages are known within about 1.5 percent.

Two different size fractions of sample NM-5 (granite from Sandia Mountains, New Mexico), +50 mesh [NM-5(a)] and −100 +150 mesh [NM-5(b)], were analyzed separately. The uranium concentrations of the two fractions are identical within analytical errors; so are the nearly concordant ages. The results date the sphene accurately at about 1480 × 10⁶ years, a value in close agreement with Pb^{207}-Pb^{206} ages of discordant zircons from the same rock sample (*10*). The two zircon results (Table 2) represent the extremes in their data; the uranium concentrations are 418 parts per million (ppm) for the most concordant sample and 652 ppm for the most discordant. The sphene age of 1480 × 10⁶ years coincides on the concordia curve with the upper intercept of the best-fit linear array defined by the zircon data; the result is compatible with the model of episodic loss of lead for the zircons.

It is interesting that the sphene from this rock contains strontium having an anomalous isotopic-Sr composition (*11*). Since the ages of the sphene samples are concordant and agree with the extrapolated age for the zircons, we believe that the sphene results give the time of crystallization. Possibly the sphene crystallized with anomalous Sr. Alternatively, radiogenic Sr may have been added to the mineral during an episode of metamorphism under conditions such that radiogenic lead was retained.