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Journal

Palaeogeography, Palaeoclimatology, Palaeoecology, 40(1-3)

ISSN

0031-0182

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Publication Date

1982

DOI

10.1016/0031-0182(82)90088-8

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DEEP CIRCULATION IN THE LATE CRETACEOUS: OXYGEN ISOTOPE PALEOTEMPERATURES FROM *INOCERAMUS* REMAINS IN D.S.D.P. CORES

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(Received May 12, 1982)

ABSTRACT

Saltzman, E. S. and Barron, E. J., 1982. Deep circulation in the Late Cretaceous: oxygen isotope paleotemperatures from *Inoceramus* remains in D.S.D.P. cores. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 40: 167–181.

Inoceramus is an epibenthic bivalve which lived in a wide variety of paleoenvironments encompassing a broad range of paleodepths. A survey of all Cretaceous sediments from Deep Sea Drilling Project legs 1–69 and 75 revealed over 500 *Inoceramus* specimens at twenty sites. Of these, 47 well-preserved Late Cretaceous specimens from the South Atlantic, Pacific and Indian Oceans were analyzed for oxygen and carbon isotopes. The specimens exhibit small internal isotopic variability and oxygen isotopic paleotemperatures that are consistent with a deep-sea habitat. Paleotemperatures ranging from 5 to 16°C show that Late Cretaceous oceans were significantly warmer than the present oceans. The data suggest that deep water was formed both by cooling at high latitudes and by evaporation in the subtropics.

INTRODUCTION

Warm, equable paleoclimates, typified by the Cretaceous Period, are a focus of research because they are a large contrast from the present-day climate. Cretaceous paleoceanography is of particular significance because the lack of polar ice, the reduced vertical and horizontal temperature gradients and the widespread record of anoxic sediments all imply large differences in the factors which controlled the ocean circulation.

Two major concepts of ocean circulation during warm, equable time periods have been proposed:

(1) *Stagnant oceans*. This concept holds that the ocean circulation was sluggish due to the reduced temperature gradients and because, at present, deep-water formation is associated with high-latitude cooling and salt exclusion during freezing. This has been extended to suggest that ocean-wide stagnation is the key to the interpretation of oceanic sedimentation during warm,

geologic periods (Degens and Stoffers, 1976; Schlanger and Jenkyns, 1976). Closely associated with these ideas is the assumption that warm bottom temperatures reflect polar surface temperatures (the source of the deep water).

(2) *Warm, saline bottom water*. This proposal states that the ocean circulation may not have been stagnant because warm, saline water produced in the subtropics by evaporative processes has the potential to become bottom water (Berger, 1978, Brass et al., 1982). In this case, anoxic sedimentation could be explained by the reduced oxygen solubility in warm, saline sea water. Deep-sea temperatures would then reflect subtropical rather than high-latitude surface ocean temperatures.

These hypotheses have considerable implications for oceanic heat transport, chemistry and deep-sea sedimentation. In addition, oceanic heat transport and polar temperatures have important implications for understanding the mechanisms which might explain warm climates (Barron et al., 1981).

Quantitative estimates of climatic variables, such as paleotemperatures, are essential in order to reconstruct climatic conditions, test various hypotheses of climatic change and verify results from predictive models. This goal requires isotopic data from all the ocean basins at a variety of paleodepths. Unfortunately, Cretaceous oxygen isotopic paleotemperature data from open ocean paleoenvironments are extremely limited (Douglas and Savin, 1971, 1973, 1975; Saito and Van Donk, 1974; Margolis et al., 1977; Boersma and Shackleton, 1981). At present the goal of reconstructing Cretaceous oceanography cannot be accomplished using Foraminifera because of a lack of suitably preserved specimens. New data sources are required.

Inoceramus, an extinct epibenthic bivalve, lived in a variety of paleoenvironments, in a broad range of paleodepths and is preserved in Deep Sea Drilling Project cores from all of the major ocean basins (Thiede and Dinkelman, 1978; Barron et al., 1982). The coarse crystalline calcite ostracum of *Inoceramus* is suitable for oxygen isotopic analysis and provides additional data of considerable importance in reconstructing Cretaceous oceanography.

OXYGEN ISOTOPIC EQUILIBRIUM IN *INOCERAMUS*

The validity of oxygen isotope paleotemperature studies depends on the precipitation of calcium carbonate in isotopic equilibrium with ambient waters and the retention of the original isotopic composition of the shell. These conditions are impossible to test directly on an extinct organism such as *Inoceramus*. Instead, they are commonly tested indirectly by comparison of *Inoceramus* paleotemperatures to those measured on other fossils from the same location.

Lowenstam and Epstein (1954) obtained reasonable *Inoceramus* paleotemperatures in good agreement with those from belemnites in Cretaceous epicontinental sea deposits from England, Denmark and Sweden. Tourtelot and Rye (1969) found good agreement between *Inoceramus* and a cephalopod

in a Tennessee deposit and between an *Inoceramus* specimen and an *Ostrea* specimen attached to it from the Northwest Territory.

However, at two other localities in the Cretaceous Seaway of North America (Oral, South Dakota and Pueblo, Colorado) *Inoceramus* paleotemperatures were found to be unreasonably warm, about 10°C above those from *Baculites*. These inoceramids also exhibited an offset in $\delta^{18}\text{O}$ between aragonite and calcite layers in the same specimen. Rye and Sommer (1980) suggested that this offset reflects the equilibrium fractionation between aragonite and calcite layers in the same specimen. Rye and Sommer (1980) originally assumed by Tourtelot and Rye. Rye and Sommer ascribed the difference in $\delta^{18}\text{O}$ between *Inoceramus* and *Baculites* to migration of the cephalopods from waters of normal salinity into the brackish seaway in which the *Inoceramus* lived.

In deep-sea sediments, *Inoceramus* paleotemperatures can be compared to those from benthic Foraminifera. This comparison is perhaps more meaningful than those discussed above, since both organisms are benthic and the deep sea is more uniform in temperature and isotopic composition. Saito and Van Donk (1974) analyzed pairs of *Inoceramus* and benthic Foraminifera samples from three core catcher samples from D.S.D.P. Site 21 in the South Atlantic Ocean. They found close agreement between the two samples in each pair, with *Inoceramus* slightly (about 0.5‰) heavier than the benthic Foraminifera. Saito and Van Donk interpreted this offset as evidence of post-depositional exchange of *Inoceramus* with subsequently cooler pore waters. However, in the present study we examined the isotopic composition of diagenetically altered *Inoceramus* fragments and found them invariably depleted in ^{18}O . Metabolic effects of this magnitude are not uncommon and may be responsible for the observed offset. A more extensive comparison of *Inoceramus* and benthic Foraminifera is presently being undertaken to investigate this phenomenon.

THE DISTRIBUTION OF *INOCERAMUS*

All Cretaceous sediments recovered from the Pacific, Indian, North and South Atlantic Oceans by the Deep Sea Drilling Project from legs 1–69, and including leg 75, were examined for *Inoceramus*. *Inoceramus* occurs in every D.S.D.P. core which penetrated Cretaceous sediments in the South Atlantic Ocean (Sites 21, 327A, 330, 355, 356, 357, 361, 363, 364, 530A). Sixteen sites from the Indian Ocean penetrated Cretaceous sediments and *Inoceramus* occurs at five sites (217A, 249, 250A, 255, 258A). Thirty-five sites penetrated Cretaceous sediments in the Pacific Ocean. However, only five sites contain *Inoceramus* (48.2, 204, 317A, 465, 466). Although 62 sites in the North Atlantic recovered Cretaceous sediments only four sites contained *Inoceramus* (105, 146, 369A, 382).

The *Inoceramus* specimens from the South Atlantic range in age from the Aptian to the Maestrichtian. North Atlantic specimens are from the Early

Cretaceous, the Aptian—Albian, the Santonian and the Campanian. Indian Ocean specimens range from the Coniacian to the Maestrichtian, and the Pacific Ocean specimens are from the Campanian and Maestrichtian with two isolated *in situ* Aptian specimens at Site 317A.

Paleodepths were reconstructed from data from D.S.D.P. site reports and age-depth thermal subsidence curves. Careful examination for sedimentologic indicators of downslope transport indicates an *in situ* depth habitat ranging from 4500 m at Site 530A (Barron et al., 1982) to approximately 500–1000 m (e.g. Site 21). The majority of the specimens are found at paleodepths of less than 2500 m.

Inoceramus occur most frequently in calcareous sediments but also are found in claystones and mudstones. The *Inoceramus* remains found in deep-sea cores are typically fragmented rather than whole shells, most likely as a result of predation (E. Kauffman, pers. comm., 1981).

A total of 500 specimens of *Inoceramus* were recorded at the twenty D.S.D.P. sites. A rigorous selection procedure for well-preserved specimens eliminated almost 90% of the *Inoceramus* fragments from consideration for paleotemperature determination. The remaining 49 samples from seven sites are described in detail below.

Pacific Ocean

The Pacific Ocean samples include thirteen specimens from two sites, Site 48.2 and 465A, on the Shatsky and Hess Rises, respectively. All the Pacific specimens are from Maestrichtian sediments. These shallow plateaus (Site 48.2: 2619 m; Site 465A: 2161 m) were probably at somewhat shallower depths than 2000 m during the Maestrichtian. The Maestrichtian paleolatitude of these two sites was between 5 and 15°N (Firstbrook et al., 1979).

Indian Ocean

The Indian Ocean samples include six specimens from two sites, Site 217A on the flank of the Ninety-East Ridge and Site 249 on the Mozambique Ridge. Specimens from Site 217A are Late Campanian—Early Maestrichtian in age and specimens from Site 249 are Early Maestrichtian in age. In both cases the specimens are from clayey nannofossil chalks. Shallow-water indicators recovered at Site 217 (Von der Borch, Sclater et al., 1974) suggest a Maestrichtian paleodepth of less than 1000 m. Site 249 on the Mozambique Ridge is at a water depth of 2088 m, but basement was not reached (Simpson, Schlich et al., 1974) and therefore paleodepths cannot be accurately constrained. A paleodepth of less than 2000 m is likely. The Maestrichtian—Campanian paleolatitude of Sites 217A and 249 were 20°S and 47°S, respectively, according to Firstbrook et al. (1979), but are both near 40°S according to Barron and Harrison (1980).

South Atlantic

The South Atlantic Ocean samples include thirty specimens from three sites, Site 21 on the Rio Grande Rise, Site 355 in the Brazil Basin and Site 530A in the Angola Basin. The specimens from Site 21 are of Late Campanian to Early Maestrichtian age. The specimens from Site 355 range in age from the Middle to Late Campanian. The specimens from Site 530A are from the Coniacian, Santonian, Early Campanian and Late Campanian—Early Maestrichtian. The specimens from Site 21 are from nannofossil—foraminiferal oozes while the specimens from Sites 355 and 530A occur in mudstones, claystones and marlstones. Based on shallow-water indicators at Site 21 on the Rio Grande Rise (Maxwell, Von Herzen et al., 1970), a paleodepth of approximately 500 m is suggested. The paleodepths at Sites 355 and 530A can be based on a standard thermal subsidence history of oceanic crust. The basement age of 78 m.y. at Site 355 (Perch-Nielsen, Supko et al., 1977) suggests a paleodepth of approximately 3000 m during the Middle to Late Campanian. The basement age of 102.5 m.y. at Site 530A (Hay, Sibuet et al., 1982) indicates that the Coniacian specimen was probably from a paleodepth greater than 3500 m. The majority of the specimens at Site 530A lived at depths greater than 4000 m. The paleolatitude of these sites are 35°S, 20°S and 20°S for Sites 21, 355 and 530A, respectively (Firstbrook et al., 1979; Barron and Harrison, 1980).

Summary

Although the selection of well-preserved specimens greatly reduced the spatial and temporal distribution of *Inoceramus* available for paleotemperature analysis, Campanian–Maestrichtian data are available from at least two cores from each of the Indian, Pacific and South Atlantic Oceans. These data also include a paleodepth range from 4000 m to less than 1000 m and a paleolatitude distribution from the Northern Hemisphere tropics to greater than 40°S. In addition the *Inoceramus* at Site 530A record a paleotemperature history from the Coniacian through the Maestrichtian.

ANALYTICAL METHODS

Samples were taken from the calcite prismatic layer of *Inoceramus* fragments either by breaking off pieces, prying free individual crystals or by drilling small holes in the shell with a high speed burr. No detectable isotope effects were associated with the drilling procedure.

Oxygen and carbon isotopic compositions were measured by analyzing CO₂ evolved by the reaction of samples and working standards (B-1 and NBS-20) with 100% H₃PO₄ at 50°C. Analyses were performed on a Micromass 602 ratio mass spectrometer, and the raw data were corrected following Craig (1957). The measurement technique has an accuracy of approximately

$\pm 0.05\text{‰}$. Analyses are reported relative to the PDB standard taking the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of B-1 to be $+0.29\text{‰}$ and $+0.32\text{‰}$, respectively, on the PDB scale, as determined by I. Friedman (U.S. Geological Survey).

ISOTOPIC RESULTS

Diagenetic trends

In order to evaluate the isotopic effects of diagenesis, analyses were performed on several *Inoceramus* samples from Site 530A which exhibited a variety of altered textures including recrystallization and overgrowth. Altered samples were strongly depleted in ^{18}O and moderately depleted in ^{13}C relative to well-preserved specimens of similar age. Well-preserved specimens at this site ranged from 1.1 to -2.6‰ in $\delta^{18}\text{O}$ and 1.9 to -1.25‰ in $\delta^{13}\text{C}$. Poorly preserved specimens yielded values as light as -6.75‰ in $\delta^{18}\text{O}$ and -3.2‰ in $\delta^{13}\text{C}$ (Barron et al., 1982).

The observed depletion in ^{18}O in diagenetic carbonates results from two effects: (1) increasing temperature with burial depth, and (2) pore water ^{18}O depletion due to the formation of authigenic silicates. The depletion in ^{13}C probably reflects the incorporation of isotopically light carbon released and oxidized during metabolism and diagenesis of organic matter. Similar isotopic trends have been observed in various types of carbonate sediments at several D.S.D.P. sites (Matter et al., 1975; Lawrence et al., 1975; Douglas and Savin, 1975).

Well-preserved specimens

All *Inoceramus* specimens were examined microscopically for evidence of post-depositional alteration. Only those samples showing no evidence of overgrowth, dissolution or recrystallization were selected for paleotemperature analysis. Oxygen and carbon isotopic measurements were made on 49 well-preserved Late Cretaceous *Inoceramus* specimens from the South Atlantic, Pacific and Indian Oceans. Isotopic variability within single specimens is only slightly greater than analytical error, on the order of a few tenths of a per mill or less. Multiple analyses of three *Inoceramus* specimens are presented in Table I. Such small variability is characteristic of *Inoceramus* fragments from D.S.D.P. cores and is consistent with a deep-sea habitat.

The isotopic results from all well-preserved specimens are shown in Fig. 1 and listed in Table II. There is relatively little variability in the data from each site, considering that the ages of the samples range over several million years at some sites. The data fall roughly into three groups, which do not correspond to ocean basins. Instead, the grouping appears more closely related to the paleodepth of the sites. The deepest site, 530A in the South Atlantic, has the lightest isotopic composition, with $\delta^{18}\text{O}$ values ranging from -0.91 to $+0.40\text{‰}$ and $\delta^{13}\text{C}$ values from $+0.39$ to 1.32‰ . The intermediate depth

TABLE I

Multiple analyses of single *Inoceramus* specimens showing internal isotopic variability (data are reported relative to the PDB standard, means and standard deviations are shown)

Leg	Site	Core	Section	Depth (cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
75	530A	79	5	140	-0.57	1.26
					-1.00	1.42
					-0.82	1.47
					-1.00	1.30
					-0.79	1.30
					-0.66	1.31
					-0.57	1.25
					-0.51	1.17
					-0.62	1.35
					mean -0.73 $\pm$ 0.19	1.31 $\pm$ 0.09
3	21	6	6	30-34	0.72	1.37
					0.83	1.41
					0.51	1.43
					0.74	1.31
					mean 0.70 $\pm$ 0.14	1.38 $\pm$ 0.05
39	355	17	4	95-96	1.19	2.41
					1.30	2.45
					1.42	2.42
					1.30	2.39
					mean 1.30 $\pm$ 0.09	2.42 $\pm$ 0.03

sites, South Atlantic Site 355 and Pacific Sites 48.2 and 465A, are isotopically heavy with $\delta^{18}\text{O}$ values from 0.66 to 1.88‰ and $\delta^{13}\text{C}$ values from 1.79 to 3.01‰. Samples from the shallowest sites, South Atlantic Site 21 and Indian Ocean Site 217A, exhibit isotopic compositions which lie between the other two groups, with $\delta^{18}\text{O}$ values from 0.44 to 1.19‰ and $\delta^{13}\text{C}$ values from 1.19 to 1.79‰ (excluding one anomalously heavy value). The paleo-depth of Indian Ocean Site 249 is only approximately constrained, because basement was not drilled. The isotopic composition of the one sample which was analyzed falls within the range of the shallow samples.

Paleotemperatures

Paleotemperatures were calculated from the oxygen isotope data using the equation of Epstein (unpublished manuscript; Yapp, 1979). The oxygen isotopic composition of mean ocean water during the Late Cretaceous was taken to be -1‰ relative to SMOW (Standard Mean Ocean Water), assuming polar ice volume to have been negligible at the time (Shackleton and Kennett,

Fig.1. Oxygen and carbon isotopic results from Late Cretaceous *Inoceramus* at seven D.S.D.P. sites.

1975). Fig.2 is a plot of the Late Cretaceous paleotemperature data as a function of paleolatitude and depth. The data are listed in Table I.

A striking feature of the data is the difference in paleotemperature between the Brazil Basin (Site 355) and Angola Basin (Site 530A) in the South Atlantic Ocean. Though considerably deeper, the Angola Basin bottom waters were warmer than those in the Brazil Basin. Fig.3 is a schematic representation of the South Atlantic paleotemperature data for two Late Campanian time intervals during which there are data from both basins. Clearly, the formation of bottom waters was different in the two basins and circulation between them was not sufficient to homogenize their properties.

In order to become dense enough to sink, the warm Angola Basin bottom waters must have been made saline by evaporation. Hence, they were probably enriched in $\delta^{18}\text{O}$ relative to mean ocean water. Therefore, the actual temperatures may have been warmer than the calculated paleotemperatures.

One factor which probably played an important role in determining the patterns of abyssal circulation in the Angola Basin is the isolation of its deep waters. The Angola Basin is bounded by Africa, the Romanche Fracture Zone, the Mid-Atlantic Ridge and the Walvis Ridge. During the mid-Cretaceous, sections of the Walvis Ridge were above sea level (Hay, Sibuet et al., 1982). Even today the Walvis Ridge is an impenetrable barrier to the northward flow of Antarctic Bottom Water. The circulation of Antarctic Bottom Water is also influenced by the Mid-Atlantic Ridge. In the Late Cretaceous, the Angola Basin deep waters were considerably more isolated than at present. A second factor is the presence of extensive epicontinental seas on Africa

TABLE II

Oxygen and carbon isotopic results from D.S.D.P. *Inoceramus* (data are reported relative to the PDB standard; paleotemperatures are calculated using the Epstein equation assuming a water $\delta^{18}\text{O}$ of -1% SMOW)

Leg	Site	Age	Core	Section	Depth (cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	Paleo- temperature (°C)
<i>South Atlantic</i>								
3	21	Late Campanian— Early Maestrichtian	4	5	105—107	1.09	1.24	8.0
			4	6	31—32	1.10	1.19	7.9
			5	2	73—75	0.83	1.32	8.9
			5	2	125—128	0.74	1.19	9.2
			5	3	93—99	0.63	1.51	9.6
			5	5	69—71	1.19	1.73	7.6
			5	6	53—56	0.66	1.49	9.5
			6	6	30—34	0.70	1.38	9.4
			6	6	58—61	0.44	1.73	10.4
			6	6	71—72	0.66	2.54	9.5
			6	6	106—107	0.69	1.50	9.5
			6	6	112	0.69	1.64	9.4
			6	6	114—116	0.55	1.55	10.0
			7	2A	143—145	0.87	1.41	8.8
39	355	Mid—Late Campanian	17	2	137—138	1.59	2.55	6.2
			17	4	95—96	1.30	2.42	7.2
			17	4	113—114	1.50	2.63	6.5
			18	1	104—105	0.66	2.63	9.5
			18	2	118—119	0.86	3.01	8.9
			18	3	83—84	1.14	2.35	7.8
			19	2	85—87	1.48	2.62	6.6
75	530A	Late Campanian— Early Maestrichtian	60	1	121—124	−0.27	0.80	13.1
			61	2	53—54	0.40	0.93	10.5
			61	2	56—57	−0.17	0.64	11.4
			61	2	65—66	−0.91	1.11	15.7
			61	2	78—81	−0.82	1.32	15.3
		Early Campanian Coniacian	63	1	37—40	0.20	1.07	11.3
			63	3	104—105	0.35	0.39	10.7
			79	5	140	−0.62	1.31	14.5
			89	1	88—89	−2.41	−1.27	22.2
			<i>Pacific</i>					
6	48.2	Maestrichtian	2	4	130	1.83	2.33	5.4
			2	4	138	1.75	2.34	5.6
			2	5	10	1.60	2.01	6.2
			2	5	88—89	1.61	2.44	6.1
			2	5	140—141	1.82	2.37	5.4
			2	6	10—11	1.86	2.30	5.3
			2	6	36—37	1.42	2.61	6.8
			2	6	40	1.34	2.63	7.1

(continued on p. 176)

TABLE II (continued)

Leg	Site	Age	Core	Section	Depth (cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	Paleo- temperature (°C)
62	465A	Maestrichtian	9	2	140	1.70	2.19	5.8
			9	3	2—3	1.84	2.03	5.3
			9	3	11—14	1.60	1.79	6.2
			9	3	51—53	1.71	1.86	5.8
			9	4	14—15	1.88	1.82	5.2
<i>Indian</i>								
22	217	Late Campanian—	28	3	0—2B	1.01	1.17	8.3
		Early Maestrichtian	28	3	29—30	0.67	1.41	9.5
			28	4	117—119	0.89	1.22	8.7
			28	6	100	0.91	1.34	8.6
			28	6	113	0.58	1.30	9.8
25	249	Early Maestrichtian	30	3	95	0.62	1.43	9.7

LATE CAMPANIAN-EARLY MAESTRICHTIAN PALEOTEMPERATURES

Fig.2. Oxygen isotope paleotemperature data from Late Cretaceous *Inoceramus* plotted as a function of reconstructed paleolatitude and paleodepth. The boxed values are from planktonic foraminifera from Saito and Van Donk (1974) and Boersma and Shackleton (1981).

SOUTH ATLANTIC PALEOTEMPERATURES-70-71 M.Y.

SOUTH ATLANTIC PALEOTEMPERATURES-71-72 M.Y.

Fig.3. Schematic cross-section of the Late Cretaceous South Atlantic Ocean showing paleotemperature data at two time intervals: above, 70–71 m.y.; below, 71–72 m.y.

CRETACEOUS PALEOTEMPERATURES
FROM INOCERAMUS: HOLE 530A

Fig.4. Oxygen isotope paleotemperature data from *Inoceramus* at Site 530A in the Angola Basin, South Atlantic Ocean.

during the Cretaceous. At this time much of the Angola Basin and its adjoining seas were located in the subtropics, which was then, as it is now, a zone of intense evaporation.

At present, Antarctic bottom waters flow northward into the Brazil Basin through deep fractures in the Rio Grande Rise. It is possible that during the Late Cretaceous these passageways were open, permitting exchange of waters between the Brazil and Argentine Basins. Bottom water temperatures in the Brazil Basin may have resulted from the mixing of warm salty Angola Basin bottom waters and cooler bottom waters from the south.

The warm Angola Basin temperatures evidently persisted for several million years as shown by the Santonian paleotemperature of 14.5°C. The Coniacian sample gave a value of 22.2°C (see Fig.4). This specimen was located adjacent to a black shale layer. The high paleotemperature may be an indication that during the Coniacian episode of increased carbon deposition, the Angola Basin was nearly isothermal.

Inoceramus from the equatorial Pacific sites gave paleotemperatures of 5–7°C. These relatively cool temperatures may be explained in one of two ways: (1) all Pacific deep water was produced by cooling at high latitudes, or (2) the temperatures measured are the result of mixing of cold polar deep water with warm salty low-latitude deep water. The first possibility yields an estimate of polar sea surface temperatures of around 5°C. This is consistent with sedimentologic and paleontologic evidence for warm poles during the Late Cretaceous. In the second case, polar temperatures must have been even cooler, a conclusion which may be difficult to reconcile with the high-latitude geologic record.

Inoceramus from two sites with paleodepths of less than 1000 m gave paleotemperatures of 8–10°C. These sites were located in the Indian (Site 249) and South Atlantic Oceans (Site 21) with paleolatitudes of 30–40°S. These *Inoceramus* paleotemperatures are cooler than surface water temperatures (17–20°C) at these latitudes as measured on planktonic foraminifera (Saito and Van Donk, 1974), but are warmer than those obtained from the deeper Pacific and Brazil Basin sites (48.2, 465A and 355). There are two plausible explanations for the *Inoceramus* temperatures at the shallow sites: (1) they simply reflect downward mixing of surface waters during colder months; (2) they indicate the presence of an intermediate water mass. Such a water mass might be formed by sinking of subpolar surface waters in the same way as Antarctic Intermediate Water forms today. From the limited data available it is not possible to distinguish between these alternatives.

A major obstacle to the interpretation of oxygen isotope paleotemperatures is our inability to differentiate between the effects of temperature and the isotopic composition of the water. Today, spatial variations in the $\delta^{18}\text{O}$ of the deep oceans are minor (Epstein and Mayeda, 1953; Craig and Gordon, 1965). This stems from the fact that deep water is formed almost exclusively by cooling and freezing at high latitudes, processes which do not involve isotopic fractionation. However, if deep waters were produced by evaporation

during warmer climates then, in the past, some water masses may have differed from the mean $\delta^{18}\text{O}$ of the oceans.

A rough estimate of the magnitude of this salinity effect may be obtained from the present-day Mediterranean Sea. The Mediterranean is enriched in $\delta^{18}\text{O}$ by a factor of 0.25‰ for each 1‰ increase in salinity relative to open ocean water (Epstein and Mayeda, 1953). In terms of paleotemperatures this effect amounts to a decrease of 1°C for an increase of 1‰ in salinity. Assuming that Cretaceous deep water formed at high latitudes had a temperature of 5°C and a salinity of 35‰, then subtropical waters of 15°C need only have been 3‰ more saline (39‰) to achieve equal density. The paleotemperature calculated for a calcite shell in equilibrium with this water would be 12°C, in error by only three degrees. Simple calculations such as this one show that evaporation reduces the apparent temperature signal of warm saline deep waters only slightly. Thus, in spite of the isotopic effect, paleotemperature measurements from deep waters formed by evaporation will always appear warmer than paleotemperatures from deep waters formed by cooling.

CONCLUSIONS

The oxygen isotope paleotemperature data from D.S.D.P. *Inoceramus* are consistent with the hypothesis that the organism lived in the deep sea and deposited its shell in oxygen isotopic equilibrium with ambient waters. In general, the data support sedimentological and paleontological evidence that the Late Cretaceous oceans were much warmer than today's ocean. In detail, the data provide a more complex picture of Late Cretaceous circulation than was previously assumed.

The picture of Late Cretaceous deep circulation which emerges from this study is one of great variability in the deep ocean compared to the present day. The data indicate that deep waters were formed both by cooling in polar regions and by evaporation in the subtropics. This contradicts the widely held belief that a reduced pole-to-equator temperature gradient necessarily implies a globally stagnant or sluggish deep circulation.

The effectiveness of a deep-water source is a function of both the density and the amount of water which it produces. This applies to both polar and subtropical source regions. In addition, the effectiveness of a subtropical source is determined by its area and evaporation rate. Equally important is the rate of return of fresh water to the region. For this reason the open ocean, even in the subtropics, is unlikely to produce deep water since most of the fresh water removed by evaporation is quickly returned by horizontal mixing from higher and lower latitudes. Thus, isolation of the source region is important. Marginal basins and epicontinental seas appear most likely to fulfil the necessary conditions, provided they do not receive appreciable continental runoff.

The input of fresh water to polar regions is an important constraint on the rate of deep-water formation by cooling. During periods of warm climate the

poleward flux of water vapor was probably much greater than today in order to balance the earth's heat budget (Manabe and Wetherald, 1980).

Thus, the formation rate of deep waters during the geologic past is a result of several factors rather than a simple function of the latitudinal temperature gradient. Although the mechanisms by which climate and paleogeography interact to influence thermohaline circulation are only beginning to be understood, they concur with the isotopic evidence from *Inoceramus* to describe a dynamic and highly variable deep-water circulation in Cretaceous oceans.

ACKNOWLEDGMENTS

We wish to thank D. A. Price, J. L. Sloan, G. W. Brass, C. Emiliani and W. W. Hay for helpful discussion and support and R. Douglas and M. Dinkleman for reviewing the manuscript. We also wish to thank the curatorial staff at Deep Sea Drilling Project for their strenuous efforts in our behalf. This research was supported by National Science Foundation grants OCE 81-11149 and OCE 81-11909 to the University of Miami. The National Center for Atmospheric Research is sponsored by the National Science Foundation. Contribution of the Rosenstiel School of Marine and Atmospheric Science, University of Miami.

REFERENCES

- Barron, E. J. and Harrison, C. G. A., 1980. An analysis of past plate motions: The South Atlantic and Indian Oceans. In: P. A. Davies and S. K. Runcorn (Editors), *Mechanisms of Continental Drift and Plate Tectonics*. Academic Press, London, pp. 89-109.
- Barron, E. J., Thompson, S. L. and Schneider, S. H., 1981. An ice-free Cretaceous? Results from climate model simulations. *Science*, 212: 501-508.
- Barron, E. H., Saltzman, E. S. and Price, D. A., 1982. *Inoceramus*: Occurrence in the South Atlantic and oxygen isotopic paleotemperatures at Hole 530A. Init. Rep. Deep Sea Drill. Proj., 75, in press.
- Berger, W. H., 1978. Impact of deep sea drilling on paleoceanography. In: M. Talwani et al. (Editors), *Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment*. Am. Geophys. Union, Washington, D.C., pp. 297-314.
- Boersma, A. and Shackleton, N. J., 1981. Oxygen and carbon isotope variations and planktonic foraminiferal depth habitats, Late Cretaceous to Paleocene, central Pacific DSDP sites 463 and 465. Init. Rep. Deep Sea Drill. Proj., 62: 513-527.
- Brass, G. W., Hay, W. W., Holser, W. T., Peterson, W. H., Saltzman, E. S., Sloan, J. L. and Southam, J. R., 1982. Ocean circulation, plate tectonics and climate. In: J. Crowell and W. Berger (Editors), *Pre-Pleistocene Climates*. National Research Council Report, in press.
- Craig, H., 1957. Isotopic standards for carbon and oxygen and correction factors for mass spectrometric analysis of carbon dioxide. *Geochim. Cosmochim. Acta*, 12: 133-149.
- Craig, H., 1965. The measurement of oxygen isotope paleotemperatures. In: *Stable Isotopes in Oceanographic Studies*. Consiglio Nazionale delle Ricerche, Pisa, pp. 1-24.
- Craig, H. and Gordon, L. I., 1965. In: E. Tongiorgi (Editor), *Stable Isotopes in Oceanographic Studies and Paleotemperatures*. Consiglio Nazionale delle Ricerche, Rome, pp. 9-130.
- Degens, E. T. and Stoffers, P., 1976. Stratified waters as a key to the past. *Nature*, 263: 22-26.

- Douglas, R. G. and Savin, S. M., 1971. Isotopic analysis of planktonic foraminifera from the Cenozoic of the northwest Pacific, Leg. 6. Init. Rep. Deep Sea Drill. Proj., 6: 691-708.
- Douglas, R. G. and Savin, S. M., 1973. Oxygen and carbon isotope analyses of Cretaceous and Tertiary foraminifera from the central north Pacific. Init. Rep. Deep Sea Drill. Proj., 17: 591-606.
- Douglas, R. G. and Savin, S. M., 1975. Oxygen and carbon isotope analyses of Tertiary and Cretaceous microfossils from Shatsky Rise and other sites in the north Pacific Ocean. Init. Rep. Deep Sea Drill. Proj., 32: 509-520.
- Epstein, S. and Mayeda, T., 1953. Variation of ^{18}O content of waters from natural sources. *Geochim. Cosmochim. Acta*, 4: 213-224.
- Firstbrook, T. L., Funnel, F. M., Hurley, A. M. and Smith, A. G., 1979. Paleocene Reconstructions 160-0 Ma. Deep Sea Drilling Project Publication, Scripps Institute of Oceanography, La Jolla, Calif., 41 pp.
- Hay, W. W., Sibuet, J. C., et al., 1982. Site 530. Init. Rep. Deep Sea Drill. Proj., 75.
- Lawrence, J. R., Gieskes, J. M. and Broecker, W. S., 1975. Oxygen isotope and cation composition of DSDP pore waters and the alteration of Layer II basalts. *Earth Planet. Sci. Lett.*, 27: 1-10.
- Lowenstam, H. A. and Epstein, S., 1954. Paleotemperatures of the post-Aptian Cretaceous as determined by the oxygen isotope method. *J. Geol.*, 62: 207-248.
- Manabe, S. and Wetherald, R. T., 1980. On the distribution of climate changes resulting from an increase in CO_2 content of the atmosphere. *J. Atmos. Sci.*, 37: 97-118.
- Margolis, S. V., Kroopnick, P. M. and Goodney, D. E., 1977. Cenozoic and late Mesozoic paleoceanographic and paleoglacial history recorded in circum-Antarctic deep-sea sediments. *Mar. Geol.*, 25: 131-147.
- Matter, A., Douglas, R. G. and Perch-Nielsen, K., 1975. Fossil preservation, geochemistry and diagenesis of pelagic carbonates from Shatsky Rise, northwest Pacific. Init. Rep. Deep Sea Drill. Proj., 32: 891-922.
- Maxwell, A. E., Von Herzen, R. P., et al., 1970. Site 21. Init. Rep. Deep Sea Drill. Proj., 3: 376-411.
- Perch-Nielsen, K., Supko, P., et al., 1977. Site 355: Brazil Basin. Init. Rep. Deep Sea Drill. Proj., 39: 101-120.
- Rye, D. M. and Sommer II, M. A., 1980. Reconstructing paleotemperature and paleosalinity regimes with oxygen isotopes. In: D. C. Rhoads and R. A. Lutz (Editors), *Skeletal Growth of Aquatic Organisms*. Plenum Press, New York, N.Y., pp. 169-202.
- Saito, T. and Van Donk, J., 1974. Oxygen and carbon isotope measurements of Late Cretaceous and Early Tertiary foraminifera. *Micropaleontology*, 20: 152-177.
- Schlanger, S. and Jenkyns, J. C., 1976. Cretaceous oceanic anoxic events: causes and consequences. *Geol. Mijnb.*, 55: 179-184.
- Shackleton, N.J. and Kennett, J.P., 1975. Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: Oxygen and carbon isotope analyses. Init. Rep. Deep Sea Drill. Proj., 29: 743-755.
- Simpson, E. S. W., Schlich, R., et al., 1974. Site 249. Init. Rep. Deep Sea Drill. Proj., 25: 287-348.
- Thiede, J. and Dinkelman, M. G., 1978. Occurrence of *Inoceramus* remains in Late Mesozoic pelagic and hemipelagic sediments. Init. Rep. Deep Sea Drill. Proj., 34: 899-910.
- Tourtelot, H. A. and Rye, R. O., 1969. Distribution of oxygen and carbon isotopes in fossils of Late Cretaceous age, western interior region of North America. *Geol. Soc. Am. Bull.*, 80: 1903-1922.
- Von der Borch, C. C., Sclater, J. G., et al., 1974. Site 217. Init. Rep. Deep Sea Drill. Proj., 22: 267-324.
- Yapp, C. R., 1979. Oxygen and carbon isotope measurements of land snail shell carbonate. *Geochim. Cosmochim. Acta*, 43: 629-635.