*Annals of Glaciology* 22 1996


# 20th-century glacial-marine sedimentation in Vitus Lake, Bering Glacier, Alaska, U.S.A.

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ABSTRACT. Vitus Lake, the ice-marginal basin at the southeastern edge of Bering Glacier, Alaska, U.S.A., is a site of modern, rapid, glacial-marine sedimentation. Rather than being a fresh-water lake, Vitus Lake is a tidally influenced, marine to brackish embayment connected to the Pacific Ocean by an inlet, the Seal River. Vitus Lake consists of five deep bedrock basins, separated by interbasinal highs. Glacial erosion has cut these basins as much as 250 m below sea level. High-resolution seismic reflection surveys conducted in 1991 and 1993 of four of Vitus Lake's basins reveal a complex, variable three-component acoustic stratigraphy. Although not fully sampled, the stratigraphy is inferred to be primarily glacial-marine units of (1) basal contorted and deformed glacial-marine and glacial sediments deposited by basal ice-contact processes and submarine mass-wasting; (2) acoustically well-stratified glacial-marine sediment, which unconformably overlies the basal unit and which grades upward into (3) acoustically transparent or nearly transparent glacial-marine sediment. Maximum thicknesses of conformable glacial-marine sediment exceed 100 m. All of the acoustically transparent and stratified deposits in Vitus Lake are modern in age, having accumulated between 1967 and 1993. The basins where these three-part sequences of "present-day" glacial-marine sediment are accumulating are themselves cut into older sequences of stratified glacial and glacial-marine deposits. These older units outcrop on the islands in Vitus Lake.

In 1967, as the result of a major surge, glacier ice completely filled all five basins. Subsequent terminus retreat, which continued through August 1993, exposed these basins, providing new locations for glacial-marine sediment accumulation. A correlation of sediment thicknesses measured from seismic profiles at specific locations within the basins, with the year that each location became ice-free, shows that the sediment accumulation at some locations exceeds 10 m year$^{-1}$.

## INTRODUCTION

Vitus Lake is a 24 km long by 8 km wide, sediment-accumulating, marine to brackish embayment, located at the southeastern margin of 191 km long Bering Glacier, the largest and longest glacier in continental North America. Vitus Lake lies just north of the Gulf of Alaska and extends south to nearly 60° N (Fig. 1). The eastern part of Bering Glacier, which borders Vitus Lake, experiences major surges with a 25–30 year cycle.

The purpose of this study is to describe the glacial-marine sedimentation history of Bering Glacier and Vitus Lake for the 26 year period between the last two major surges, one which ended in 1967 and one which began in 1993. Long-term observations and monitoring of the glacier and embayment during this period provide a detailed data base for documenting the opening of basins in Vitus Lake for sedimentation, documenting ice-margin retreat and changes in terminus position, describing bathymetry and basin morphology and characterizing sediment thickness and sediment distribution. Subsequent to our data collection, the 1993–95 surge covered most of the study area.

In spite of at least five post-1900 surges, Bering Glacier has been thinning and retreating for much of this century (Molnia and Post, 1995). Continuing retreat has resulted in the emergence of Vitus Lake and the exposure of five large, deep, ice-marginal basins (Fig. 1) which have been filled at different times by varying mixtures of brackish and saline water (Gray and others, 1994). Detailed bathymetric surveys of the lake from 1990 to 1993 (Molnia and others, 1991; Trabant and others, 1991) and two high-resolution seismic reflection surveys of Vitus Lake, in 1991 (Carlson and others, 1993a) and 1993

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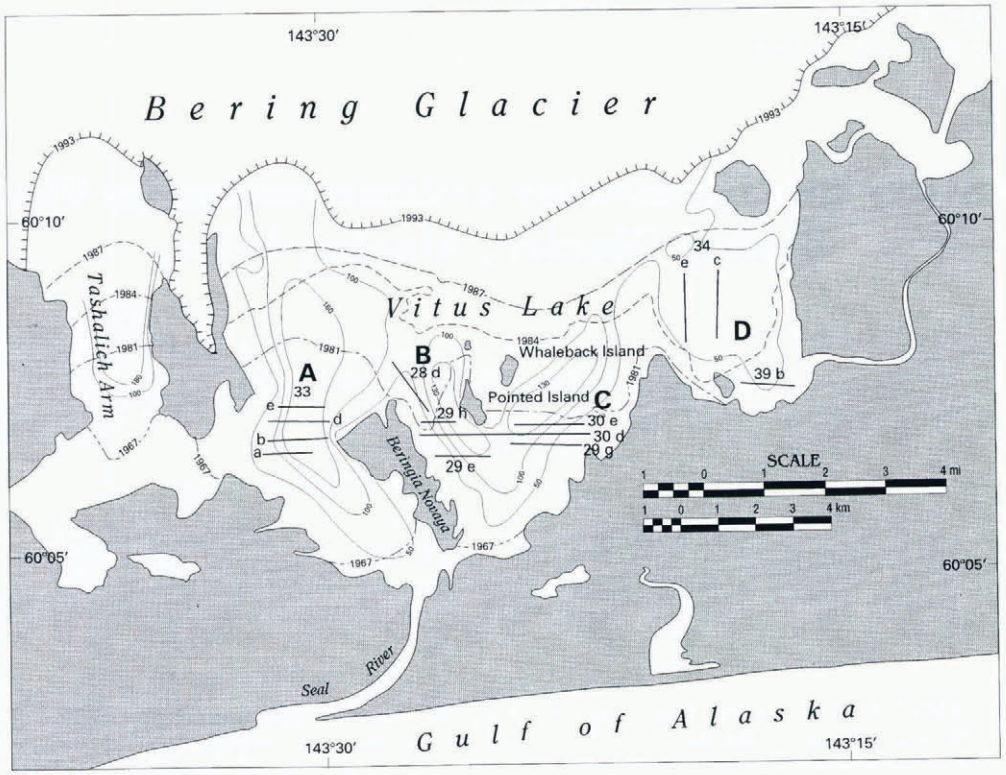


*Fig. 1. Map of the Vitus Lake area showing bathymetry, location of the glacier margin in 1993, 1987, 1984, 1981 and 1967; location of the five bedrock basins (labeled A, B, C, D and Tashalich Arm); and the location of geographic features described in the text. Bathymetry is in meters. Open contours in Tashalich Arm and basin A result from dense iceberg concentrations preventing completion of surveys, or from the location of the ice margin at the time of the survey. The deepest part of basin B is approximately 1 km southeast of letter B, while the deepest part of basin C is approximately 2 km west of letter C.*

(presented here) reveal a complex basin morphology with basins cut more than 250 m below sea level and maximum modern glacial-marine sediment thicknesses of more than 100 m. The thickest sediment found in the seismic surveys is located in four deep basins, informally termed basins A, B, C and D (Fig. 1), with maximum water depths of 165, 130, 130 and 60 m, respectively (Carlson and others, 1993b). In both 1991 and 1993, densely packed icebergs prevented seismic surveys of the fifth basin, Tashalich Arm. There, fathometer surveys in 1991 and 1992 showed maximum water depths of greater than 180 m (Fig. 1).

## SEISMIC STRATIGRAPHY OF VITUS LAKE

In July 1993, approximately 500 km of high-resolution seismic reflection profiles were collected in Vitus Lake. Track-lines, spaced 50–200 m apart, were located using global positioning system (GPS) navigation and visual reference points. As differential GPS was not always used, positional errors may be as much as 30–50 m. Seismic data were obtained using a Geopulse high-resolution sub-bottom profiling system, operated at a 0.5 s firing rate and a power of 350–500 J. Acoustic returns were received with a Benthos 15/30 hydrophone system and recorded on an EPC 4800 seismic recorder at a 0.5 s sweep rate. All returns were filtered between 300 and 1000 Hz.

The resulting seismic profiles reveal a nearly complete picture of sediment distribution, sediment thickness and bedrock morphology in Vitus Lake. Profiles of basins A–D and their recent sediment fill and the adjacent inter-basinal areas reveal a variable three-phase, acoustic glacial-marine stratigraphy consisting of basal, contorted and jumbled glacial-marine and other glacial sediment, unconformably overlain by well-stratified glacial-marine sediment, which is conformably overlain by or grading into acoustically transparent to near-transparent glacial-marine sediment.

Maximum thicknesses of the upper two conformable glacial-marine sediment units exceed 100 m. All sediment thicknesses presented in this study are based on measurements from seismic profiles assuming a seismic velocity in glacial-marine sediment of 1500 m s$^{-1}$. Based on seismic profiles and sediment samples obtained from the Gulf of Alaska and other Alaskan fjords (Molnia and Carlson, 1978), we interpret the individual units of the Vitus Lake stratigraphy as follows:

(1) The basal unit, composed of broken, contorted and jumbled acoustic reflection, may have formed through a combination of several different sedimentation processes, all of which would produce acoustically similar reflectors. In one scenario, pre-existing basin fill may have been overridden by ice of the 1965–67 surge and disturbed, deformed and displaced. In a second scenario, sediment may have accumulated contemporaneously in contact with the surging glacier margin, and have been subsequently deformed by the glacier. In a third scenario, during and after glacial retreat, sediment may have accumulated through submarine slumping and

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mass-wasting from the deglacierized walls of the submarine basin adjacent to the glacier margin and elsewhere along the entire length of the basin.

(2) Unconformably overlying the basal unit is the middle unit, interpreted as acoustically well-stratified glacial-marine sediment. The sediment in this unit formed in an "ice-proximal" depositional environment and probably has a significant water-borne sand and silt component. As deposition was very close to the glacier margin, the role of iceberg-rafting was probably significant, hence there may also be a significant coarse-sand and gravel component. Overburden pressure has resulted in compaction and dewatering, increasing acoustic reflectivity. This unit is unconformably overlain by or grades into the upper unit.

(3) The upper, acoustically transparent to near-transparent glacial-marine sediment unit represents "distal" deposition, extending up to several kilometers from the glacier margin. It is composed of very recently deposited, fine-grained, high-water-content, rock-flour-rich silt, deposited predominantly by settling-out of the water column. Sediment gravity flows may redistribute some sediment into deeper parts of the basins. Samples show that iceberg-rafted sand and gravel are not a significant component of the upper part of this unit, but their percentage probably increases with depth, resulting in an increase in acoustic reflectivity. The decrease in percentage of iceberg-rafted sediment likely correlates with the depositional sites being progressively farther from the retreating glacial margin.

## Basin A

Ten-kilometer-long basin A, located on the west side of Vitus Lake, contains the thickest glacial-marine sediment. Four profiles of the basin (Fig. 2a–d), with locations shown in Figure 1, are presented to characterize the basin's glacial-marine fill. They show a 60–95 m thick transparent unit conformably overlying a 5–15 m thick, faintly reflective unit. These sediments overlie and grade down into a highly reflective 10–25 m thick basal unit characterized by contorted and distorted reflections.

The locations of lines 33a (Fig. 2a), 33b (Fig. 2b), 33d (Fig. 2c) and 33e (Fig. 2d), all from the central part of basin A (Fig. 1), were free from the glacier by 1977. The maximum thickness of transparent sediment (unit 3) measured on each of the profiles is 60, 70, 85 and 90 m, respectively. Where sampled, the surface sediment in

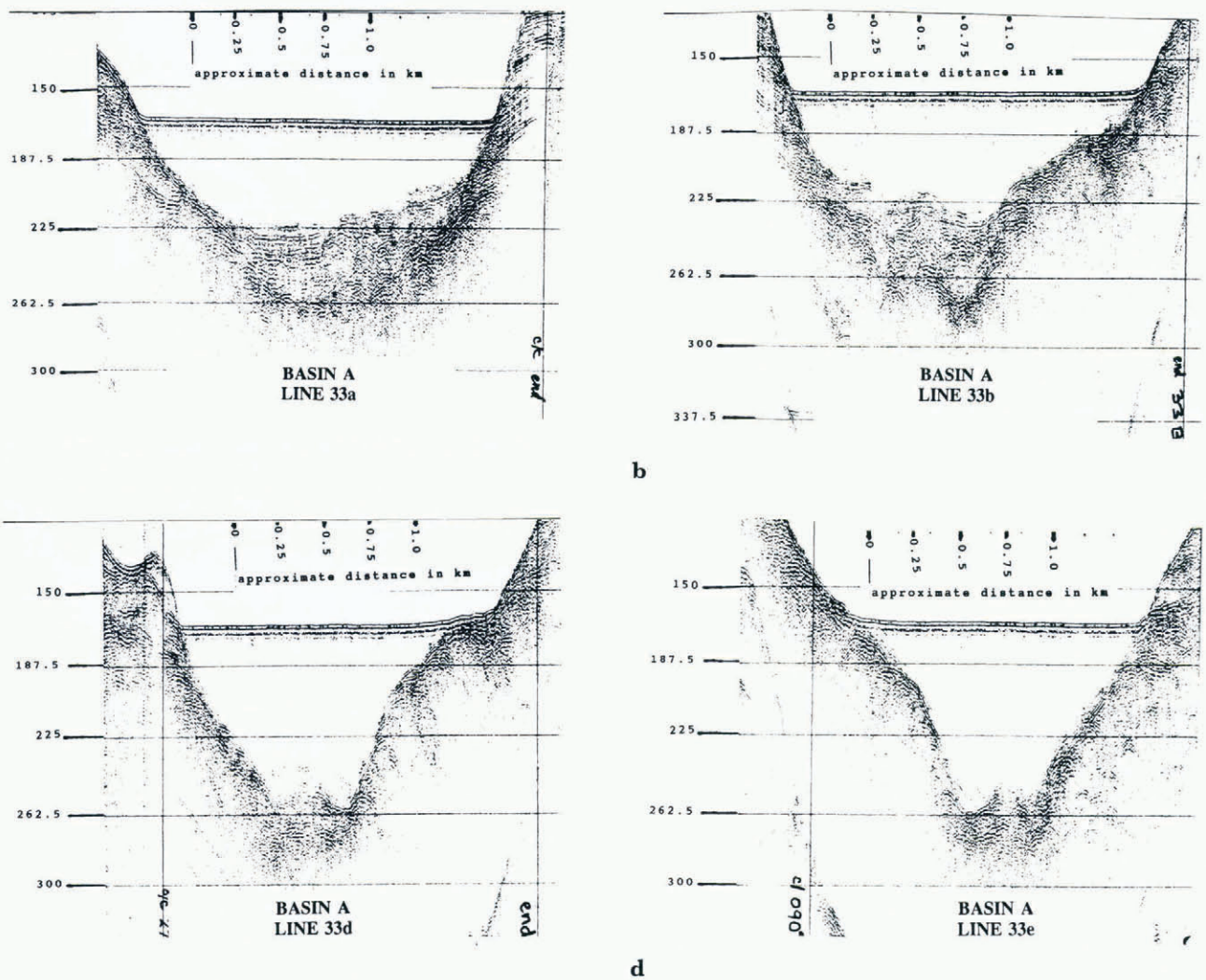


*Fig. 2. Four high-resolution seismic profiles across basin A: (a) east–west along line 33a; (b) east–west along line 33b; (c) east–west along line 33d; and (d) west–east along line 33e. In all cases, water depth, in meters, is shown on the lefthand side, and distance, in kilometers, is shown across the top.*

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basin A is a gray-green mud. No samples of the two lower units have been collected from basin A.

### Basin B

Five-kilometer-long basin B, located on the east side of Beringia Novaya, the largest island in Vitus Lake, contains a more highly reflective glacial-marine sediment section than that of basin A. Three profiles of basin B (Fig. 3a–c) are presented to characterize its glacial-marine fill. The profiles show a 20–30 m thick unit with increasing reflectivity at depth, overlying a 5–30 m thick highly reflective basal unit characterized by contorted and distorted reflections. The locations of lines 29e (Fig. 3a) and 29h (Fig. 3b), approximately 1 km apart, both from the south-central part of basin B, were covered by the glacier until the early 1980s.

The walls and floor of the basin depicted on lines 29e and 29h are composed of an older sequence of dipping, bedded sediment composed of glacial outwash, glacial-lacustrine and glacial-marine deposits. These deposits, which crop out on several of the islands within Vitus Lake, are of Holocene age and may be several thousand years old (Molnia and Post, 1995). Similar older stratigraphic units form the basin walls and floors in many Vitus Lake profiles.

Figure 3c shows an enlarged section of the stratigraphy on line 28d, located several hundred meters north of line 29h. Here the complex character of the basin B fill can be more clearly seen. All basin B profiles are more reflective than the basin A profiles. This may be a function of grain-size, compaction, water content or a combination of the three. Where sampled, the surface sediment in basin B is a gray-green mud. No samples of the two lower units have been collected from basin B.

### Basin C

Five-kilometer-long basin C is located between the east sides of Whaleback and Pointed Islands and the southeast shoreline of Vitus Lake. Two profiles of the basin (Fig. 4a and b) are presented to characterize the glacial-marine fill of basin C. They clearly show the three-part stratigraphy, a 15–20 m thick parallel to sub-parallel reflective unit overlying a 5–25 m thick, more reflective unit, overlying a thinner, highly reflective basal unit characterized by contorted and distorted reflections. The locations of lines 29g (Fig. 4a) and 30e (Fig. 4b), spaced about 500 m apart, both from the central part of basin C, became free from the glacier by 1977.

Figure 5, a profile along line 30d which crosses both basins B and C, shows the much more reflective character of basin C sediment. All basin C profiles are more reflective than nearby basin B profiles. This may be a function of coarser grain-size, compaction, water content or a combination of the three. Where sampled, the surface sediment in basin C is a gray-green sandy mud with a greater sand content than in basins A and B. No samples have been collected of the deeper sediment fill in basin C.

### Basin D

Four-kilometer-diameter basin D, located on the eastern

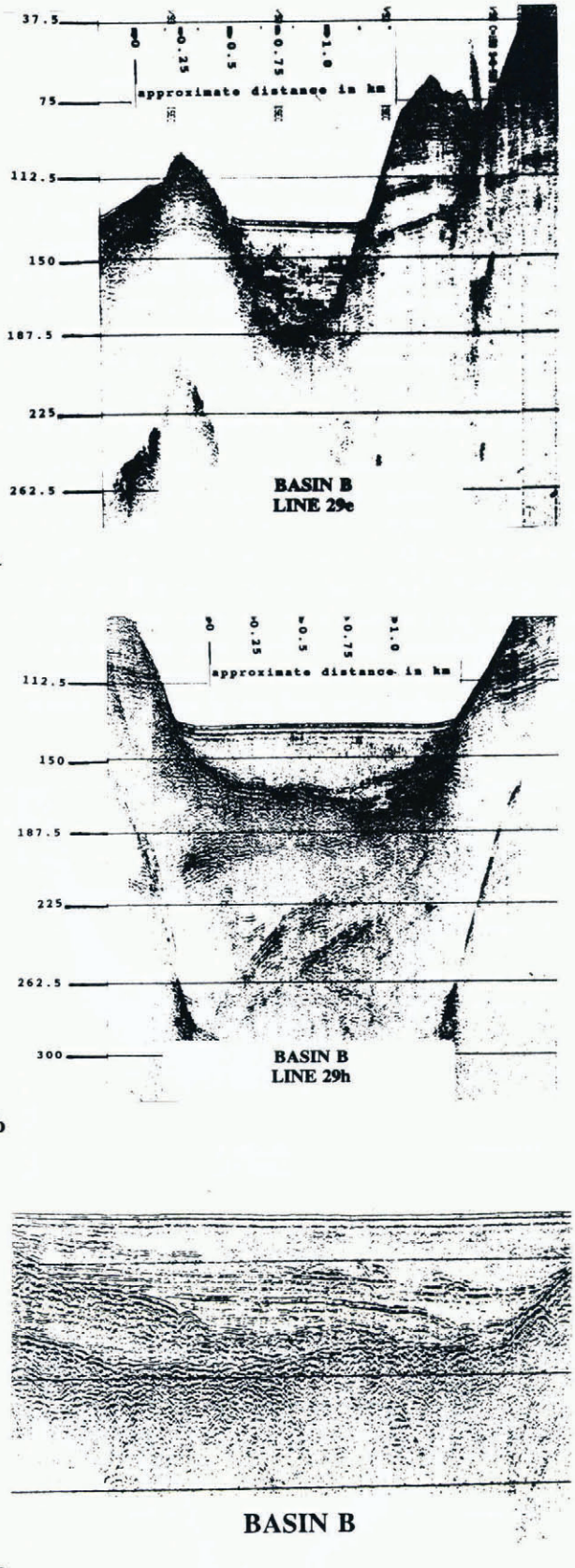


*Fig. 3. Two high-resolution seismic profiles across basin B: (a) east–west along line 29e and (b) west–east along line 29h. In both cases, water depth, in meters, is shown on the lefthand side, and distance, in kilometers, is shown across the top. (c) Close-up of the seismic stratigraphy on line 28d, a northwest–southeast profile across basin B. From left to right, the profile covers a distance of about 2 km. Horizontal depth lines are spaced 37.5 m apart.*

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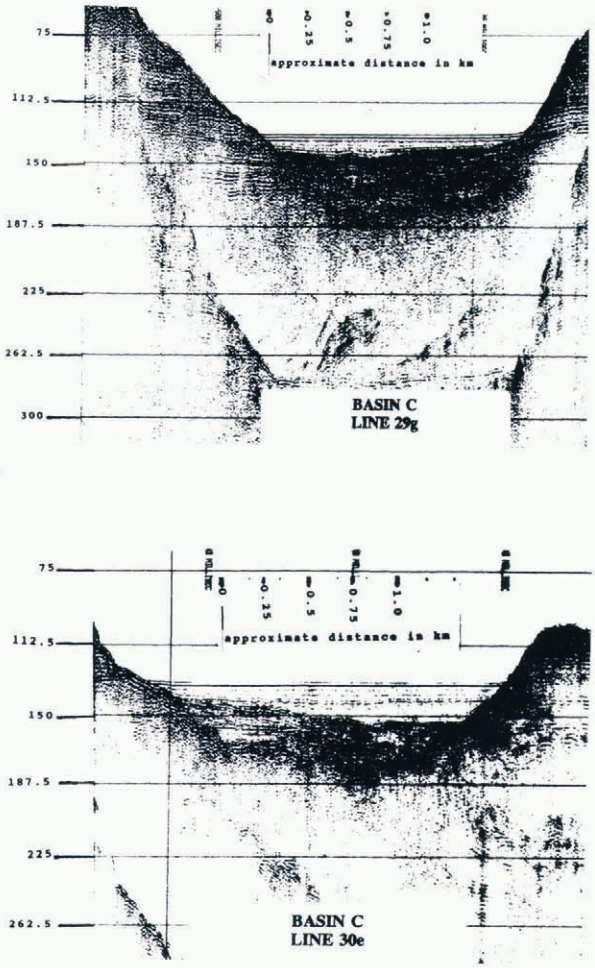


*Fig. 4. Two east–west, high-resolution seismic profiles across basin C along lines 29g (a) and 30e (b). In both cases, water depth, in meters, is shown on the lefthand side, and distance, in kilometers, is shown across the top.*

side of Vitus Lake, is the shallowest of the basins, with a water depth of about 50 m. It is also the "youngest" basin, having been glaciated until after 1980. Here, maximum average annual deposition rates, calculated by dividing sediment thicknesses measured from acoustic records by the number of years that those locations have been ice-free, exceed 10 m. Basin D also contains a three-component glacial-marine sediment section, similar to that in basin A. Three profiles of the basin (Fig. 6a–c) are presented to characterize the glacial-marine fill of basin D. They show the variability that typifies the three-part stratigraphy here and elsewhere within Vitus Lake. Line 39b (Fig. 6a), the southernmost line, shows a 30 m thick unit, characterized by parallel reflections, overlying a steeply dipping, much more reflective unit. This unit overlies a reflective basal unit characterized by contorted and distorted reflections. Lines 34c (Fig. 6b) and 34e (Fig. 6c), located about 1 km apart, both from the central part of basin D, show a 75–100 m thick transparent unit

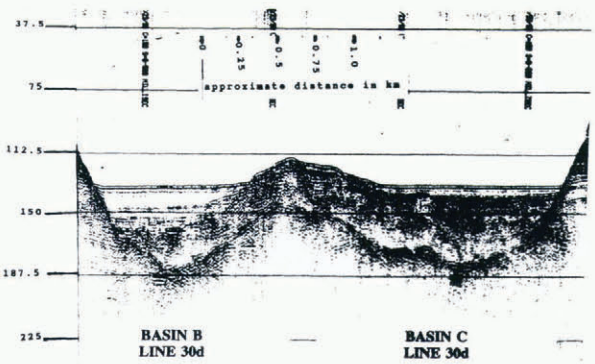


*Fig. 5. West–east, high-resolution seismic profile across basins C and D along line 30d. Water depth, shown on the lefthand side, is in meters, while distance, in kilometers, is shown across the top.*

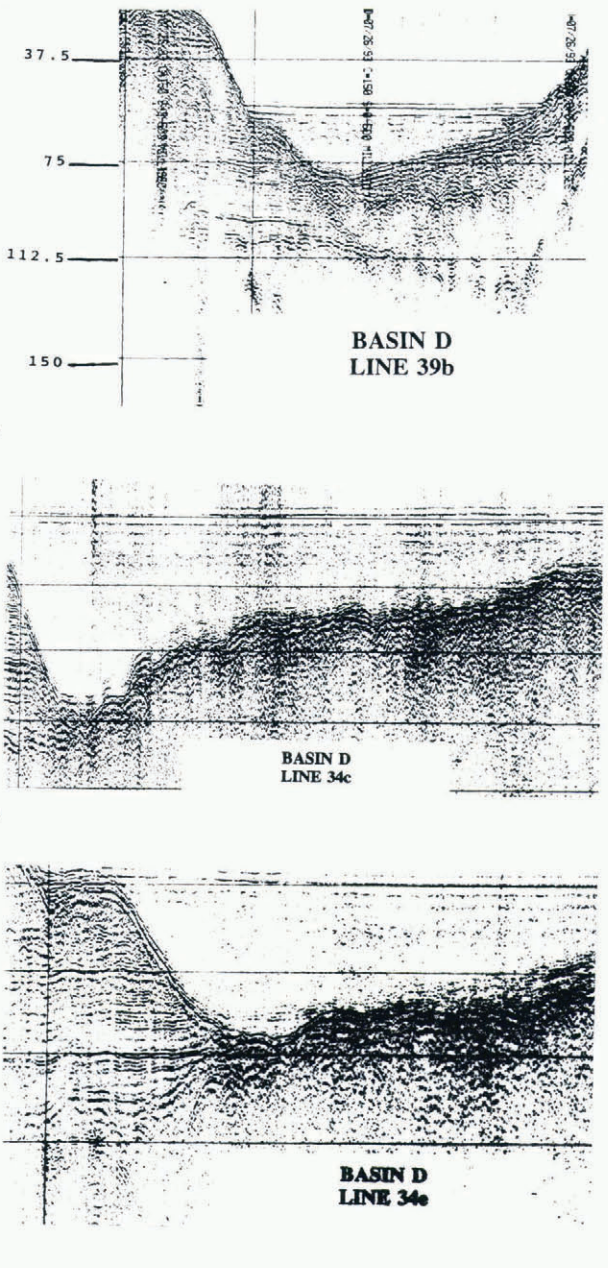


*Fig. 6. West–east, high-resolution seismic profile across basin D along line 39b (a); and two south–north, high-resolution acoustic seismic profiles across basin D along line 34c (b) and line 34e (c). From left to right, the profiles covers a distance of about 2 km. Horizontal depth lines are spaced 37.5 m apart.*

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overlying more reflective and contorted sediment. Both lines are from part of the basin that was ice-covered until after 1984. Sediment samples have not been collected from basin D.

## SUMMARY

Between surges which ended in 1967 and began in 1993, Vitus Lake, the ice-marginal basin which fronts the southeastern margin of Bering Glacier, was the site of modern, rapid, glacial-marine sedimentation. A high-resolution seismic reflection survey, conducted in 1993 in four of Vitus Lake's deeper basins, revealed a complex three-component stratigraphy, inferred to consist of deformed glacial-marine and other glacial deposits, unconformably overlain by acoustically well-stratified glacial-marine sediment, which is conformably overlain by, and grades into, transparent glacial-marine sediment. Maximum thicknesses of conformable glacial-marine sediment fill exceed 100 m. As the transparent and stratified deposits have accumulated since 1967, average maximum sedimentation rates at some locations, based on sediment thicknesses measured on seismic profiles, exceed 10 m year$^{-1}$.

## REFERENCES

Carlson, P. R., A. R. Tagg and B. F. Molnia. 1993a. Acoustic profiles of sediment in a melt-water lake adjacent to the Bering Glacier, Alaska; *RV Karluk* cruise K2-91-YB, July 1–7, 1991. *U.S. Geol. Surv. Open File Rep.* 93-266.

Carlson, P. R., B. F. Molnia and A. Post. 1993b. Pre-Holocene and Holocene erosional and depositional history of Bering Trough and Vitus Lake, Bering Glacier, Alaska. [Abstract] *EOS*, **74**(43), Supplement, 292.

Gray, J. R., R. J. Hart and B. F. Molnia. 1994. 1994 changes in physical and sedimentary characteristics of proglacial Vitus Lake resulting from the surge of Bering Glacier, Alaska. [Abstract] *EOS*, **75**(44), Supplement, 63.

Molnia, B. F. and P. R. Carlson. 1978. Surface sedimentary units of the northern Gulf of Alaska continental shelf. *AAPG Bull.*, **62**(4), 633–643.

Molnia, B. F. and A. Post. 1995. Holocene history of Bering Glacier, Alaska: a prelude to the 1993–94 surge. *Phys. Geogr.*, **16**(2), 87–117.

Molnia, B. F., A. Post, P. R. Carlson and D. C. Trabant. 1991. Evolution and morphology of proglacial Vitus Lake, Bering Glacier, Alaska. [Abstract] *EOS*, **72**(44), Supplement, 158–159.

Trabant, D. C., B. F. Molnia and A. Post. 1991. Bering Glacier, Alaska — bed configuration and potential for calving retreat. [Abstract] *EOS*, **72**(44), Supplement, 159.

https://doi.org/10.3189/1996AoG22-1-205-210 Published online by Cambridge University Press