38. OCCURRENCE OF INOCERAMUS REMAINS IN LATE MESOZOIC PELAGIC AND HEMIPELAGIC SEDIMENTS

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ABSTRACT

Remains of the bivalve genus *Inoceramus* have long been known to occur in Cretaceous neritic marine sediments from many regions of the globe. In recent years, *Inoceramus* fragments and prisms have also been found in fine-grained hemipelagic and pelagic Mesozoic sediments sampled by the Deep Sea Drilling Project. A common characteristic of these occurrences is that they have been found most frequently in drill sites close to continental margins, though occurrences from open ocean paleoenvironments have also been reported. Since the *Inoceramus* fossils have been observed in sediments presently under several hundred to several thousand meters water depth, a re-evaluation of the paleoecology of this fossil group seems timely, especially with respect to paleodepth of deposition. It can be shown that *Inoceramus* was confined to the upper bathyal and neritic environments (continental and island slopes and shelves) where they lived as epibenthos on the substratum. In several regions these sediments indicate reducing conditions below the sediment/water interface.

INTRODUCTION

Macrofossils are relatively rare in the sediments recovered by the Deep Sea Drilling Project in the world ocean (see also Kauffman, 1976). Macrofossils occur in a number of drill sites where the nature of the sediments and their contained fossil assemblages indicate warm shallow-water environments at different times in geologic history. However, most of the reported macrofossil occurrences seem to be restricted to late Mesozoic pelagic and hemipelagic sediments and represent molluscs, largely cephalopods and bivalves. This fact is not so intriguing with respect to cephalopods because they belong largely to the marine nekton and their shells can drift over wide stretches of open ocean after they have died (Schäfer, 1962). The occurrences of remains of large bivalves, however, pose a different problem, since most marine bivalves are known to live on and in the sea bottom either as infauna, or as attached or free-living benthos in shallow to moderate water depths (Thorson, 1957).

Many of the large bivalve remains which have been found in oceanic Late Cretaceous sediments cored and sampled at sites drilled by the Deep Sea Drilling Project (see Table 1) belong to the genus *Inoceramus*. This genus, now extinct, produced a large number of widely used guide fossils in the epicontinental Late Cretaceous (Albian-Maestrichtian; Kauffman, 1968, 1969; Seitz, 1956). The *Inoceramus* shells are round to egg-shaped, both shells being asymmetric, as is common for many species belonging to genera closely related to *Inoceramus* (Müller, 1963). Most shells are ornamented with typcal concentric rings, and specimens of the Late Cretaceous *Inoceramus* frequently possess a very thick ostracum which can easily fall apart along the crystal boundaries of its large calcite prisms. The size of shells varies from a few centimeters to several decimenters in diameter.

Ecologically, *Inoceramus* is known to occur in a wide variety of continental and island margin marine paleoenvironments, in different water depths and on many different substrates. It is interesting to note that *Inoceramus* seems to have adapted to live as epibenthos on soft mud bottoms indicative of poorly oxygenated conditions, either in the sediment or in the overlying bottom water (Kauffman, 1967; Frey, 1972). It has also been suggested that *Inoceramidae* have their highest diversities in middle to outer shelf sediments (Kauffman, 1967), and that large thin and relatively flat shells are typical of species living on soft mud surfaces. Though recent relatives of *Inoceramus* (e.g., the bivalve genus *Isognomon*) live in warm temperate to tropical shallow waters, the apparently wider range of habitats occupied by *Inoceramus* indicates that this modern analog cannot be used to evaluate the paleoenvironment of the latter genus. However, *Inoceramus* might produce mero-planktonic planktotrophic larvae during its reproductive cycle, as oysters do for example

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TABLE 1
Listing of *Inoceramus* Occurrences in DSDP Sites up to Leg 43 (Compiled after DSDP Descriptions, as Listed in References of this Paper)

Vol.	Site	Core	Section	Appearance of *Inoceramus*	Latitude Longitude	Water Depth (m)	Sediment Depth (m)	Sediment Type	Age
3	21	4	4-6	Fragments and lower in core abundant prisms	28°35.10′S 30°35.85′W	2102	92	Nannofossil-chalk/ooze	Maestrichtian
	21	6	6	Common fragments			113.5-115		Campanian
	21	7	1-2	Abundant prisms			115-118		Campanian
	21	8	2+6	Common prisms			126-130.5		Campanian
6	47.2	13-14	All	Common to abundant shell fragments and prisms	32°26.9′N 157°42.7′E	2689	115-125	Nannofossil-chalk-ooze	Maestrichtian
	48.2	1	6	Rare to abundant fragments	32°24.5′N 158°01.3′E	2619	51-60	Nannofossil-chalk-ooze	Maestrichtian
	48.2	2	4-6	Large pieces of shells			64-66		Maestrichtian
4	105	33-38	Scattered throughout	Prisms of *Inoceramus*(?) found together with fragments of aptychi, parts of barnacles, rhyncholites, nepionic shells of bivalves, and holothurian skeletal elements	34°53.72′N 69°10.40′W	5251	576-612	Red and green (clayey) limestone	Kimeridgian to Valanginian-Tithonian
12	111A	11	1-6	Fragments and prisms, in some samples more than 50% of washed residue	50°25.57′N 46°22.05′W	1797	182-190	Moderately mottled chalk ooze	Lower to upper Maestrichtian
15	146	31	1-4	Few prisms	15°06.99′N 69°22.67′W	3949	656-665	Limestones with argillaceous matrix	Late Cretaceous (Santonian-Campanian)
21	204	6-8	Thoughout	Rare prismatic *Inoceramus*?sp. indet., fragments, up to 12 mm long; transportation from original site of deposition not ruled out	24°27.27′S 174°06.69′W	5354	131-138	Tuffaceous sandstone and conglomerate	(?Early) Cretaceous
22	211	12-14	Not specified	Varying abundances of prisms	09°46.53′S 102°41.95′E	5528	409-437.5	Clay-rich nanno ooze and nanno clay, laminated	Early Campanian to early Maestrichtian
22	217	23-25	Scattered throughout	Prisms and shell fragments	08°55.57′N 90°32.33′E	3030	478-591	Micarb chalk, partly shelly, chert	Campanian to mid-Maestrichtian
	217	36-37	Scattered throughout	Rare fragments			591-614.5	Dolarenite chert, some silicified and shell micarb chalk	Campanian
	217A	13	1	Shell fragments	08°55.57′N 90°32.33′E	3030	616-625.5	Chert, Micrite, Dolomite	Campanian
	217A	15	1	Occasional fragments			635-644.5	Chert, dolomite	Campanian
26	255	9-10	All	Thick prismatic fragments	31°07.87′S 93°43.72′E	1144	88-99	Limestones	Santonian

27	261	31-33	All	Abundant small prisms	12°56.83′S 117°53.56′E	5667	503.5-532	Semilithified claystone	Upper Jurassic (Oxfordian) to Lower Cretaceous (Valanginian)
	263	20-29	Not Specified	Fragments	23°19.43′S 110°58.81′E	5048	470-746	Olive-black semi-lithified silty quartz-bearing to quartz-rich silty claystone	?Aptian-upper Albian
30	288A	27-30	Not Specified	Common shell fragments	05°58.35′S 161°49.53′E	3000	932-988.5	Limestone and silicified limestone, interbedded with chert	Aptian-Albian
33	317A	8	Scattered throughout	Common large prisms	11°00.09′S 162°15.78′W	2598	601.5-611	Claystone nannofossil ooze black chert	Upper Albian-Cenomanian
	317A	9	1	Solitary prisms			611-620.5	Clayey micritic chalk to micritic nannofossil chalk	Lower-middle Albian
	317A	10	1	Some prismatic fragments			620.5-630	Micritic nannofossil chalk, chert layers	Barremian-Aptian
	317A	12 13	1	Large prismatic shell fragments			639.5-641	Nannofossil micritic limestone	Upper Aptian
36	327A	12	3	Fragments	50°52.28′S 46°47.02′W	2410	113	Nanno ooze to nanno foram micarb ooze	Maestrichtian
	327A	14	2-6 Particularly 5	Fragments and prisms			149-156.5	Zeolitic clay to silty clay interbedded with micarb ooze	Late Albian-Santonian
	327A	15 16	1-2 1-6	Fragments			176	Zeolite-rich nanno clay	Albian-Cenomanian
	330	1	1-6	Fragment and prisms	50°55.19′S 46°47.02′W	2636	129-138.5	Zeolite-rich nanno clay	Albian
		2	1	Fragments			176.5-178	Nanno claystone	Albian
	330	6	1-6	Fragments	50°55.19′S 46°53.00′W	2636	309.5-319	Olive-black zeolite-rich clay-claystone	Callovian-Oxfordian
	330	7	1-6	Prismatic fragments			319.5-328.5	Olive-black sapropelic zeolite-rich claystone	Callovian-Oxfordian
	330	8	1-4	Fragments			347.5-353.5	Olive-black zeolite rich claystone	Middle-Late Jurassic
39	356	34-38	Scattered throughout	Shells and prismatic pieces of ostracum up to several cm long	28°17.72′S 41°05.28′W	3175	513-655.6	Marly calcareous chalk	Santonian-late Campanian
	356	40	1-6	Occasional fragments			693.5-673.5	Calcareous mudstone	Late Turonian-Coniacian
	357	36-38	Scattered throughout	Shells and large pieces of ostracum	30°00.25′S 35°33.59′W	2086	607-673.5	Foram-nanno chalk and limestones	Early to late Campanian
	357	39-51	Scattered throughout	Prisms and fragments, up to 5 cm long			673.5-797	Gray marly chalk to silicified limestones	Coniacian to early Campanian

TABLE 1 – *Continued*

Vol.	Site	Core	Section	Appearance of *Inoceramus*	Latitude, Longitude	Water Depth (m)	Sediment Depth (m)	Sediment Type	Age
40	361	15	Core catcher	Fragment	35°03.97'S 15°26.91'E	4549	411.5	Bluish gray mudstone and brown claystone	Late Cretaceous
	364	13	2	Fragment	11°34'S 11°58'E	2448	398-400	Calcareous nannofossil chalk	Late Campanian-early Maestrichtian
	364	39	5	Large valves			967-976	Marly limestone and black shale	Late Aptian to early Albian
43	382	16	6	Prisms	34°25.04'N 56°32.25'W	5527	364.0	Variegated, laminated brownish clays, locally silty	Early Maestrichtian
	382	19	6	Plate	–	–	387.0	Marly limestone and calcareous claystone	Early Campanian

(Ockelmann, 1965). Studies of the distribution of living mero-planktonic planktotrophic bivalve larvae (Thiede, 1974) have also shown that this type of larval development is much more common in warm water regions of the ocean than in temperate or cold water environments; these larvae are photopositive, drifting most of the time close to the sea surface, and they are produced by species living in the upper few hundred meters of the water column (Thorson, 1965; Ockelmann, 1965). This mechanism might explain the rapid worldwide distribution of this genus during late Meoszoic times.

The finding of *Inoceramus* in sediments which are found at great depth in the ocean is not in agreement with the above facts. Several possibilities arise which will be evaluated using the occurrences of *Inoceramus* sampled in cores of the Deep Sea Drilling Project:

1) The *Inoceramus* could have been living in the deep sea during the late Mesozoic.

2) *Inoceramus* remains could have been displaced from shallow water regions into deep water environments.

3) The sediments and the contained *Inoceramus* remains have undergone vertical tectonic movements since their deposition.

INOCERAMUS IN LATE MESOZOIC DEEP SEA SEDIMENTS

The data reported and discussed here were taken from the Initial Reports of the Deep Sea Drilling Project, and for the most recent legs from the published report in Geotimes. It is critical to this project that no quantitative, only qualitative, descriptions of the occurrence of *Inoceramus* are available for several DSDP legs; it was therefore impossible in several instances to evaluate the occurrences to their full extent; this would have required redescription of the cores, impossible within the necessary time frame. All occurrences are listed in Table 1 and are described and discussed below; for further details the reader is referred to the source.

DSDP Leg 39 Occurrences

Let 39, Site 356 on the southern part of São Paulo Plateau (Southwest Atlantic Ocean off Brazil), Figure 1: *Inoceramus* shells and pieces of their thick prismatic ostracum up to severall centimeters long (Figure 2) are common constituents in laminated medium to dark gray calcareous mudstones and olive-gray dolomitic marly chalks of late Turonian (*Micula staurophora* Zone), Coniacian, Santonian to Campanian (*Tetralithus gothicus* Zone) age. Several clay pebble conglomerates in Core 39 indicate that portions of this sediment column have been displaced from nearby topographic highs. No other megafossils have been observed.

Leg 39, Site 357 on the western Rio Grande Rise (Southwest Atlantic Ocean), Figure 1: *Inoceramus* shells and large pieces of the ostracum have been observed in laminated medium to dark gray marly foraminifer nannofossil limestones of early Santonian (*Marthasterites furcatus* Zone) to late Campanian/early

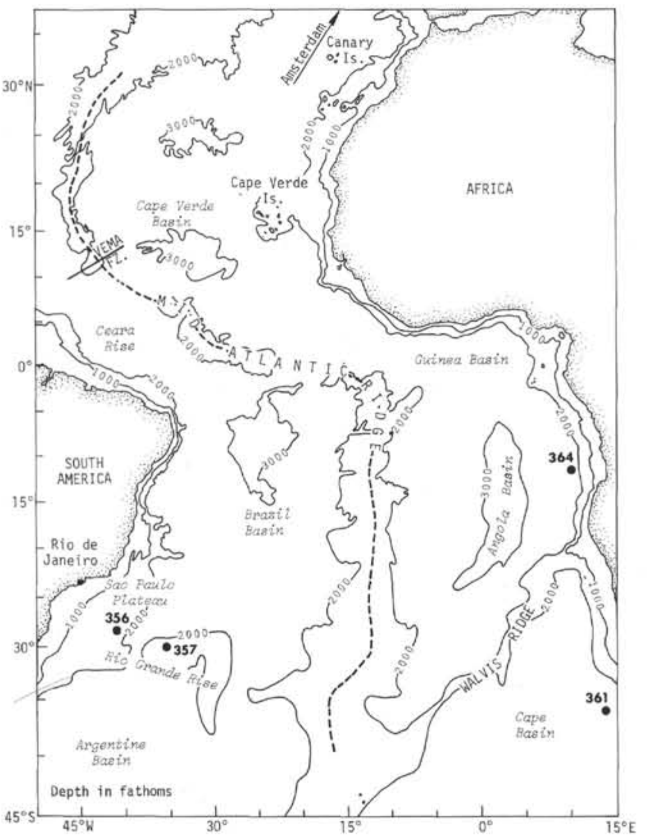

Figure 1. *Positions of drill sites with Cretaceous* Inoceramus-*bearing sediments occupied during Legs 39 and 40 of the Deep Sea Drilling Project.*

Maestrichtian (*Tetralithus trifidus* Zone) age (Figure 3). The abundance of *Inoceramus* has been plotted versus depth subbottom (Figure 4) illustrating that this fossil group is restricted almost entirely to the Santonian. These sediments are believed to have been deposited in an island slope/outer shelf sublittoral to bathyal environment a few hundred meters below the former sea surface (Thiede et al., 1975; Thiede, 1977). This interpretation is supported by evidence from benthic foraminiferal faunas (Sliter, this volume).

Observations of Previous DSDP Legs

The distribution of sites with *Inoceramus* in late Mesozoic sediments (Table 1) has been plotted in Figure 5. Some observations in the site reports are not clearly enough described to allow the identification of *Inoceramus*. Thus the discussion has been restricted to undisputable evidence, and all questionable occurrences are omitted. Exceptions are made for the reported occurrences in sediments recovered from DSDP Sites 105 and 211 where the authors believe the available evidence to be positive.

Leg 3, Site 21 (Maxwell, Von Herzen, et al., 1970) on the eastern part of Rio Grande Rise (Southwest Atlantic Ocean) Figure 5: *Inoceramus* remains have been observed in Campanian (*Planuglobulina glabrata* Zone) to Maestrichtian (*Rugotruncana subcircumnodifer* Zone) pink foraminiferal nannofossil chalks which are underlain by a Campanian/pre-Campanian coquina of unquestionable shallow water origin (as proven by the presence of remains of red algae). Whole shells of *Inoceramus* have been observed in several places in the Maestrichtian sediments, but in most instances the shells have disintegrated into large pieces or even into the calcitic prisms which are so typical of the *Inoceramus* ostracum. There is no evidence for redeposition, and it is believed that these *Inoceramus* lived in an island margin paleoenvironment (Thiede, 1977).

Leg 6, Site 47 (Heezen, Fischer, et al., 1971a) on the crest of the Shatsky Plateau (tropical Southwestern Pacific Ocean), Figure 5: *Inoceramus* shells are common in white foraminifer nannofossil oozes of Maestrichtian (*Globotruncana gansseri* = *Lithraphidites quadratus* Zone and *Abathomphalus mayaroensis* = *Tetralithus murus* Zone) age.

Leg 6, Site 48 (Heezen, Fischer, et al., 1971b) on the crest of Shatsky Plateau (tropical West Pacific Ocean), Figure 5: Prismatic *Inoceramus* fragments and whole shells have been observed in white nannofossil oozes of Maestrichtian (*Abathomphalus mayaroensis* = *Tetralithus murus* and *Globotruncana gansseri* = *Lithraphidites quadratus* Zones) age. No evidence for displacement has been reported. Shatsky Rise is a morphological feature which rises to less than 3000 m, while the surrounding sea floor is approximately 6000 meters deep (Heezen, Fischer, et al., 1971a).

Leg 11, Site 105 (Hollister, Ewing, et al., 1972) at the northern limit of Hatteras Abyssal Plain (Western North Atlantic), Figure 5: Prisms of *Inoceramus*(?) are found scattered throughout a red and green clayey limestone of Kimmeridgian to Tithonian age. The association of *Inoceramus*(?) with remains of pelagic crinoids and rare radiolarians suggest an upper bathyal environment.

Leg 12, Site 111 (Laughton, Berggren, et al., 1972) on Orphan Knoll off eastern Canada (Northwest Atlantic Ocean), Figure 5: *Inoceramus* fragments and prisms have been found in early to late Maestrichtian (*Globotruncana gansseri* = *Reinhardtites anthophorus* and *Globotruncana stuarti-G. contusa-Globotruncanella mayaroensis* = *Arkhangelskiella cymbiformis* Zones) white nannofossil oozes and chalks (Figure 6), which have been deposited in an outer neritic and upper bathyal paleoenvironment (van Hinte, 1972). These sediments are underlain by shallow water marine sediments capping the continental fragment of Orphan Knoll. *Inoceramus* make up more than 50% of the coarse fractions of several early and late Maestrichtian samples.

Leg 15, Site 146 (Edgar, Saunders, et al., 1973) in the Caribbean (Figure 5): Few *Inoceramus* prisms have been found in Late Cretaceous foraminiferal radiolarian limestones. No detailed age determination is available for Core 31 with *Inoceramus* remains, but this core is directly under- and overlain by Santonian (*Globorotruncana concavata carinata* Zone) sediments.

Leg 21, Site 204 (Burns, Andrews, et al., 1973) east of the Tonga Trench (Southwest Pacific Ocean) Figure 5: Up to 15 mm long white calcareous prisms have been found in tuffaceous pebbly granule conglomerates of probable Late Cretaceous age. It is not certain that

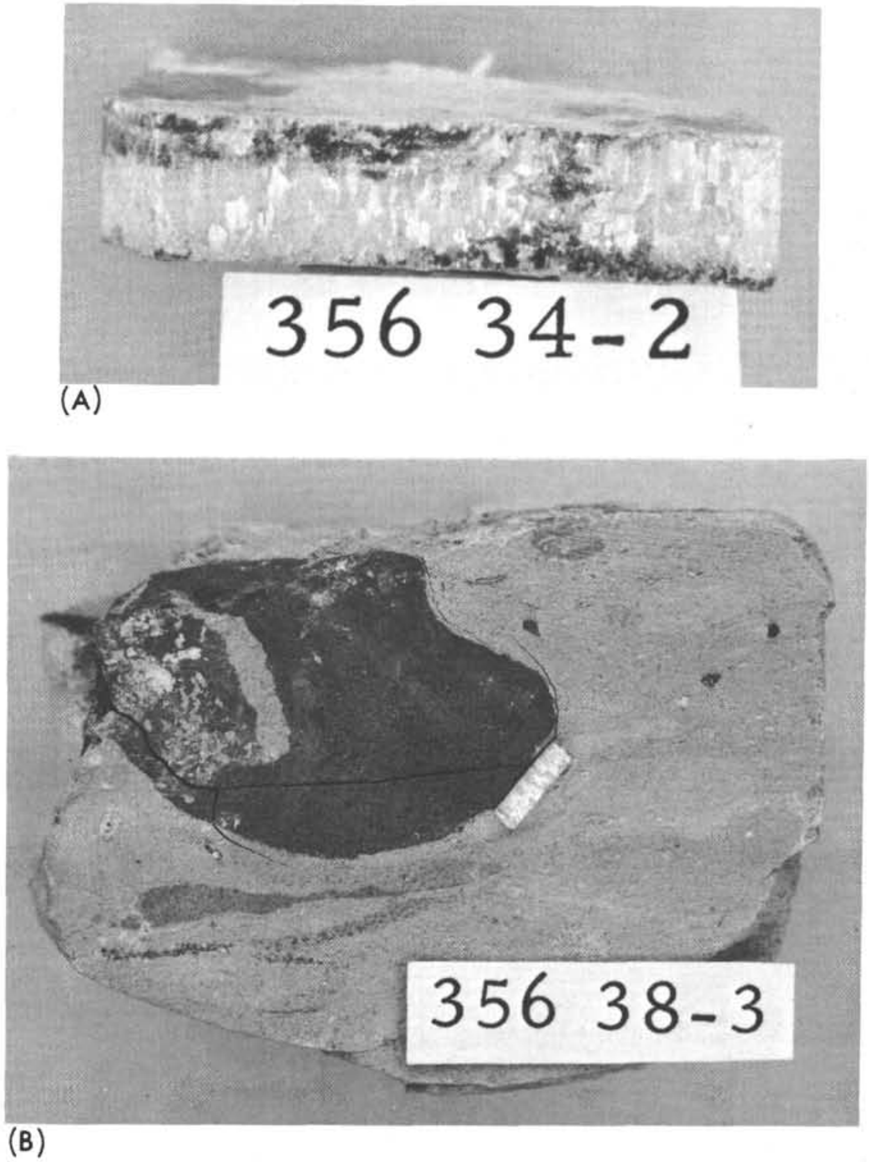

Figure 2. *Typical appearance of* Inoceramus *fragments in the sediments of Site 356 on the São Paulo Plateau. (A) from Core 34, Section 2; (B) from Core 38, Section 3. Scale: The numbers are 3 mm high.*

these prisms are *Inoceramus* remains, as similar shell structures are known from other thick-shelled bivalve taxa. Furthermore, sedimentary structures, and rounding and sorting of the sediment associated with *Inoceramus*, suggest displacement after deposition in a high energy environment.

Leg 22, Site 211 (von der Borch, Sclater, et al., 1974a) just south of the Java Trench and west of Christmas Island (Eastern Indian Ocean), Figure 5: Varying abundances of *Inoceramus* prisms have been found in variegated nannofossil oozes and clays of early Campanian to early Maestrichtian age (*Eiffellithus augustus* and *Tetralithus nitidus trifidus* zones). Interpretation of the calcareous microfossil assemblages allows for a depositional environment either on the inner shelf or on the upper slope. In the latter case it is conceivable that downslope movement has affected the sedimentary assemblages.

Leg 22, Site 217 (von der Borch, Sclater, et al., 1974b on the eastern flank of the northern Ninetyeast Ridge (East Indian Ocean), Figure 5: *Inoceramus* has been found together with other megafossils in shelly micarb chalks of Campanian to middle Maestrichtian age (*Globotruncanella mayaroensis* Zone; *Eiffellithus augustus-Tetralithus nitidus trifidus* zones) (Figure 7). Remains of *Inoceramus* and oysters make up 20%-30% of the total sediment; they are believed to indicate a relatively shallow paleoenvironment.

Leg 26, Site 255 (Davies, Luyendyk, et al., 1974) on Broken Ridge (Southeast Indian Ocean), Figure 5: *Inoceramus* remains have been detected in Late Cretaceous (= Santonian) (*Marthasterites furcatus* Zone) hard gray limestones with interbedded black cherts.

Leg 27, Site 261 (Heirtzler, Veevers, et al., 1974a) in Argo Abyssal Plain northwest off Australia (East

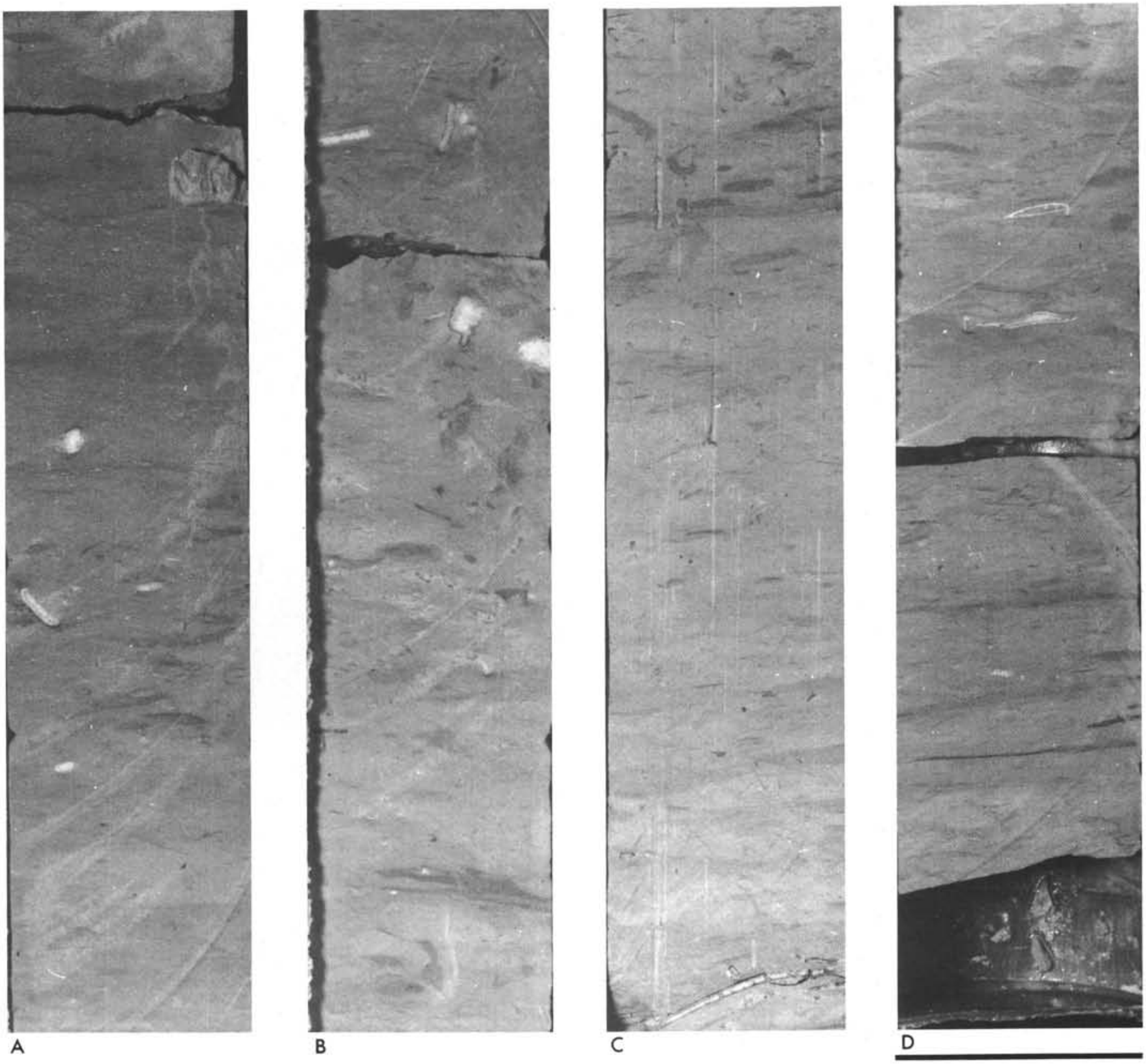

Figure 3. *Typical occurrences of* Inoceramus *remains in Santonian sediments from Site 357 on the western Rio Grande Rise (Core 47: (A) Section 4, 75-100 cm; (B) Section 4, 125-150 cm; (C) Section 5, 75-100 cm; (D) Section 6, 0-25 cm).*

Indian Ocean), Figure 5: Numerous small prisms of disintegrated *Inoceramus* occur in Kimmeridgian dark brown claystones (see also Speden, 1974). A shallow environment of deposition is inferred from faunal evidence.

Leg 27, Site 263 (Heirtzler, Veevers, et al., 1974b) on the eastern margin of Cuvier Abyssal Plain (Southeast Indian Ocean), Figure 5: *Inoceramus* fragments have been observed in olive-black semilithified quartz-bearing to quartz-rich laminated silty claystones of Cretaceous (Aptian?) age. The accompanying benthic foraminiferal faunas (Scheibnerová, 1974) indicate a shallow to extremely shallow marine paleoenvironment of probably <100 meters water depth.

Leg 30, Site 288, (Andrews, Packham, et al., 1975) on the eastern salient of the Ontong-Java Plateau (Western Pacific Ocean), Figure 5: *Inoceramus* shell fragments are common to abundant in laminated, partially silicified limestones interbedded with chert of Aptian to late Albian age (*Eiffellithus turriseiffeli* Zone). Faunal evidence indicates sedimentation well above the carbonate compensation depth.

Leg 33, Site 317, (Schlanger, Jackson, et al., 1976) on the Manihiki Plateau (Western Pacific Ocean), Figure 5: Unreplaced *Inoceramus* prisms are contained in black cherts (Core 8) of late Albian/Cenomanian age. Valves and prismatic fragments also occur in laminated and mottled light olive-gray nannofossil micritic lime-

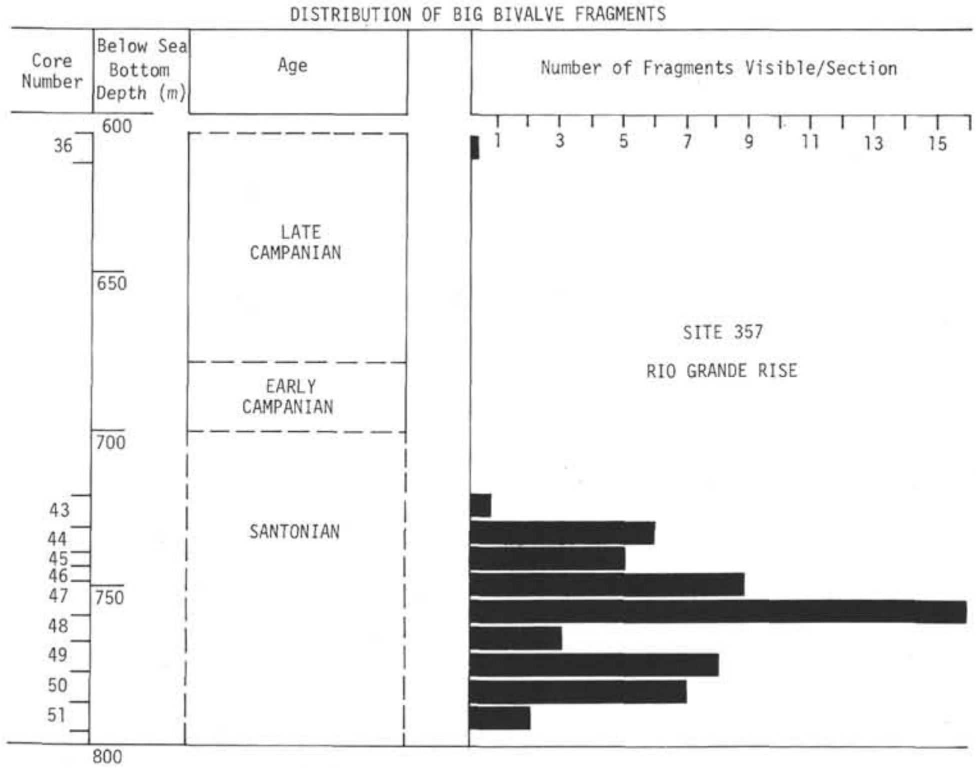

Figure 4. *Distribution of* Inoceramus *in Cretaceous sediments of Site 357 of the Deep Sea Drilling Project on the western Rio Grande Rise.*

stones of ? Barrêmian-Aptian (*Leupoldina cabri*, *Globigerinelloides algerianus*, *Hedbergella trocoida*, and *Ticinella roberti* zones) and early to middle Albian age. They overlie volcanogenic sand and siltstones of Early Cretaceous age which were probably deposited in relatively shallow water.

Leg 36, Site 327, (Barker, Dalziel, et al., 1976a) on the elevated eastern part of the Falkland Plateau (South Atlantic Ocean), Figure 5: This part of the Falkland Plateau was subaerial sometime before the Middle Jurassic (Barker, Dalziel, et al., 1974). *Inoceramus* fragments and numerous remains of thin-walled pelecypods have been found in early Albian to Santonian (*Prediscosphaera cretacea*/*Eiffellithus turriseiffeli*/*Lithraphidites alatas* zones) and Maestrichtian (*Nephrolithus frequens* Zone) zeolitic clays interbedded with micarb oozes and nannofossil-foraminifer micarb oozes. The zeolitic clays grade downward into light to olive-gray nannofossil chalks in which thin-walled pelecypod tests are common. The common occurrence of pelecypods may imply an upper bathyal environment of deposition.

Leg 36, Site 330 (Barker, Dalziel, et al., 1976b) on the elevated eastern part of the Falkland Plateau (South Atlantic Ocean), Figure 5: This hole bottomed in gneisses and granites which are overlain by Middle and Late Jurassic sand- and siltstones with lignites. *Inoceramus* remains have been observed enclosed in early-middle Albian (*Prediscosphaera cretacea* Zone) nannofossil clays which overlie sapropelic claystones of Neocomian and Aptian age. *Inoceramus* has also been mentioned in sapropelic claystones of Callovian-Oxfordian age (*Vekshinella stradneri* Zone), where they are associated with thin-shelled pelecypods and belemnite rostra. The nature of the sedimentary record is suggestive of a continental shelf environment.

Observations in Post Leg 39 DSDP Drill Sites

Leg 40, Site 361 (Bolli, Ryan, et al., in press,a) near the base of the southwest African continental rise, Figure 5: A fragment was found in grayish brown shale of Late Cretaceous age. The inferred environment of deposition is bathyal.

Leg 40, Site 364 (Bolli, Ryan, et al., in press, b) in the Angola Basin on the southwest African continental margin (Figure 5): *Inoceramus* have been observed in late Campanian to early Maestrichtian (*Tetralithus trifidus* Zone) brownish to reddish calcareous marly, nannofossil chalks (Bolli, Ryan, et al., 1975). They have also been found in late Aptian to early Albian (*Globigerinelloides algerianus* = *Parhabdolithus angustus* Zone) chalks and limestones together with ammonites. It seems surprising that no *Inoceramus* have been observed in Site 363 (E Walvis Ridge) (Bolli, Ryan, et al., in press, c) though it samples sediments corresponding in age and facies to *Inoceramus* bearing deposits at Sites 356 and 357 sediments in the western South Atlantic Ocean (see above).

Leg 43, Site 382 (Tucholke, Vogt et al., 1975) near Nashville Seamount in the western North Atlantic (Figure 5): *Inoceramus* prisms occur in variegated, laminated brownish clays and claystones of late Campanian-early Maestrichtian age (*Globotruncana arca* Zone). Coarser beds contain silt- and sand-sized grains of zeolites and volcanic glass. *Inoceramus* plates also occur in marly limestone and calcareous claystone of early Campanian age (*Globotruncana elevata* Zone). These marly limestones and calcareous claystones are interbedded with thicker volcaniclastic breccias which show occasional cross-bedding and one example of reversed grading. The highly vesicular nature of the basalt clasts in the breccias indicate extrusion in less than 1000 meters of water. Downslope displacement of the volcaniclastic detritus, possibly as massive slumps, is suggested by the admixtures of fresh to highly altered clasts (Tucholke, personal communication, 1976).

No *Inoceramus* have been mentioned in the available descriptions of sites drilled on Legs 41, 42, and 44.

THE PALEOENVIRONMENT OF THE LATE MESOZOIC INOCERAMUS-BEARING PELAGIC AND HEMIPELAGIC SEDIMENTS

Distance to Continents and Islands

As evident from the descriptions, most sites (Table 1, Figure 5) where *Inoceramus* has been observed are situated close to continents, oceanic islands, former islands, or at least on former shoals. This is well documented for the drill sites on Rio Grande Rise (Thiede, 1977), on Ninetyeast Ridge (Pimm et al., 1974), on Orphan Knoll (van Hinte, 1972), on Cuvier Plateau (Scheibnerová, 1974), on the Falkland Plateau (Barker, Dalziel, et al., 1976a and b), and in the Caribbean (Edgar, Saunders, et al., 1973). However, it is less well understood in drill sites on anomalous oceanic crust, such as the Ontong-Java Plateau (Andrews, Packham, et al., 1975) the Manihiki Plateau (Schlanger, Jackson, et al., 1976), and the Shatsky Rise (Heezen, Fischer, et al., 1971a, b), though it can be assumed that these rises subside in a fashion similar to normal oceanic crust (Detrick et al., 1977) and that they were close to the sea surface during late Mesozoic time.

The worldwide distribution of the epibenthic *Inoceramus*, which has not only been found in continental margin drill sites but also in sites on isolated oceanic islands, is in agreement with the assumption that this genus developed mero-planktonic larvae during its reproductive cycle. These larvae usually live only a few weeks before they try to find a substratum suitable to settle on; however, if they are not successful in doing that, they might be able to remain planktonic for several additional months, as has been observed for larvae of Recent benthic gastropods (Scheltema, 1971), thus allowing them more time to find a suitable environment to complete their development to adult molluscs.

Type of Substratum

Sediments containing *Inoceramus* are usually relatively fine grained biogenic oozes or terrigenous muds which in many cases are known to overlie sediments indisputably deposited in very shallow water. Unlike the case of many outcrops of shallow water marine sediments of late Mesozoic age (Kauffman, 1967; Frey, 1972), the *Inoceramus* in deep-sea drill cores are usually not accompanied by a wealth of other benthic megafossils (however, see also Kauffman, 1975). They have been found in ocean sediments

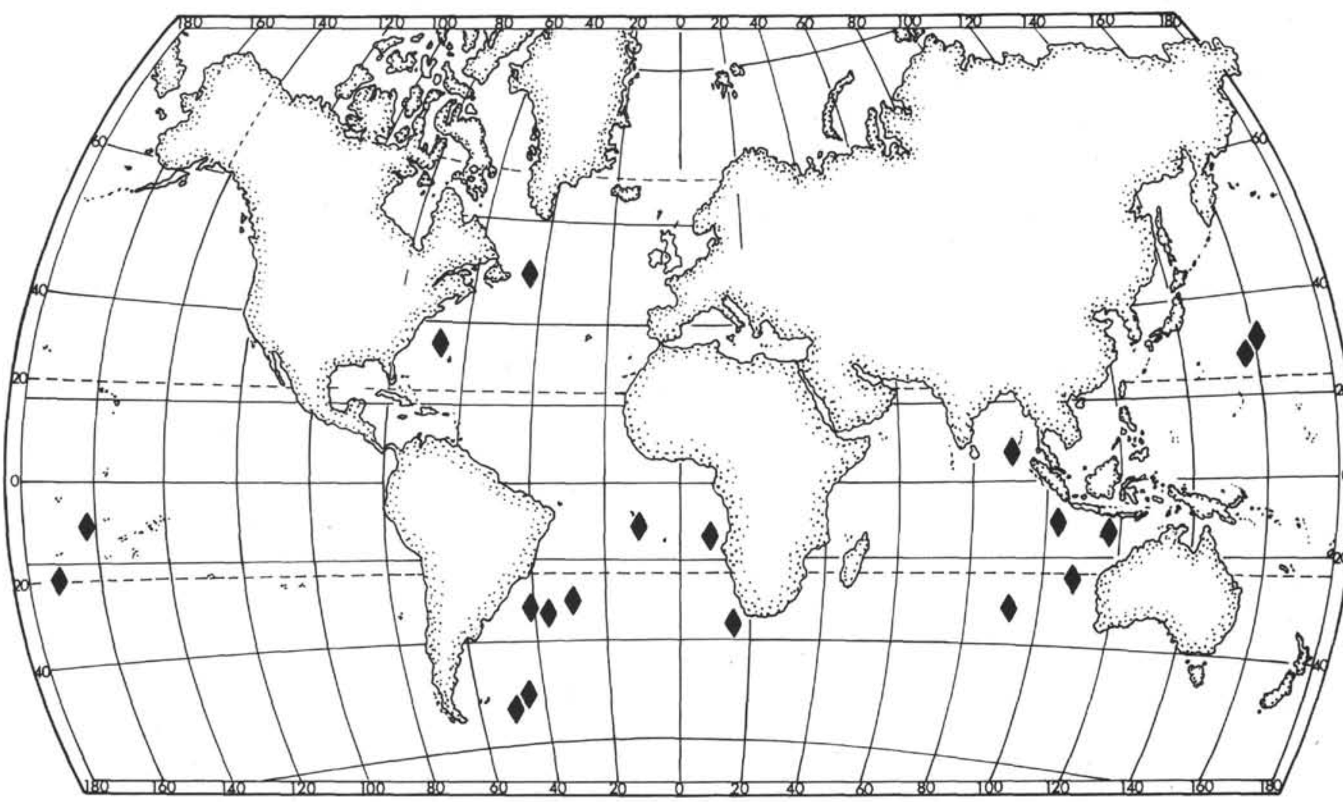

Figure 5. *Positions of Deep Sea Drilling Project sites with Late Cretaceous* Inoceramus-*bearing sediments (see Table 1).*

obviously deposited under well oxygenated conditions, such as at Sites 364 (Bolli, Ryan, et al., 1975), though the majority of *Inoceramus* occurrences have been reported from laminated, dark mudstones and chalks which must have been deposited under reducing conditions, resulting in the scarcity of a benthic infauna. Since *Inoceramus* is believed to belong to the benthic epifauna and to be autochthonous, the interface between anaerobic and aerobic conditions must have been at the sediment/water interface.

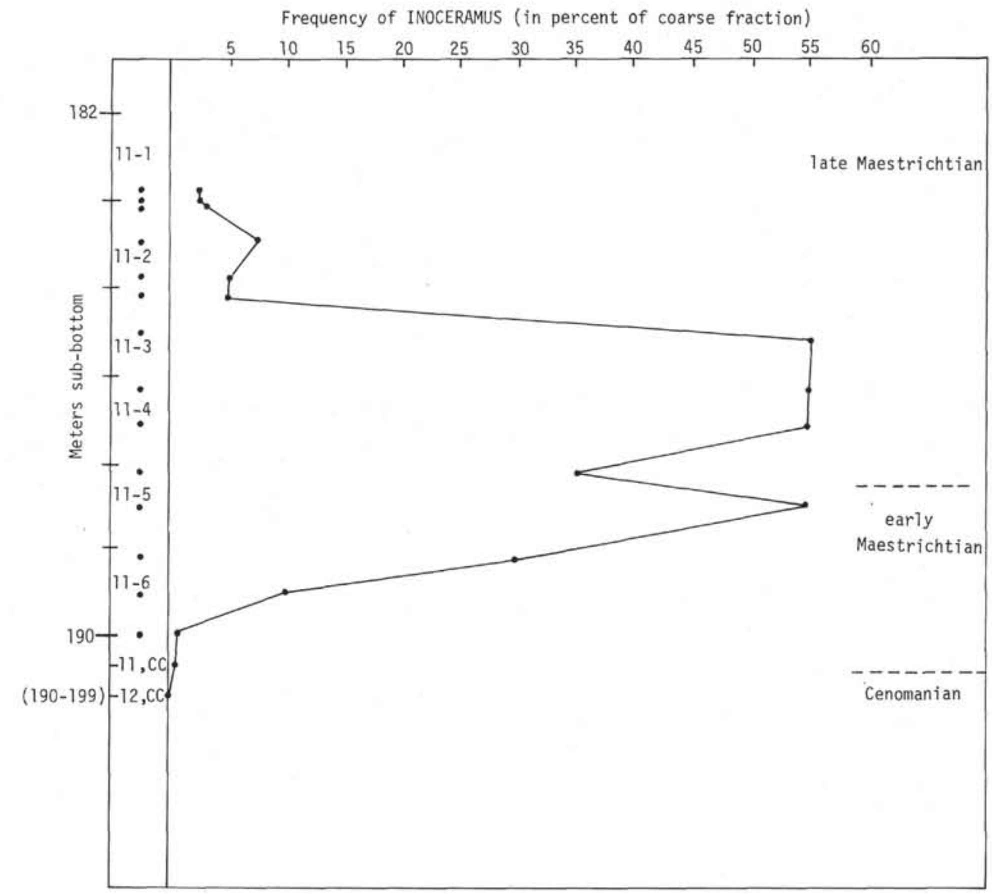

Figure 6. *Distribution of* Inoceramus *remains in Maestrichtian sediments from Orphan Knoll, Northwest Atlantic Ocean (after van Hinte, 1972). The sediments directly above Core 12-111A-11 are of early Eocene age; a major hiatus is suspected between Cores 10 and 11 of Hole 111A (Laughton, Berggren, et al., 1972).*

Paleodepth

The water depth of time of deposition of many of the *Inoceramus*-bearing sediments remains an open question because many sites are either on anomalous oceanic crust, on continental crust, or close to the continental margin above a crystalline basement of unknown age and nature (Table 1). Attempts to reconstruct the water depth at time of deposition of these sediments have been carried out for the sites on Rio Grande Rise (Thiede, 1977), on Ninetyeast Ridge (Pimm et al., 1974), Orphan Knoll (van Hinte, 1972), and Cuvier Plateau (Scheibnerová, 1974); all seem to point to a relatively shallow depth (maximum 500 m, minimum 100-200 m) at time of deposition of these sediments. These reconstructions are probably correct because aseismic ridges seem to subside in a fashion similar to regular oceanic crust (Detrick et al., 1977). They are similarly successful for drill sites located on relatively small slices of continental crust surrounded by normal oceanic crust, i.e., Sites 327 and 330. At present the paleodepth of deposition of many continental margin sites cannot be reconstructed in the same detail, since their history of subsidence is not fully understood (Kinsman, 1974), since crystalline basement below them has not been sampled.

The fact that *Inoceramus* has been observed at several drill sites in sediments which have been deposited under reducing conditions is in agreement with the previously discussed paleodepth information (Thiede and van Andel, 1977). Sediments on the upper continental slope and on the outer shelf in certain regions are known to resemble those deposited under reducing conditions since they are deposited under bottom waters of reduced oxygen contents (oceanic midwater oxygen minimum) and since their contents and accumulation rates of organic matter are high compared to the open pelagic environment (van Andel, 1964). Oxidation of

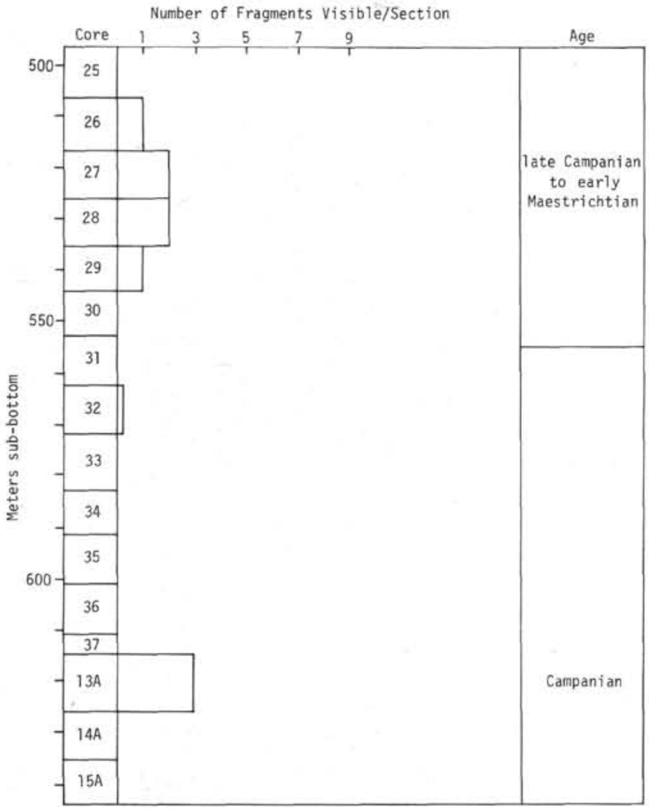

Figure 7. *Distribution of* Inoceramus *remains in Campanian to early Maestrichtian sediments from Holes 217 and 217A on the eastern flank of the northern Ninetyeast Ridge (von der Borch, Sclater, et al., 1974b).*

the organic matter depletes the available oxygen already at the sediment/water interface. This creates a reducing environment below this interface, but allows an epibenthic life on top of the sediments, including *Inoceramus*.

CONCLUSIONS

1. Remains belonging to the extinct genus *Inoceramus* have been found in deep-sea drill cores from the Atlantic, Pacific, and Indian oceans.

2. All occurrences can be linked to a paleoenvironment close to continental and island margins or on shoal areas in the open ocean. The worldwide distribution of habitats of *Inoceramus* and the occupation of isolated biotopes in the pelagic realm suggest that *Inoceramus* developed larvae such as their recent relatives do. During the mero-planktonic stage of development, such larvae can drift across wide open ocean regions.

3. *Inoceramus*, which is known to occur together with rich megafossil faunas in many late Mesozoic marine shallow water paleoenvironments in continental platform deposits, invaded the sublittoral-upper bathyal region of the ocean. Since *Inoceramus* belonged to the epibenthos, it was even able to occupy sediments under reducing conditions below the sediment-water interface. Sediments of this type are known to occur in regions where the oceanic midwater oxygen minimum is impinging upon shallow areas.

4. *Inoceramus* can therefore be used as a sensible paleodepth indicator in pelagic and hemipelagic sediments where this genus represents the sole megafossil.

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REFERENCES

Andrews, J.E., Packham, G., et al., 1975. Site 288. *In* Andrews, J.E., Packham, G., et al., Initial Reports of the Deep Sea Drilling Project, Volume 30: Washington (U.S. Government Printing Office), p. 175-229.

Barker, P.F., Dalziel, I.D.W., et al., 1974. Leg 36: Geotimes, v. 10, no. 11, p. 16-18.

———, 1976a. Site 327. *In* Barker, P.F., Dalziel, I.D.W., et al., Initial Reports of the Deep Sea Drilling Project, Volume 36: Washington (U.S. Government Printing Office), p.

———, 1976b. Site 330. *In* Barker, P.F., Dalziel, I.D.W., et al., Initial Reports of the Deep Sea Drilling Project, Volume 36: Washington (U.S. Government Printing Office), p.

Bolli, H.M., Ryan, B.F., et al., 1975. Basins and margins of the eastern South Atlantic: Geotimes, v. 20, no. 6, p. 22-24.

———, in press (a). Site 361. *In* Bolli, H.M., Ryan, W.B.F., et al., Initial Reports of the Drilling Project, Volume 40: Washington (U.S. Government Printing Office).

———, in press (b). Site 364. *In* Bolli, H.M., Ryan, W.B.F., et al., Initial Reports of the Deep Sea Drilling Project, Volume 40: Washington (U.S. Government Printing Office).

———, in press (c). Site 363. *In* Bolli, H.M., Ryan, W.B.F., et al., Initial Reports of the Deep Sea Drilling Project, Volume 40: Washington (U.S. Government Printing Office).

Burns, A.E., Andrews, J.E., et al., 1973. Site 204. *In* Burns, A.E., Andrews, J.E., et al., Initial Reports of the Deep Sea Drilling Project, Volume 21: Washington (U.S. Government Printing Office), p. 33-56.

Davies, T.A., Luyendyk, B.P., et al., 1974. Site 255: *In* Davies, T.A., Luyendyk, B.P., et al., Initial Reports of the Deep Sea Drilling Project, Volume 26: Washington (U.S. Government Printing Office), p. 281-294.

Detrick, R.S., Sclater, J.G., and Thiede, J., in press. Subsidence of aseismic ridges: Earth Planet. Sci. Lett.

Edgar, N.T., Saunders, J.B., et al., 1973. Site 146/149. *In* Edgar, N.T., Saunders, J.B., et al., Initial Reports of the Deep Sea Drilling Project, Volume 15: Washington (U.S. Government Printing Office), p. 17-168.

Frey, R.W., 1972. Paleoecology and depositional environment of Fort Hays limestone member, Niobrara chalk (upper Cretaceous), west-central Kansas: Univ. Kansas Paleont. Contrib. Art. 58 (Cretaceous 3).

Heezen, B.C., Fischer, A.G., et al., 1971a. Site 47. *In* Fischer, A.G., Heezen, B.C., et al., Initial Reports of the Deep Sea Drilling Project, Volume 6: Washington (U.S. Government Printing Office), p. 67-143.

———, 1971b. Site 48. *In* Fischer, A.G., Heezen, B.C., et al., Initial Reports of the Deep Sea Drilling Project, Volume 6: Washington (U.S. Government Printing Office), p. 145-169.

Heirtzler, J.R., Veevers, J.J., et al., 1974a. Site 261. *In* Heirtzler, J.R., Veevers, J.J., et al., Initial Reports of the Deep Sea Drilling Project, Volume 27: Washington (U.S. Government Printing Office), p. 129-192.

———, 1974b. Site 263. *In* Heirtzler, J.R., Veevers, J.J., et al., Initial Reports of the Deep Sea Drilling Project, Volume 27: Washington (U.S. Government Printing Office), p. 279-335.

Hollister, C.D., Ewing, J.I., et al., 1972. Site 105. *In* Hollister, C.D., Ewing, J.I., et al., Initial Reports of the Deep Sea Drilling Project, Volume 11: Washington (U.S. Government Printing Office), p. 219-312.

Kauffman, E.G., 1967. Coloradoan macroinvertebrate assemblages, central Western Interior, United States. *In* Kauffman, E.G. and Kent, H.C. (Eds.), Paleoenvironments of the Cretaceous Seaway—A Symposium: Golden Colorado (Colorado School of Mines), p. 67-143.

———, 1968. The Upper Cretaceous *Inoceramus* of Puerto Rico: Transact. 4. Caribbean Geol. Conf. (Port-of-Spain, Trinidad, 1965): Trinidad and Tobago (Caribbean Printers), p. 203-218.

———, 1969. Population systematics, radiometrics and zonation: the new biostratigraphy: Chicago J. Paleontol., v. 43, p. 890.

———, 1976. Deep-sea Cretaceous macrofossils: Hole 317A, Manihiki Plateau. *In* Jackson, E.D., Schlanger, S.O., et al., Initial Reports of the Deep Sea Drilling Project, Volume 33: Washington (U.S. Government Printing Office), p. 503-535.

Kinsman, D.J.J., 1974. Rift valley basins and sedimentary history of trailing continental margins. *In* Fischer, A.G., Judson, S. (Eds.), Petroleum and global tectonics: Princeton (Princeton University Press), p. 83-126.

Lancelot, Y., Seibold, E., et al., 1975. The eastern North Atlantic: Geotimes, v. 20, no. 7, p. 18-21.

Laughton, A.S., Berggren, W.A., et al., 1972. Site 111. *In* Laughton, A.S., Berggren, W.A., et al., Initial Reports of the Deep Sea Drilling Project, Volume 12: Washington (U.S. Government Printing Office), p. 33-159.

Maxwell, A.E., von Herzen, R.P., et al., 1970. Site 21. *In* Maxwell, A.E., von Herzen, R.P., et al., Initial Reports of the Deep Sea Drilling Project, Volume 3: Washington (U.S. Government Printing Office), p. 367-411.

Müller, A.H., 1963. Lehrbuch der Paläozoologie. Vol. II. Invertebraten. Pt. 1. Protozoa-Mollusca I: Jena (VEB Gustav Fischer Verlag).

Ockelmann, K.W., 1965. Developmental types in marine bivalves and their distribution along the Atlantic coast of Europe: Proc. I. Europ. Malac. Congr. (1962), p. 25-35.

Pimm, A.C., McGowran, B., and Gartner, S., 1974. Early sinking history of Ninetyeast Ridge, northeastern Indian Ocean: Geol. Soc. Am. Bull., v. 85, p. 1219-1224.

Schäffer, W., 1962. Aktuo-Paläontologie nach Studien in der Nordsee: Frankfurt/M (Verlag Waldemar Kramer).

Scheibnerovâ, V., 1974. Aptian-Albian benthonic foraminifera from DSDP Leg 27, Sites 259, 260, and 263, eastern Indian Ocean. *In* Heirtzler, J.R., Veevers, J.J., et al., Initial Reports of the Deep Sea Drilling Project, Volume 27: Washington (U.S. Government Printing Office), p. 697-741.

Scheltema, R., 1971. The dispersal of the larvae of shoal-water benthic invertebrate species over long distances by ocean currents. Proc. 4. *In* Crisp, D.J. (Ed.), Europ. Mar. Biol. Symp.: Cambridge (Cambridge University Press), p. 7-28.

Schlanger, S.O., Jackson, E.D., et al., 1976. Site 317. *In* Jackson, E.D., Schlanger, S.O., et al., Initial Reports of the Deep Sea Drilling Project, Volume 33: Washington (U.S. Government Printing Office), p. 161-300.

Seitz, O., 1956. Über Ontogenie, Variabilität und Biostratigraphie einiger Inoceramen: Paläont. Z., v. 20, p. 3-6.

Speden, I.G., 1974. Cretaceous Bivalvia from cores, Leg 27. *In* HeirtzlerQ J.R., Veevers, J.J., et al., Initial Reports of the Deep Sea Drilling Project, Volume 27: Washington (U.S. Government Printing Office), p. 977-981.

Thiede, J., 1974. Marine bivalves; Distribution of meroplanktonic shell-bearing larvae in eastern North Atlantic surface waters: Palaeogeogr., Palaeoclimat., Palaeoecol., v. 15, p. 267-290.

———, in press. The subsidence of aseismic ridges: Evidence from sediments on Rio Grande Rise (S.W. Atlantic Ocean): Am. Assoc. Petrol. Geol. Bull.

Thiede, J., et al., 1975. Sediments on Rio Grande Rise (SW Atlantic Ocean): Subsidence of an aseismic ridge: Nice, France, 9. Congr. Internat. Sediment., v. 8, p. 67-70.

Thiede, J. and van Andel, T.H., 1977. The paleoenvironment of anaerobic sediments in the late Mesozoic South Atlantic Ocean: Earth Planet. Sci. Lett., v.33, p.301-309.

Thorson, G., 1957. Bottom communities (sublittoral or shallow shelf): Geol. Soc. Am. Mem., v. 67, p. 461-534.

———, 1965. The distribution of benthic marine mollusca along the NE Atlantic shelf from Gibraltar to Murmansk: Proc. 1. Europ. Malac. Congr. (1962), p. 5-23.

Tucholke, B., Vogt, P.R., et al., 1975. *Glomar Challenger* drills in the North Atlantic, Geotimes, v. 20, no. 12, p. 18-21.

van Andel, T.H., 1964. Recent marine sediments of the Gulf of California; Am. Assoc. Petrol. Geol. Mem., v. 3, p. 216-310.

van Hinte, J.E., 1972. List of selected Mesozoic planktonic and benthonic foraminifera and ostracoda, and conclusions on age and environment. *In* Laughton, A.S., Berggren, W.A., et al., Initial Reports of the Deep Sea Drilling Project, Volume 12: Washington (U.S. Government Printing Office), p. 115-119.

von der Borch, C.C., Sclater, J.G., et al., 1974a. Site 211. *In* von der Borch, C.C., Sclater, J.G. et al., Initial Reports of the Deep Sea Drilling Project, Volume 22: Washington (U.S. Government Printing Office), p. 13-36.

von der Borch, C.C., Sclater, J.G., et al., 1974b. Site 217. *In* von der Borch, C.C., Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project, Volume 22: Washington (U.S. Government Printing Office), p. 267-324.