GEOLOGICAL CONSTRAINTS FOR TECTONIC MODELS OF THE ALPHA RIDGE

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ABSTRACT

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Initial interpretations of the CESAR geological samples are re-examined in light of new data from the Alpha Ridge and circum-Arctic region. A composite stratigraphy for the CESAR and Fletcher Island (T-3) pre-Neogene cores shows a sequence of Campanian-Maastrichtian organic-rich terrigenous mud overlain by Maastrichtian-Eocene biosiliceous marine deposits with a low organic content, terminating in volcanoclastic mudstone of Late Eocene age. CESAR core 6 contains a transition zone in which biosiliceous sediment is replaced by volcanoclastic and terrigenous sediment of Paleocene-Eocene age. Palynomorphs provide a Late Eocene age for the volcanic outcrop dredged from Northern Alpha Ridge. Textural and geochemical studies of laminated biosiliceous sediments were made with special techniques for quantitative analyses of very small samples (1-10 mg) and particle sizes of less than 5 microns. Results show that the laminated sediments were deposited very slowly in an oxidizing environment. Laminae in CESAR core 6 mainly reflect cyclical variations in the formation and/or accumulation of particulate iron, probably due to periodic hydrothermal venting. Absence of detrital sediment, sparsity of pyroclastic material and lack of diagenetic alteration of the biogenic sediments suggest that the eastern Alpha Ridge was not an area of major tectonic activity during the Eurekan Orogeny, from ca. 80-40 Ma.

INTRODUCTION

Geological samples collected during CESAR provide direct and indirect evidence of the age, composition, paleobathymetry and diagenetic history of sediments on the Alpha Ridge. These data, when correlated with other stratigraphic records from the Alpha Ridge and the circum-Arctic region,

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impose some constraints to which tectonic models of Arctic Ocean evolution must conform in order to satisfy all available scientific observations.

Preliminary interpretations of the CESAR geological samples were published in various initial reports (Jackson *et al.*, 1985) and synthesised by Mudie and Jackson (1985). These reports, which were completed in 1984, have been used in studies of the tectonic evolution of the Alpha Ridge (e.g. Ricketts *et al.*, 1985; Forsyth *et al.*, 1986). The main purposes of this paper are to review the initial reports in light of new studies made since 1984, and to discuss the limitations of tectonic constraints that are imposed by these geological data. We also draw attention to special techniques needed for quantitative analysis of the small amounts of material available from the Alpha Ridge cores and dredge samples, and the need for further studies of key samples from CESAR and other Alpha Ridge areas. We hope that this paper will lead to a more uniform data base for detailed comparisons between various Alpha Ridge oceanic samples and geological samples from onshore areas of the circum-Arctric region.

AGE CONSTRAINTS

Altough it is possible to infer an Aptian-Santonian age (119-84 Ma) for the Alpha Ridge, based on interpretation of the relationship between topography and magnetic anomalies (Jackson, 1985), or by interpolation of dated volcanoclastic formations in the Sverdrup Basin (Sweeney, 1985; Ricketts *et al.*, 1985), the only direct evidence for the Ridge age comes from biostratigraphic dating of a bedrock sample (Mudie, 1985) and from the age of the oldest sediment overlying bedrock. Only 4 cores from the Alpha Ridge (Figure 1) contain fossiliferous sediments of pre-Neogene age: CESAR core 6, Fletcher Island (=T-3) cores F1-437, -422 and -533. Datable microfossils in these cores include several types of siliceous fossils (silicoflagellates, diatoms and archeomonads) and organic-walled microfossils (dinoflagellates, acritarchs and pollen). Of these microfossils, only the pollen are present in all lithofacies of all the cores, as well as in the Alpha Ridge bedrock sample and in type sections of the Canadian Arctic Archipelago. The pollen in the Arctic Ocean samples represent terrestrial material that was transported offshore by wind or water; therefore, guide species can be directly correlated with those in the Sverdrup Basin and related continental rocks. In contrast, correlation of the marine fossils is limited by the difficulty of comparing the offshore polar ocean assemblages from the Alpha Ridge with nearshore biofacies found in the Sverdrup Basin and Western Siberia (Bukry, 1985). Furthermore, radiolarians are the main siliceous microfossils that have been studied in Sverdrup Basin marine

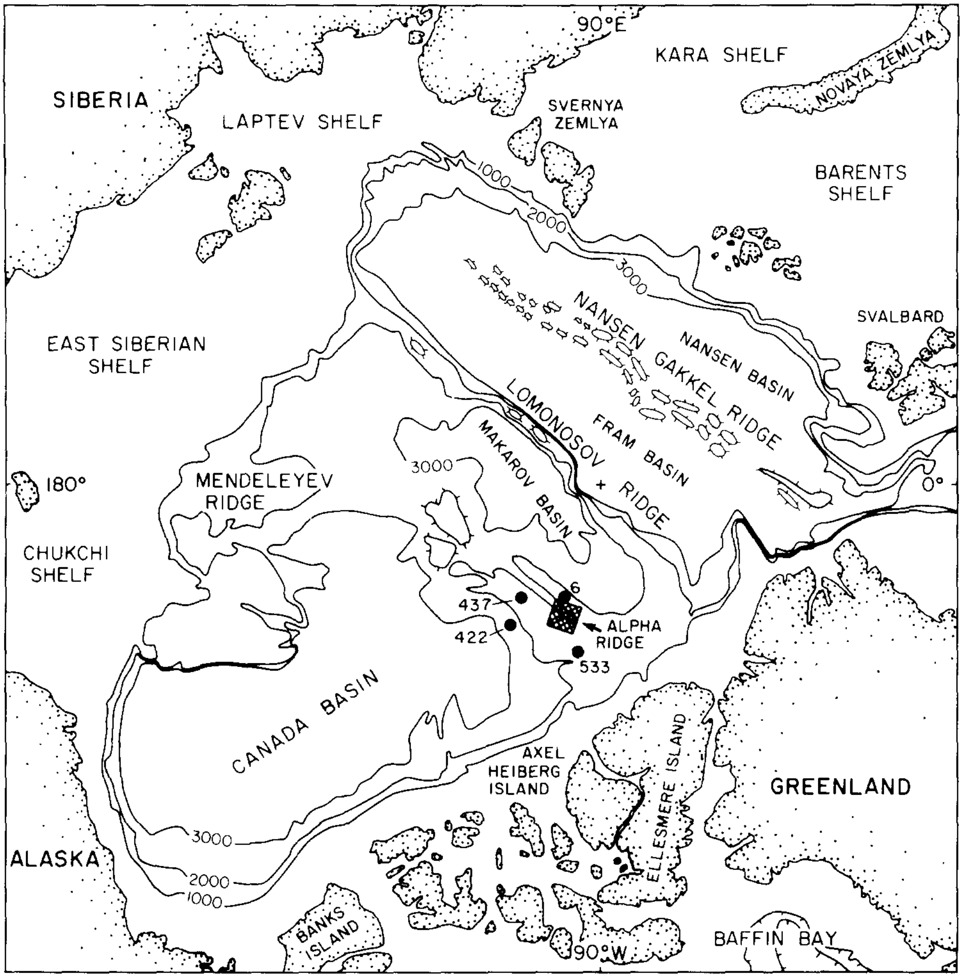

Fig. 1. Map of the Arctic Ocean showing the locations of CESAR core 6, and Fletcher Island cores 422, 437 and 533. Crosshatching marks the CESAR study area.

deposits, and these fossils do not occur in the Alpha Ridge sediments. The best known Sverdrup Basin microfossils are foraminifera, but these are not present in pre-Neogene Alpha Ridge sediments.

Figure 2 summarizes the biochronological data reported for pre-Neogene Alpha Ridge samples. Salient features of these data are:

1. good agreement between ages (Maastrichtian-Middle Eocene) that were obtained independently from the palynomorphs (Mudie, 1985) and the silicoflagellates (Ling *et al.*, 1973; Bukry, 1981; 1984; 1985);
2. the significantly older Late Campanian age assigned to diatoms in CESAR core 6 by Barron (1985).

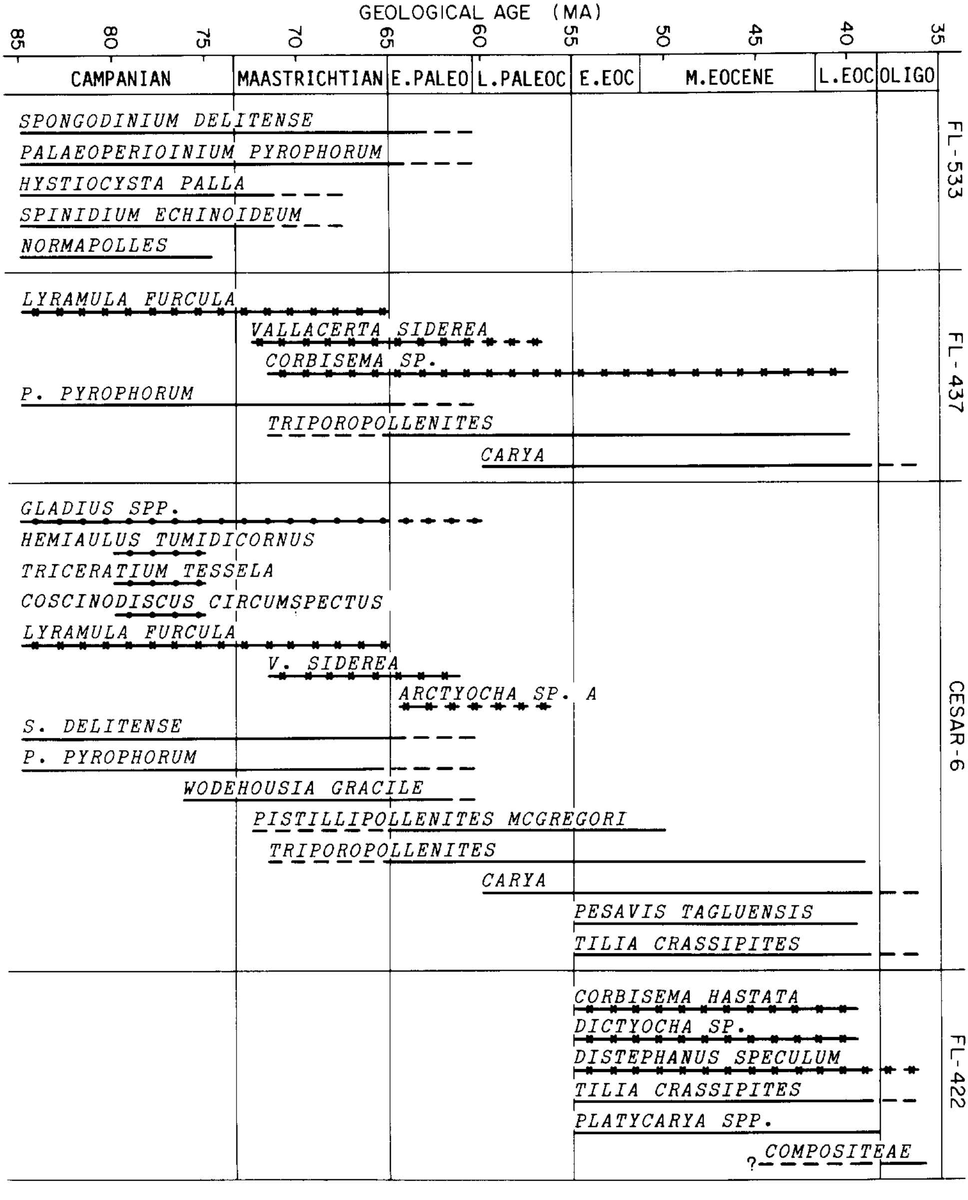

Fig. 2. Summary of microfossil data used to assign ages to the Alpha Ridge cores, showing the stratigraphic ranges of guide species designated by the following symbols:
---- Palynomorphs; X-X- Silicoflagellates; o-o-o Diatoms.

The diatoms are abundant and very well preserved. It is therefore unlikely that they are reworked in the Alpha Ridge samples, but it is possible that they had a longer stratigraphic range in the Cretaceous-Paleogene polar sea than in the nearest reference section, the Ural Mountains, 60–68°N. Several other data sources conflict with a Campanian age for the biosiliceous ooze in CESAR core 6. First, the paleomagnetic record for this sediment shows a sequence of five normal and reversed polarity events (Aksu, 1985), whereas the Late Campanian epoch is globally marked by a long "quiet" interval of uninterrupted normal polarity. Secondly, the Campanian-Maastrichtian sediments in F1-533 (Clark and Byers, 1984) do not contain diatoms like those in CESAR core 6. Thirdly, new studies of diatoms in biosiliceous sediments of F1-437 (Kitchell *et al.*, in press) indicate that there is little difference between the "Campanian" diatom flora in CESAR core 6 and the Maastrichtian-Paleocene assemblages in the core from the CESAR South Ridge. It may also be important that microfossil assemblages containing some of the Alpha Ridge guide fossils (*Gladius speciosus*, *G. pacificus*, *Pseudopyxilla americanus* and *Dictyota spinosa*) occur in tuffaceous sediments on Banks Island (Vincent *et al.*, 1983; Mudie, unpubl. data) where K/Ar and $_{19}$Ar/$_{18}$Ar dating of the tuff gives a Paleocene age of ca. 60 Ma (R. Westgate, pers. comm., 1984).

This combined evidence not only fails to support a Campanian age for the CESAR biosiliceous ooze, but it also raises important questions about the presumed Cretaceous age of the bedrock dredged from the CESAR North Ridge (Van Wagoner and Robinson, 1985). Palynomorphs from the matrix in the centre of one bedrock clast include well preserved pollen of *Tilia*, *Carya*, *Platycarya*, and *Compositae* which have maximum ages of middle Paleocene (60 Ma) to late Eocene (42 Ma). A similar pollen assemblage occurs in core F1-422 for which silicoflagellates provide a well constrained Eocene age (Bukry, 1981). The good preservation of these palynomorphs and the absence of species of mixed ages makes it unlikely that the pollen were incorporated into the bedrock by post-depositional processes. The age of the bedrock sampled on the CESAR North Ridge must therefore be set as Late Eocene.

A composite stratigraphy for the pre-Neogene Alpha Ridge sediments (Figure 3) shows a logical sequence of ages and lithofacies. This sequence commences with a black organic-rich sapropelic mud at the base of F1-533, which contains abundant pollen and dinoflagellates; rare foraminiferal organic linings are present but no other marine biota. Palynomorphs were independently dated as Campanian-Maastrichtian by Williams (1984) and Singh (pers. comm., 1984). The same palynomorph assemblage is found in a 20 cm-thick bed of yellow ?tuff (yellow and gray laminated siliceous sediment) at the top of the black mud.

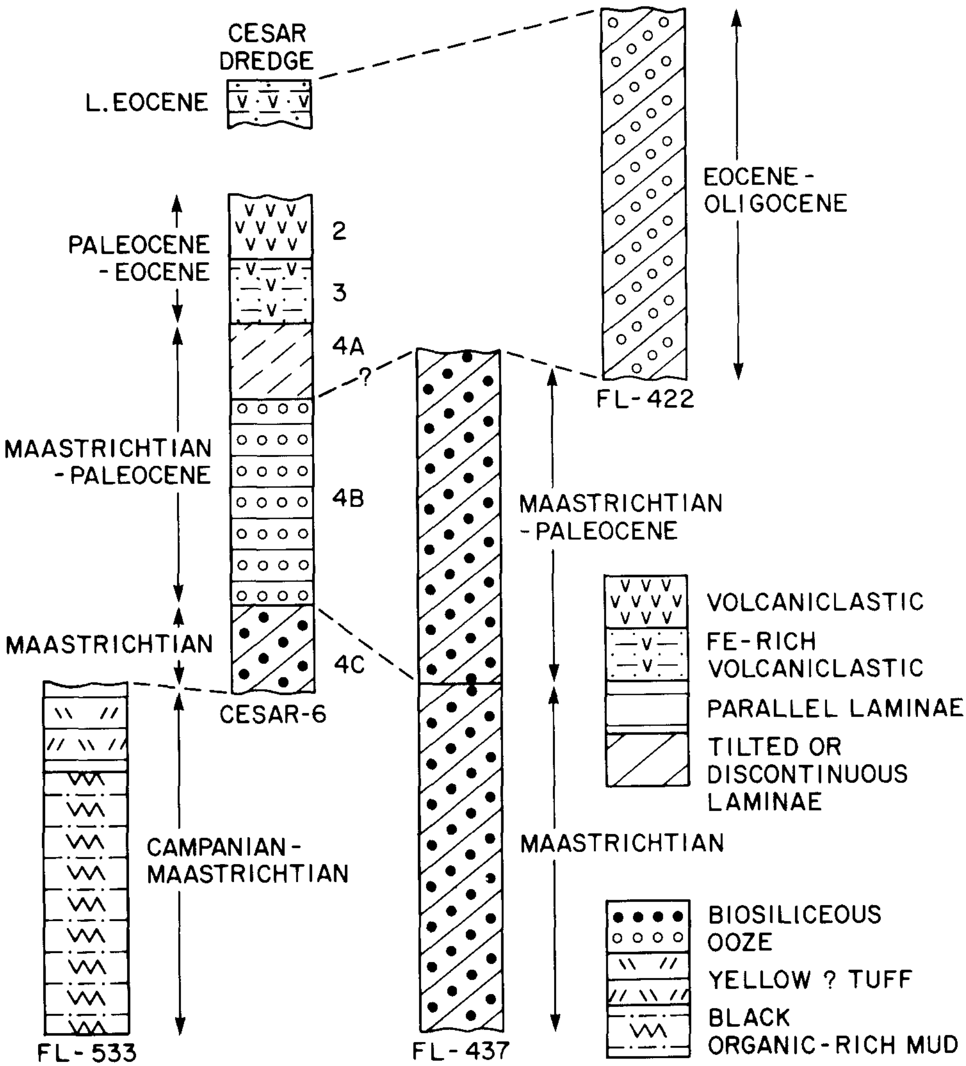

Fig. 3. Lithostratigraphy and biostratigraphic ages of the pre-Neogene Alpha Ridge sediments and bedrock sample, showing probable chronological correlations. Numbers next to CESAR-6 indicate lithological units of Mudie and Blasco (1985).

Sediment at the base of CESAR core 6 (subunit 4C) contains a mixture of well-preserved Maastrichtian-Danian palynomorphs and poorly preserved, probably reworked Albian-Campanian pollen and spores. Sediment at the base of subunit 4C is reddish brown biosiliceous ooze with common plant fragments and glass shards. Two well known late Cretaceous guide fossils, *Lyramula furcula* and *Rhizosolenia cretacea*, disappear at or just above the top of this subunit. In the other Cretaceous biosiliceous sediments, *L. fur-*

cula has its last occurence at or just below the Cretaceous-Tertiary boundary (Bukry, 1985). The last occurence of *L. furcula* also occurs in the middle of the orange-yellow to brown siliceous sediment in F1-437 (Bukry, 1981). These marine guide fossils presently provide the best means of correlating the biosiliceous sediments in the Alpha Ridge cores, and their Maastrichtian age assignment is further supported by the concurent disappearance of the Cretaceous dinoflagellate genus *Spongodinium*.

The exact age of the overlying biosiliceous sediments in F1-437 and CESAR-6, subunits 4B, A, is less certain because diagnostic siliceous microfossils are absent. The presence of abundant *Vallacerta siderea* and the absence of Paleogene guide fossils e.g. *Corbisema* and *Dictyota*, suggests that most of the laminated sediment in CESAR-6 subunit 4B and F1-437 represents a transition between the reddish brown Late Cretaceous lithofacies and the orange-yellow biosiliceous sediments of F1-422 which contain microfossils and palynomorphs of Middle-Late Eocene or Oligocene age (Bukry, 1984; Mudie, 1985). Diatoms in the upper half of core F1-437 have Campanian-Paleocene age ranges (Kitchell *et al.*, in press). Palynomorphs from the top of F1-437 and from subunit 4B to the base of Unit 2 in CESAR-6 show a disappearance of common Late Cretaceous-Paleogene species such as *Wodehousia gracile* and *Pistillipollenites mcgregorii*, and the first occurrences of common Late Paleocene species e.g. *Platycarya* and *Carya*. Units 2 and 3 contain pollen and dinoflagellates of Eocene to Oligocene age. The age of the biosiliceous ooze in core F1-422 therefore coincides with the palynological ages of Units 2 and 3 in CESAR-6 and with the age of the CESAR bedrock sample.

SEDIMENTOLOGICAL AND GEOCHEMICAL CONSTRAINTS

Pre-Neogene sediments from the Alpha Ridge cores have been described as including terrigenous mud (F1-533; Clark and Byers, 1984), tuffaceous lutite or biogenic siliceous ooze (F1-437, -422; Clark, 1974), biosiliceous ooze overlain by volcanoclastic sediment (CESAR core 6; Mudie and Blasco, 1985), and volcanoclastic rock containing 90% highly altered, glassy alkali basalt clasts with clinopyroxene phenocrysts (CESAR bedrock sample; Van Wagoner and Robinson, 1985). To date, only the CESAR samples have been described and illustrated in detail (Jackson and Mudie, 1984; Mudie and Blasco, 1985; Van Wagoner and Robinson, 1985; Stoffyn-Egli, in prep.). In an effort to make a lithological comparison of the cores, however, Table I was compiled using the CESAR data and summary descriptions of the Fletcher Island cores (Clark, 1974; Kitchell and Clark, 1982; Clark and Byers, 1984; Kitchell *et al.*, in press).

TABLE I

Summary of dominant visual characteristics, mineral content and organic particulates in pre-Neogene sediments of Alpha Ridge cores.

	Color	Bedding	Biogenic Silica	Amorphous Silica	Clay	VG	ROM	Fish Bones	Micro-Spherules
FL-533:									
348 – 288 cm	Black	None	–	–	A	–	A	–	ND
288 – 268 cm	Yellow-gray	Parallel	–	C	R	ND	C	ND	ND
FL-437:									
293 – 130 cm	Reddish-brown	45°	VA	+	R-C	+	ND	A	ND
130 – 12 cm	Orange-yellow c dark clasts	45°	VA	+	-/C	+	C	A	–
FL-422:									
	Orange-yellow c rare dark clasts	rare, 20°	A	+	F	+	R	–	–
CESAR-6:									
4C, 305 – 296 cm	Reddish-brown -yellow gray	0–30°	VA	+	R	R-C	C	C	–
4B, 296 – 167 cm	White/yellow to brown	0–20°	VA	VR	–	VR	R	–	–
4A, 167 – 125.0 cm	Yellow to	0–45°	A/-	R-C	-/C	R-C	R	R-A	-/A
3, 125 – 107 cm	Reddish brown	trace	–	–	A	R	VR	–	–
2, 107 – 99 cm	Light gray	–	–	–	A	C	VR	R	–

LEGEND: VG = Volcanic Glass; ROM = Refractive organic matter (kerogen); VA = Very abundant; A = Abundant; C = Common; R = Rare.

The most conspicuous feature of the pre-Neogene Alpha Ridge sediments in cores F1-437, -422 and CESAR core 6 is the abundance of well-preserved biosiliceous microfossils that comprise between 45% and 90% of the bulk sediment. X-ray diffraction study of samples from cores F1-437 and -422 (Kitchell and Clark, 1982) supports the observations (Mudie and Blasco, 1985) that the biogenic silica has not been transformed from Opal-A to Opal-CT. This lack of diagenetic alteration indicates that the sediments have not been heated above ca. 35°C (Siever, 1983) or covered by more than 400 m of overburden (Isaacs, 1981). Palynomorphs in the Campanian-Maastrichtian sediment of F1-533 also show little evidence of diagenetic alteration as indicated by their Thermal Alteration Index values of less than 1+.

Previous studies of the laminated biosiliceous sediments have resulted in two different interpretations of their sedimentological origin. Laminae in the Fletcher Island cores were attributed to fluctuations in biogenic productivity associated with nutrient upwelling (Kitchell and Clark, 1982). Semi-quantitative study of apparent grading in the laminae of CESAR-6 led to the conclusion that they were similar to those in forearc basins of Japan (Mudie and Blasco, 1985) which have a turbidite origin (Sugisaki *et al.*, 1982). Additional studies were made of the laminated sediments in CESAR-6 in order to address the following questions.

1. Do quantitative differences in sediment texture and biogenic composition of the laminae confirm an origin from distal turbidites or seasonal plankton production?
2. Do light and dark laminae have geochemical characteristics that explain their geological origin?
3. What is the relationship between the parallel laminated sediments and the adjoining biosiliceous sediments with discontinuous or deformed bedding?
4. What relationship is there between the clastic sediments in CESAR core 6 and the volcanic bedrock sample?

Special techniques had to be used in order to analyse the micro-quantities of sediment in the Alpha Ridge cores, such as microlaminae 1 mm thick, intra-laminar structures with diameters of 1–10 microns, and clastic materials in microgram volumes. These techniques include the combined use of a scanning electron microscope (SEM) and X-ray energy dispersive spectrometer (EDS) as described by Stoffyn-Egli (in prep.); an automated image analysis for microscopic analysis of fine-grained sediment (Dabros and Mudie, 1986); and epoxy-impregnated grain-mounts in lieu of thin sections for petrographic studies (Van Wagoner, unpublished data). The salient results of these studies summarized below.

1. *Sediment texture and biogenic composition.*

Quantitative grain size analysis of the sediment in light-dark laminae from CESAR core 6, Unit 4B, was made using an automated texture analysis system (TAS) as described by Dabros and Mudie (1986). No comsistent differences were found between grain size distributions from different laminae (Fig. 4), and F-tests show no significant differences between replicate runs or between samples at the 90% confidence level. These data confirm the earlier observation (Mudie and Blasco, 1985) that variations in colour and X-ray density of laminae in Unit 4B do not indicate changes in texture or microfossil size. The uniform grain size has two important implications. First, absence of textural gradients eliminates the possibility that the parallel laminated sediments in Unit 4B are due to processes

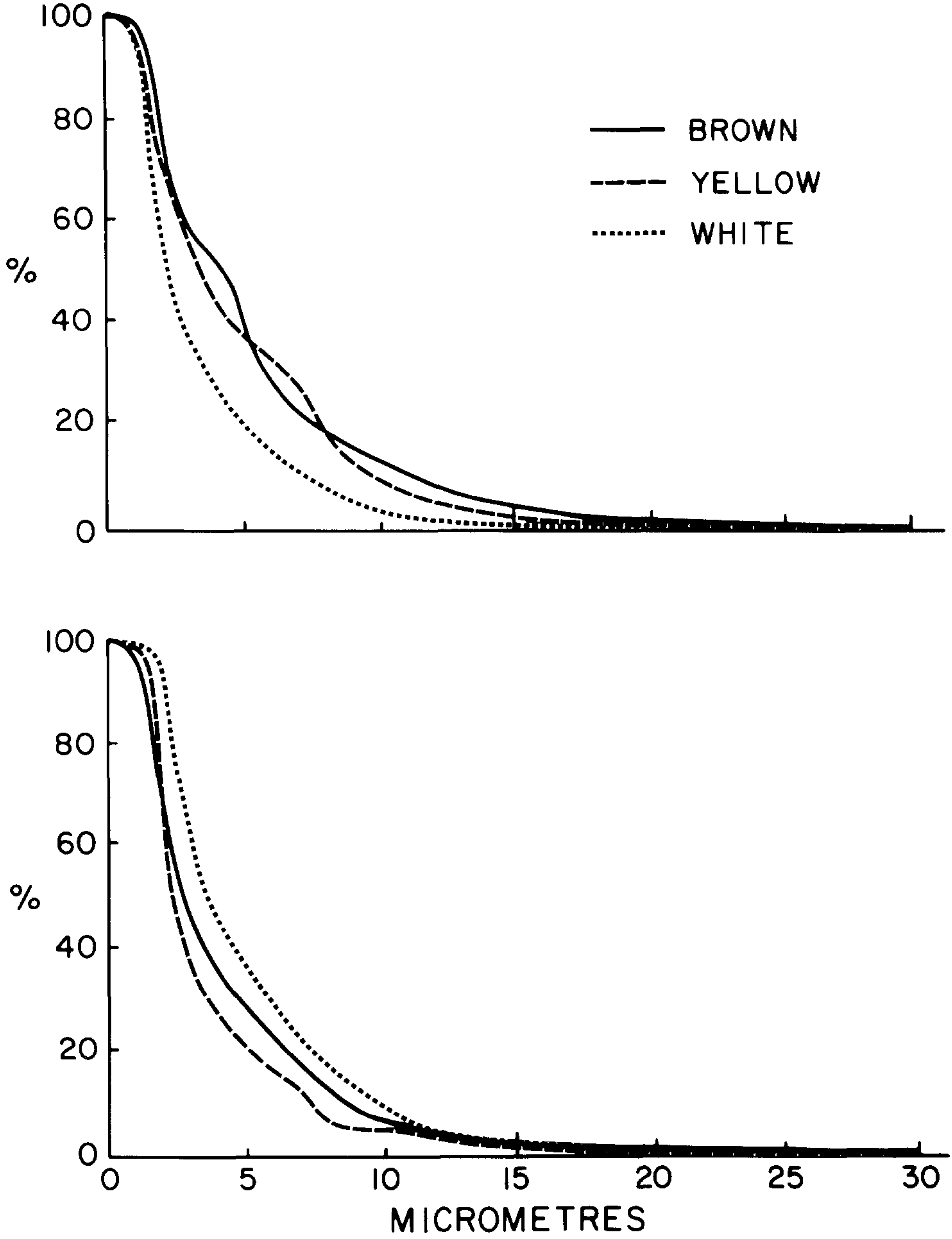

Fig. 4. Cumulative percentage curves for particle size classes in representative sequences of brown (b,d), yellow (a,e) and white (c,f) laminae in CESAR core 6, Unit 4B. Sample intervals, in cm, are a) 243.0; b) 244.6; c) 244.9; d) 245.3; e) 245.5; f) 245.9. Each graph represents a count of 214–516 particles.

involving sorting, including turbidity current flows, contour currents, and tidal currents. Secondly, absence of significant differences between microfossil sizes in light and dark laminae shows that there are no large changes in numbers of small resting-stage diatoms. The laminae in CESAR-6 therefore differ from those in core F1-437 where light laminae are dominated by large vegetative-stage diatoms and dark laminae are dominated by smaller, thick-walled resting spores (Kitchell *et al.*, in press).

2. *Geochemistry of lamina couplets.*

A detailed geochemical investigation of different coloured laminae throughout Unit 4 of CESAR core 6 was made with the SEM-EDS system (Stoffyn-Egli, in prep.). Visual inspection of the sample mounts did not reveal any consistent differences in diatom species composition or detrital sediment content of light and dark laminae. EDS analysis, however, showed that dark laminae regularly contain more iron than light laminae. This iron seems to be mainly in the form of coatings on the siliceous microfossils. Black spots scattered throughout the siliceous ooze are caused by a concentration of ferromanganese microconcretions (1–5 microns). The size, shape and patchy distribution of these microconcretions suggests a bacteria-mediated precipitation of the metals.

The importance of these geochemical data is summarized as follows.

1. Laminations in CESAR core 6 are not due to fluctuations in detrital sediment input; therefore, they are not the same as laminated biosiliceous sediments in the island arc basins of Japan (Sugisaki *et al.*, 1982) or varved sediments in the Tertiary Monterey Formation and Recent upwelling areas, e.g. the Santa Barbara Basin (Ingle, 1981).
2. The lack of detrital sediment indicates that the site of CESAR core 6 was isolated from sources of clastic sediment during the deposition of Unit 4B.
3. The preservation of Fe and Mn oxides in both dark and light laminae indicates that the depositional environment was consistently oxidizing.
4. Preservation of fine structures such as the microlaminae and microconcretions indicates the absence of significant bioturbation which suggests a low influx of organic matter. The low organic content of the laminated sediment is also consistent with an oxidizing environment.
5. The horizontally bedded light and dark laminae in the Cretaceous-Paleogene sediments of CESAR core 6 correspond mainly to fluctuations in iron content of the sediment and not to cyclical changes in biogenic composition.
6. The most plausible explanation for the uneven distribution and fine-

scale fluctuations in particulate Fe and Mn is that they were precipitated during periods of hydrothermal venting (see Stoffyn-Egli, in prep., for detailed arguments).

3. *Geochemistry of discontinuous beds and adjacent lithofacies.*

In CESAR core 6, there is a major change in the character of the bedding at the top of Unit 4. Between 137 and 131.5 cm core-depth, there is a transition from parallel laminae to discontinuous, irregular laminae in the yellowish biosiliceous ooze. Overlying beds (131.5–125 cm) are more massive and they lack microlamination. Above 125 cm, the reddish brown Unit 3 (125–107 cm) shows only traces of structure in the form of dark brown mottles and, near the top, as irregular lenses of yellowish sediment. Unit 2 (107–99 cm) is a gray mudstone with dark streaks but no discernable structure.

SEM and EDS studies of laminae in the transition zone from 137–125 cm at the top of Unit 4 (Stoffyn-Egli, in prep.) show that biosiliceous microfossils disappear at the top of the yellowish sediment, at 133.5 cm. From 137 to 135.5 cm, the microfossils show an increasing degree of dissolution and they are replaced progressively by an iron-rich clay which composes the bulk of the sediment in the transition zone at the top of Unit 4, from 137–125 cm. This attrition of biogenic silica is accompanied by inverse gradients (Fig. 5) in particulate Fe, feldspars, angular quartz, glassy volcanic shards, and biogenic apatite (including fish bones). The transition zone is also marked by the unique occurrence of microspheres of calcium phosphate enriched in REE (rare earth elements), as revealed by EDS analysis. The overlying units 3 and 2 have not been sampled in detail, but they mainly comprise clay- to silt-sized clastic sediment, with common angular quartz grains and volcanic shards. The reddish brown Unit 3 is enriched in Fe particulates and contains some fresh K-feldspar as well as crystalline clays (kaolinite, limonite, goethite and smectite). The gray Unit 2 is coarser in texture and contains more Na-feldspar and less iron-rich clays. Black spots in this unit are biogenic calcium phosphate similar to that of fish bones at the top of Unit 4.

4. *Volcanic sediments in cores and bedrock samples.*

All the pre-Neogene Alpha Ridge cores contain volcanic sediment, ranging from biosiliceous ooze with volcanic glass shards (F1-437, -422, CESAR core 6, Unit 4) or amorphous glass (F1-422), and highly altered pyroclastic sediment (CESAR core 6, Units 2 and 3). Detailed mineralogical data,

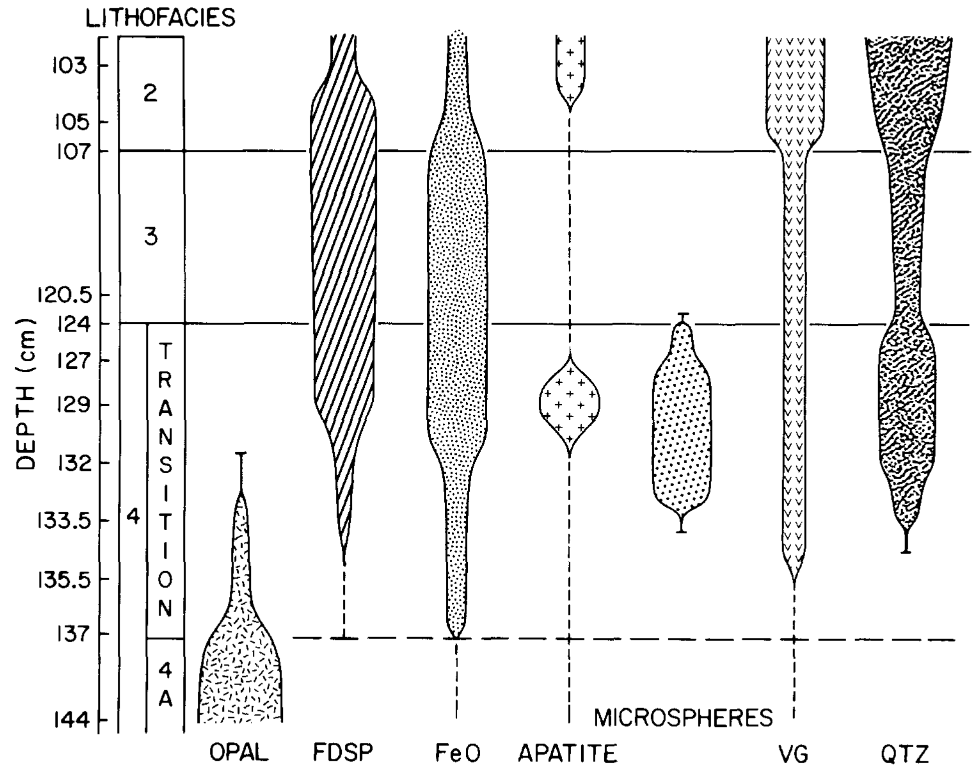

Fig. 5. Schematic summary of major changes in mineral composition, CESAR core 6, Units 4A to 2.

however, are presently available only for CESAR core 6. Samples from F1-437 (Sect. 11) and F1-422 (Sect. 13) that were studied by Mudie (1985) contain rare quartz and mica flakes but no tephra. The available data for CESAR core 6 are shown in Table I which also gives the chemistry of the clinopyroxene in the CESAR bedrock (Van Wagoner and Robinson, 1985), volcanic rock from Campanian lava flows of the Strand Fiord Formation, Axel Heiberg Island (Ricketts *et al.*, 1985), rhyolitic tuff from Northwest Greenland (Dawes and Peel, 1981), and glass shards from the Paleocene tephra bed on Banks Island (Westgate, pers. comm., 1984).

These data indicate a strong similarity between the chemistry of the volcanic shards in the sediments of CESAR core 6, Unit 4C, and the Paleocene calc-alkaline rhyolitic ash layer (0.5–2 cm thick) on Banks Island, ca. 700 km southwest of the Alpha Ridge. The vesicular to pumaceous silicic shards are characteristic of a Plinian-type ash cloud. The absence of thick ash beds on the Alpha Ridge and Banks Island indicates that the volcanic source was not close to the Arctic Ocean margin. Extensive, thick (3–17 m) tuff deposits of Late Maastrichtian-Early Paleocene age occur near Norman

Wells, Central Yukon, ca. 1200 km southwest of the Alpha Ridge (Ricketts, 1985), and these deposits include clear bubble wall glass shards. Fine bedded rhyolitic tuff of Late Cretaceous-Paleocene age also occurs in the Kap Washington area of Northwest Greenland (Dawes and Peel, 1981; Batten, 1982), ca. 300 km southeast of the Alpha Ridge. Either of these sources could account for the small amount of tephra in the Alpha Ridge sediments. Ricketts (1985) has shown that ash layers up to 5 cm thick occur within

TABLE II

Mineral composition of CESAR bedrock and CESAR core 6 lithofacies, and chemistry of selected Arctic volcanic sediments

MINERALS (%)

	Clay	Pyroxene	Felspar	Quartz	Epidote	Horneblende	Garnet	V.G.
CESAR volcanic rock*	93	5	2	–	–	–	–	–
CESAR core 6:								
Unit 1	20	–	25–30	15–28	2–15	2–10	–	0–10
Unit 2	10	–	13–33	53–79	10	trace	trace	5–20
Unit 3	50–80	trace	13–58	26–58	–	–	–	trace
Unit 4: 123–125 cm	36–65	–	9–10	21–50	–	–	–	trace
transition) 125–129cm	60–75	–	5–12	12–25	–	–	–	trace
zone) 131–132cm	97	–	1	1	–	–	–	trace
4A, ooze 135–136 cm	trace	–	3	3 (+87% opal)	–	–	–	trace

CHEMISTRY (%)

	SiO_2	TiO_2	Al_2O_3	FeO	MgO	Na_2O	K	Ca
CESAR bedrock:								
orthopyroxene	44–49	1.6–3	5–9	6–8	12–14	1.0	.01	23–24
STRAND FJORD:								
whole rock[1]	49–50	2.1–2.6	13–14	5–9	4–5	1.7–2.3	0.6–0.9	9–10
CESAR core 6:								
Unit 2, whole rock	53–79	–	+	+	–	+ +	+	+
Unit 3, whole rock	26–38	+	+ +	+ +	trace	trace	+ +	+
Unit 4, glass shards[2]	76.8	0.2	11.7	2.3	–	0.7	2.6	0.3
BANKS ISLAND glass[3]	73–78	0.3–0.5	12–15	1–2	0.4–1.3	2.8–3.0	5	0.3–0.9
KAP WASHINGTON[4]								
rhyolitic tuff	70					7.5–9		

LEGEND: V.G. = Volcanic/glass; * = total pyroclastic rock, including weathered matrix

1. From Ricketts *et al*, 1985; 2. From Robert Stevens, Memorial University of Newfoundland, pers. comm., 1984; 3. From Richard Westgate, U. of Toronto, pers. comm., 1984; and 4. From Dawes and Peel, 1981.

500–600 km of the source of Plinian-type volcanic deposits in the Norman Wells area; small amounts of silt-fine sand sized tephra may be transported much further by winds.

The fragmental nature and high vesicularity of the alkali basalt forming the Alpha Ridge bedrock sample suggest it was extruded during an explosive, perhaps Vulcanian-type eruption (Fisher and Schminke, 1984) in shallow water. The highly weathered bedrock does not contain tephra that can be compared with the other samples. The Cretaceous-Paleocene volcanic shards in CESAR core 6 (Table 2) have a much higher SiO_2 content than the Campanian subalkaline tholeoiitic volcanics of the Strand Fiord Formation on Axel Heiberg Island. The mineralogy of the volcanoclastic sediments from Units 3 and 2 in CESAR core 6 is similar to that of the weathering products of the Alpha Ridge bedrock (Table 2). The presence of 26–79% of quartz in the core sediments, however, suggests that there was also another major source of sediment influx to the Alpha Ridge during the Paleogene. Many quartz grains contain abundant microlites; this indicates a plutonic rock source such as granites of the Canadian Shield. Similar quartz grains are common in Neogene sediments (Unit 1) of CESAR core 6 and other Alpha Ridge cores, and ther presence previously has been attributed to transport of glacial and fluvial sediment discharged onto the sea ice (Clark *et al.*, 1980). In fact, there is little difference between the mineralogy of the Neogene brown mud and the volcanoclastic units 3 and 2 in CESAR core 6: lithofacies are distinguished only by the amount of clay present and by the size and quantity of Fe and Mn particulates. This observation has important implications regarding the paleoenvironmental history of the Alpha Ridge, as discussed below.

PALEOENVIRONMENTAL CONSTRAINTS

Previous studies of paleoenvironmental conditions represented by the Alpha Ridge Cretaceous-Paleogene biosiliceous sediments (Kitchell and Clark, 1982) have employed tectonic constraints in arguements for or against various paleoclimatic models. For example, it was assumed that the Canada Basin was at least 1500 m deep in Late Cretaceous time, and interpretation of the Alpha Ridge biosiliceous sediments (Kitchell and Clark, 1982) was based on comparison with other oceanic deposits which require the existence of deep (> 500 m) channels connecting the Late Cretaceous-Paleocene Arctic Basin with the global oceans. At present, however, there are no well-constrained geological data to support these assumptions (Sweeney, 1985). Therefore, we shall review the basic evidence provided by the Alpha Ridge geological samples in an effort to delimit paleoenvironmental conditions that may constrain tectonic models for the evolution of the Alpha Ridge.

The Campanian-Maastrichtian black sapropelic sediment at the base of core F1-533 contains abundant amorphous organic matter as well as terrestrial plant fragments, pollen and spores, dinoflagellates, and rare foraminiferal organic test-linings. Average carbon content is very high (15% dry wt.), H/C and O/C values are low, and $\delta^{13} C_{org}$ is $-30.7^{\circ}/_{oo}$ (Clark and Byers, 1984). These features indicate a large input of terrigenous sediment, rapid burial of organic material, and/or anoxic bottom water. It is likely that the structureless black mud facies represents fluvio-marine sediment that was rapidly deposited in relatively shallow water prior to oxidation in the water column. A turbidite origin in deeper water has been suggested (Clark and Byers, 1984), but absence of graded bedding and the abundance of well preserved palynomorphs makes this unlikely. Recent turbidites usually contain only small quantities of poorly preserved, reworked palynomorphs (Mudie and Short, 1985).

In contrast to the Campanian organic-rich terrigenous mud, the Maastrichtian-Paleocene biosiliceous sediments in CESAR core 6 contain only traces of terrigenous sediment and low amounts of organic carbon (mean $C_{tot.} = 0.33\%$ dry wt.). The geochemistry of the parallel laminated biosiliceous ooze denotes an oxidizing environment with low organic and detrital sediment input. Pollen grains are the only clear evidence of terrigenous sediment input; their small size and low diversity relative to the floras on the Canadian Arctic Islands indicates that the pollen were probably transported offshore by winds. The volcanic shards are probably also of eolian origin.

The absence of bedrock-derived sediment in the laminated biosiliceous ooze is remarkable. Bedrock peaks crop out within 4 km of the CESAR-6 site (Jackson *et al.*, 1985), and in present water depths of ca. 1100 m, they are a significant source of sediment influx to the seabed below the ridge crest (Amos, 1985). It is therefore peculiar that these peaks did not contribute some volcanic sediment to the Alpha Ridge during the Cretaceous-Paleogene interval when the top of the Ridge was probably no deeper than ca. 400 m, if a conservative estimate is made of the critical depth for explosive volcanism (Van Wagoner and Robinson, 1985). Studies of subaqueous sediment deposits associated with oceanic ridges, plateaus and islands (Sigurdsson, 1982a, b) and subduction complexes (Underwood and Bachman, 1982) show that all these deposits normally contain a large proportion of volcanic sediment, with amounts of other clastics ranging from 10 to 50%. The absence of detrital sediments in CESAR core 6, Unit 4B, C, may indicate that the entire Ridge was sediment starved during this interval, perhaps due to the fresh (non-weathered) nature of the volcanic bedrock. Alternatively, the biogenic deposits may have accumulated on ledges or in ponded areas flanked by structures (e.g. tilted blocks or trenches) which trapped the volcanic sediments. It is also possible that sediments ejected and eroded from the peaks flowed downslope in submarine channels which by-passed the sites of biogenic sediment accumulation. Both of the above scenarios suggest that volcanism and tectonic activity were subdued on the Alpha Ridge during the Cretaceous-Paleocene interval, however, because all known active pyroclastic marine environments include lava or ash flows at least a few centimeters thick.

Other remarkable features of the Alpha Ridge biosiliceous sediments are the absence of calcareous microfossils, arenaceous foraminifera and radiolarians in the relatively shallow water environment. These microfossils are normally common in offshore marine sediments from ca. 200–500 m water depth, especially where primary productivity is high. The absence of calcareous microfossils indicates that pH conditions were too low for calcite preservation. A low pH is expected for interstitial water saturated with respect to opal, as found in pure siliceous ooze. Slow sedimentation rates, acidic pore water and oxidizing conditions would account for the absence of arenaceous benthic foraminifera. At present, we cannot explain the absence of radiolarians, but it is notable that both radiolarians and foraminifera are absent from thin beds of diatomaceous sediment in shallow water Eocene volcanoclastic sediments at ODP Site 642 on the Voring Plateau in the Norwegian Sea (ODP Leg 104 Scientific Party, 1986).

The major lithological change found at the top of the laminated sediments in CESAR core 6 also cannot satisfactorily be explained at present. It is possible that the termination of biogenic deposition denotes unique events associated with global paleoceanographic changes at the Cretaceous-Tertiary boundary. There is a remarkable visual similarity between the sequence of changes in the Alpha Ridge transition zone sediments and those found in the type section of the Cretaceous-Tertiary boundary in New Zealand (Brooks *et al.*, 1984). Direct neutron activation analysis of samples from Units 4B to 2, however, has so far failed to reveal the presence of iridium in amounts greater than 0.4 parts per billion (Robert Brooks, pers. comm., Sept., 1986).

The similarity between the Paleogene sediments of Unit 3 and the Neogene sediments on the Alpha Ridge also suggests that the events which terminated the biogenic productivity continued into and beyond the Maastrichtian-Danian period of global catastrophic events. It appears that a major long-term change in climate, oceanographic and/or sedimentological conditions started during the Paleogene and continued into the Neogene. Palynological evidence from the Mackenzie Delta Richards Formation indicates a major climatic cooling in the Late Eocene-Early

Oligocene (Norris, 1982). A gradual Eocene cooling is also recorded in high latitude regions of the Northeast Atlantic (Collinson *et al.*, 1981). If these cooling events were accompanied by increased runoff from uplifted (?Eurekan Orogeny) margins of the Canada Basin, a much greater fluvial influx of clay and fine sand would be expected on the Alpha Ridge.

Hence, there is more than one paleoenvironmental scenario that might explain the nature of the geological samples from the Alpha Ridge and, at present, there are insufficient data to provide firm constraints for tectonic models which depend on knowledge of the paleobathymetry of the Ridge and ocean corridors connecting the Canada Basin and global oceans.

CONCLUSIONS

Sediments beneath the Neogene glacio-marine hemipelagic and carbonate muds draped over the Alpha Ridge have an age range of Campanian to Late Eocene or possibly, Oligocene. According to the time scale of Harland *et al.* (1982), these sediments span the interval from Anomaly 33 (80 Ma) which follows the mid-Cretaceous "quiet" magnetic interval, through the Paleogene opening of the Labrador Sea (Anomaly 29, ca. 65 Ma) and the Norwegian Sea (Anomaly 24r, ca. 55 Ma) and ending at about 40 Ma, i.e. a few million years prior to the termination of spreading in the Labrador Sea and Baffin Bay (Anomaly 13, ca. 37 Ma).

CESAR core 6 from the CESAR North Ridge appears to contain a continuous sequence of Maastrichtian to Paleocene sediments. At the top of Unit 4, there is a compressed interval of discontinuous laminae that records a transition from the parallel laminated biosiliceous ooze to unfossiliferous sediments of Unit 3 which have minerological features like those of a bedrock outcrop on the Ridge. The entire biosiliceous unit is only 146 cm long but it must span a time interval of at least 10 Ma, which indicates that sedimentation rates were no more than about 0.2 mm per thousand years. This appears to be a remarkably slow deposition rate but it is compatible with Pleistocene deposition rates of ca. 1 mm per thousand years in CESAR cores (Aksu and Mudie, 1985) and with paleomagnetic data for CESAR-6 which show 7 polarity reversals in the Cretaceous-Paleogene interval (Aksu, 1985). The short depth intervals (2-5 cm) in which the reversals occur in Unit 4C also indicate slow sedimentation. In fact, the steepness of the reversals makes it impossible to interpret the laminated sediments as annual deposits because transitions in the earth's magnetic field are not known to occur within times of less than 100 years. The geochemistry of the parallel laminated sediments is also best explained by a very slow sedimentation rate.

The age of the oldest Alpha Ridge samples constrains only the time at which unconsolidated sediments were accumulating on the Alpha Ridge. The Late Campanian-Eocene age is therefore not incompatible with postulated Jurassic-Campanian tectonic events (e.g. Sweeney, 1985; Jackson *et al.*, in press) that may have occurred during the formation of the Canada Basin and Alpha Ridge. The lack of thermal alteration in the biosiliceous microfossils, palynomorphs and organic materials, however, constrains the likelihood that the Ridge was tectonically active during the rifting stages in the North Atlantic, the Eurekan Deformation in the Sverdrup Basin, and the opening of the Eurasian Basin in the eastern Arctic Ocean.

We are presently unable to equate the paleoenvironment of the oldest Alpha Ridge sediments with any very similar ancient or modern marine environment. New data, however, allow us to eliminate some previous interpretations made during initial studies of the CESAR samples (Mudie and Blasco, 1985). The absence of evidence for gravity flow deposition or bottom current winnowing makes it unlikely that the biosiliceous sediments in Unit 4 were transported far from their primary site of deposition, and the undeformed parallel laminae eliminates the likelihood of transport as a slump block. The Cretaceous-Paleocene sediments in CESAR core 6 are therefore not similar to those associated with island arcs or active hot-spot environments such as Iceland (Sigurdsson, 1982 a, b). Absence of detrital sediment in most of Unit 4 and lack of microfossils normally associated with upwelling areas also reduces the likelihood of a basinal environment analogous to the Monterey Formation. The simplest explanation for the parallel laminated biosisiliceous sediments entails slow deposition in a ponded, shallow water, oxidizing environment in which pH and temperature conditions prohibited calcite preservation. The most similar types of marine deposits are found at DSDP Site 348 on the Iceland Plateau (Talwani *et al.*, 1976) and at DSDP Site 317 on the Manihiki Plateau (Schlanger *et al.*, 1976). Samples from these environments, however, are not finely laminated and they include a much higher content of volcanic detritus than CESAR core 6.

More detailed geochemical studies are needed of the volcanoclastic and detrital minerals in sediments above the biosiliceous ooze of CESAR core 6, and of clastic sediments in the Fletcher Island cores in order to make close comparisons between samples from CESAR North and South Ridge and to permit accurate comparison with other volcanic rocks in the circum-Arctic region. The dramatic switches from Upper Cretaceous opal deposition in an acidic, oxidizing environment to Cenozoic clastic (hemipelagic and/or volcanoclastic) deposition, however, clearly indicate that there were major changes in the Paleogene Arctic climate and ocean circulation. Some of these changes may be related to the depths and widths of ocean corridors connecting the Arctic Ocean with the North Atlantic and Pacific Oceans. At present, however, it is not possible to distinguish between the roles of volcanic and fluvial cycles, sea level changes and climatic cooling in determining the main causes of these changes in depositional environments. In order to provide better constraints for tectonic models, many more samples are required from the Arctic Ocean, including long cores from the basins and continental slopes, and high resolution seismostratigraphic data that permits correlation of the sediment layers at the different core sites.

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