STRATIGRAPHIC AND SEISMIC ANALYSES OF OFFSHORE YAKATAGA FORMATION SECTIONS, NORTHEAST GULF OF ALASKA

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ABSTRACT

Foraminiferal and sedimentological data from petroleum exploration wells and seismic stratigraphic correlation provide new information on the depositional history of the Yakataga Formation (Fm.), which was deposited on a glaciated, subarctic continental margin. Data from three offshore petroleum exploration wells (Exxon OCS Y-0080 No. 1, Exxon OCS Y-0050 No. 1, and ARCO OCS Y-0007 No. 1) are presented. All three wells penetrated the Quaternary through Pliocene part of the Yakataga Fm., and two wells penetrated the underlying Poul Creek Fm. (Late Miocene to Oligocene). The offshore section contains normal-marine mudstones and sandstones with a few scattered dropstones at the base; and glacial-marine clastics, including muddy sandstones, sandy mudstones, and dropstones are common throughout most of the section.

Six stratigraphic sequences have been identified on the basis of foraminiferal and seismic stratigraphic analyses. Sequence boundaries are recognized as major unconformities that truncate or incise older strata. These boundaries correspond with relative sea-level falls, as identified by benthic foraminiferal biofacies analysis. Several of these unconformities may be due to glacial erosion. In addition to the seven sequence boundaries, over a dozen other horizons that correspond to relative sea-level falls also are recognized in the seismic data. The complex geometric patterns of these sequences are the result of the interplay of tectonics, sedimentation, eustasy, and glacial processes affecting this margin.

INTRODUCTION

The Late Miocene to Recent Yakataga Fm. of the northeastern Gulf of Alaska contains a thick (> 7 km) record of interbedded glacial-marine and normal-marine clastics deposited along a tectonically active continental margin. Its stratigraphic sequence records both the initiation of localized late Cenozoic glaciation in the far North Pacific Ocean and the onset of major northern hemisphere glaciation in the Pliocene (Plafker and Addicott, 1976; Armentrout, 1983; Lagoe, 1983; Eyles et al., 1991). Glacial-marine diamictites in the lowermost Yakataga Fm. at Yakataga Reef represent initial, localized tidewater glaciation during the latest Miocene to earliest Pliocene as uplift continued in the Alaskan coastal ranges (Lagoe et al., 1993). The widespread occurrence of glacial-marine deposits in onshore Yakataga sections, in offshore sections, and in DSDP sites throughout the North Pacific Ocean, indicates the onset of large-scale, regional glaciation in the North Pacific during the mid-Pliocene (3.0-3.5 Ma) (Lagoe et al., 1993)

Outcrop studies have focused on understanding the depositional history of the lower to middle part of the Yakataga Fm. (Plafker and Addicott, 1976; Armentrout, 1983; Lagoe, 1983; Eyles et al., 1991; Lagoe et al., 1993). Until recently, only a few studies were published on the youngest (< 2-3 Ma) part of the Yakataga Fm., which comprises the Gulf of Alaska continental shelf from Montague Island in the west to just east of Yakutat Bay (see Molnia and Carlson, 1978; Lattanzi, 1981; Bruns, 1983, 1985; Bruns and Schwab, 1983; Plafker, 1987). Recent integrated seismic, paleontologic, and well log studies of the offshore Yakataga Fm. (Zellers and Lagoe, 1992; Zellers, 1993) have documented the depositional history of the youngest part of the Yakataga Fm. These offshore studies illustrate the geometries characteristic of depositional sequences throughout the Yakataga Fm. and provide insights into the controls on the formation of these sequences. The purposes of this paper are to: (1) present new biostratigraphic, paleoenvironmental, and lithostratigraphic information for the offshore Yakataga Fm. on the northeastern Gulf of Alaska continental margin (offshore Yakataga continental margin) and (2) describe the seismic stratigraphic sequences within the offshore Yakataga Fm.

DATABASE AND METHODS

The data for this study include well log suites from petroleum exploration wells, ditch cuttings for lithologic and foraminiferal analyses, a few cores from the wells, and a grid of multichannel reflection seismic data (Fig.1). Three of the 11 exploration wells drilled in the northeastern Gulf of Alaska were examined for both planktonic and benthic foraminifera (Fig.2). Also, foraminiferal samples from several other wells and Minerals Management Service consultant reports on the ARCO COST No. 1 well were used.

The following suite of logs is available for each well: Dual Induction SFL, Sonic, Neutron Density, Formation Density, Gamma-Gamma, Dip-meter, and Mud Logs. Well depths cited are in meters below the Kelly bushing. A velocity survey from Exxon OCS Y-0050 No. 1 was used for velocity control to tie well information to the seismic data for depths less than 3,000 m. For greater depths, the travel-time-to-depth conversions of Bruns and Schwab (1983), based on seismic stacking velocities, are used as estimates.

Approximately 1,200 km of a grid of 24- to 48-fold multichannel reflection seismic data collected during 1975 by the U.S. Geological Survey with the M/V *Cecil H. Green* were used in this study (Fig.1). An additional 1,800 km of data from the M/V *Cecil H. Green* and the R/V *S.P. Lee* are available for further research. The seismic data used in this study are unmigrated. Information about the acquisition and processing of this data can be found in Bruns (1985).

Sequence boundaries are defined here as horizons, representing relative sea-level falls, that truncate or incise older strata (Fig.3). Estimations of the age of sequence boundaries and the duration of sequences are made largely on the basis of planktonic foraminiferal biostratig-

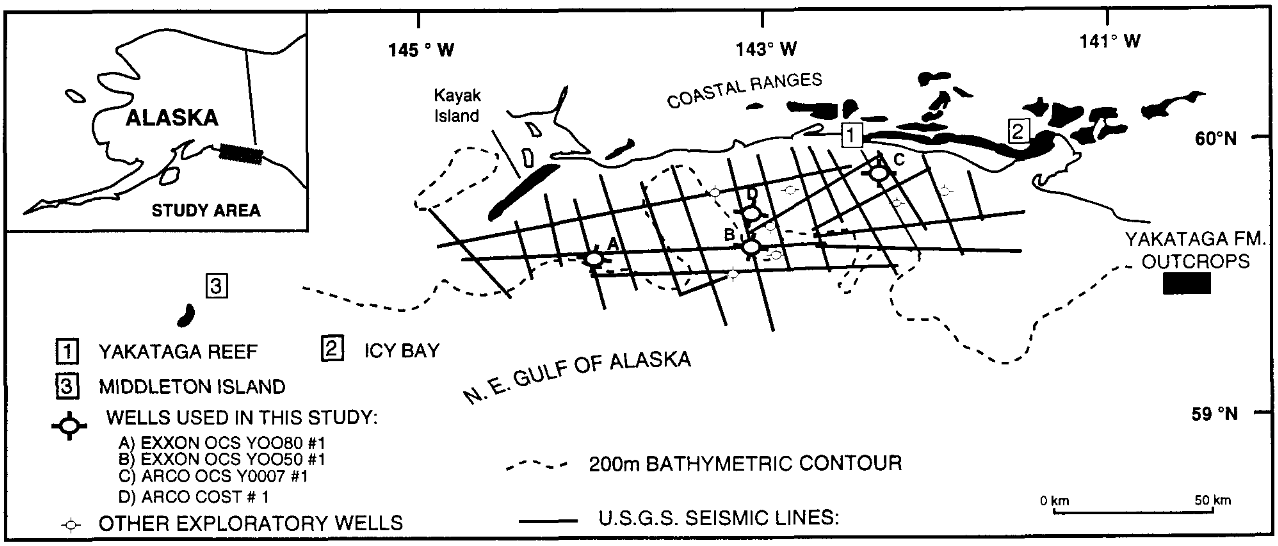

Fig.1. Location map, showing seismic lines used in this study and in the available database, exploration wells, and key Yakataga outcrops. Modified from Bruns (1983) and Bruns and Schwab (1983).

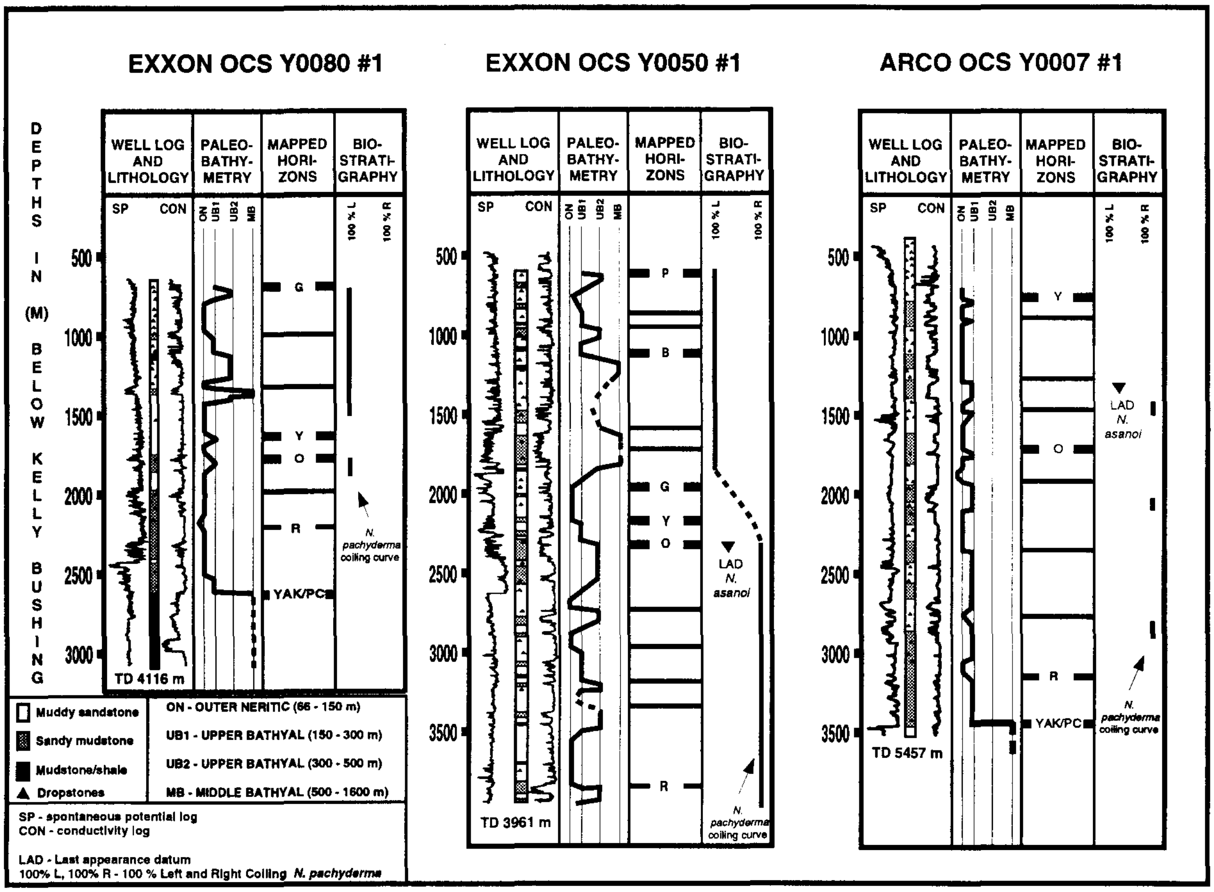

Fig. 2. Summary diagram of lithologic, biostratigraphic, and paleobathymetric in formation for the Exxon OCS Y-0080 No. 1, Exxon OCS Y-0050 No. 1, and ARCO OCS Y -0007 No. 1 wells. Wells are displayed from west (left) to east (right). For each well, column 1 shows Spontaneous Potential (SP) and Conductivity (CON) curves with lithologies interpreted from mud logs; column 2 shows paleobathymetry interpreted from foraminiferal assemblages; column 3 shows horizons mapped throughout the seismic grid that correspond to relative sea-level falls as identified by paleobathymetric determinations. Column 4 provides biostratigraphic information including: (1) the local last appearance datum of Neogloboquadrina asanoi whose extinction is at 1.8 Ma and (2) the distribution of left- and right-coiling N. pachyderma.

raphy using the North Pacific Neogene chronostratigraphic framework refined by Lagoe and Thompson (1988) and Lagoe (1992). The important biostratigraphic events used here are the changes in coiling ratios of *Neogloboquadrina pachyderma* and the extinction of *Neogloboquadrina asanoi* at 1.8 Ma (LAD-last appearance datum). Major changes in the coiling of *N. pachyderma* occur at 1.3 Ma (CD10 [left]/CD11[right]), 1.8 Ma (CD11 [right]/CD12 [left]), and 2.5 Ma (CD14 [left]/CD15 [right]).

The following paleoenvironments and the key benthic foraminifera used in defining them have been identified in the offshore Yakataga Fm.: inner neritic, 0 to 66 m (*Elphidium excavatum clavatum* and *Buccella frigida*); outer neritic, 66 to 150 m (*Cassidulina spp.*); uppermost bathyal (UB1), 150 to 300 m (*Epistominella pacifica*); lower upper bathyal (UB2), 300 to 500 m (*Uvigerina peregrina*); and middle bathyal, 500 to 1600 m (*Bolivina spissa*).

Bruns and Schwab (1983) documented a series of broad, northeasterly trending anticlines and high-angle thrust faults on the Yakataga continental shelf and upper slope that show a seaward, southeasterly progression of deformation through time. Although the horizons mapped in this study are different than those mapped by Bruns and Schwab (1983) using the same data, similar conclusions regarding the structural development of the Yakataga continental margin can be drawn. This study adds to the work of Bruns and Schwab (1983) by providing more direct age, paleoenvironmental, and lithostratigraphic information for the offshore section. For convenience, this study uses the letter and number designation for anticlines of Bruns and Schwab (1983) (e.g., A7 for the A7 anticline, see Fig.3).

RESULTS--SEQUENCE INTERPRETATIONS

Offshore, the Yakataga Fm. is over 7 km thick (> 4.6 s) in the central part of the shelf (Fig.3d) and thins to as little as 1 km near Yakataga Reef (Fig.1) as the result of erosion. The contact between the Yakataga and Poul Creek is recognized offshore in several wells using both paleontological and sedimentological evidence. Paleontological evidence for this boundary includes the first occurrence of *Elphidium excavatum clavatum*, a subarctic/arctic benthic foraminifer. Physical sedimentologic evidence for this contact includes the last occurrence of glauconite and the first occurrence of dropstones. In the eastern part of the study area (Fig.1), at the ARCO Y-0007 No. 1 well, the Yakataga/Poul Creek contact is an unconformity (Yak/PC) separating mid-Pliocene glacial-marine shelf deposits (< 150 m of water depth) from deep water (> 500 m of water depth) Oligocene rocks of the Poul Creek Fm. In the western part of the study area, at Exxon Y-0080 No. 1, the Yakataga/Poul Creek boundary separates mid-Pliocene Yakataga deposits from upper Miocene Poul Creek rocks (Lattanzi, 1981), indicating that the age of this unconformity is no older than late Miocene. The age of the onshore Yakataga/Poul Creek boundary at Yakataga Reef, based on foraminiferal biostratigraphy and magnetostratigraphy, is considered to be 5 to 6.5 Ma (see Lagoe et al., 1993). The age of the Yakataga/PoulCreek boundary in the offshore section therefore is approximately considered to be in the range of 5 to 6.5 Ma (late Miocene) and to average 5.7 Ma.

Six stratigraphic sequences have been identified within the Yakataga Fm. on the continental shelf between Kayak Island to the west and Icy Bay to the east. Starting with the oldest, these sequences are: Yak/PC to O, O to Y, Y to G, G to B, B to P, and P to the sea floor. The thickness, lithology, paleobathymetry, and age of each sequence are described below.

Sequence Yak/PC to O

The oldest and thickest Yakataga sequence, Yak/PC to O, exceeds 2,500 m in the central part of the shelf near anticline A7 and thins to 850 m near anticline A11 to the west. The sequence is bounded by horizon O, an unconformity that truncates older strata to the west of anticline A7 (Fig.3d).

Sequence Yak/PC to O consists of sandy mudstones and minor interbedded muddy sandstones with scattered outsized clasts that are interpreted as dropstones. This sequence can be further divided into two distinct units separated by horizon R: (1) a lower unit that mainly contains mudstones with only a few scattered dropstones at the base (Yak/PC to R), and (2) an upper unit containing increased amounts of sandy material and abundant dropstones (R to O). The upper unit is penetrated by all three wells studied; however, the Exxon OCS Y-0050 No. 1 well just penetrates the uppermost part of the lower unit. The lower unit contains scattered dropstones, suggesting only a minor influence of glacial-marine sedimentation, whereas abundant dropstones in the upper unit indicate common glacial-marine conditions.

Paleobathymetry within sequence Yak/PC to O varies locally (Fig.2). To the west, at the Exxon OCS Y-0080 No. 1 well, paleobathymetry ranges from inner neritic to uppermost bathyal; however, it is mainly in the outer neritic zone. In the central study area, at the Exxon OCS Y-0050 No. 1 well, paleobathymetries within the R to O unit fluctuate episodically from outer neritic to middle bathyal. To the northeast, at the ARCO OCS Y-0007 No. 1 well, paleobathymetry ranges from outer neritic to uppermost bathyal.

Strata within sequence Yak/PC to O contain right-coiling *N. pachyderma* and *N. asanoi*, which places a minimum age of 1.8 Ma (LAD of *N. asanoi*) for the top of this sequence (Fig.2). It is likely, however, that the age of horizon O is older than 1.8 Ma because the LAD of *N. asanoi* is usually in a left-coiling zone (zone CD12 of Lagoe and Thompson, 1988). The youngest co-occurrence of *N. asanoi* with consistent right-coiling *N. pachyderma* assemblages is at the top of the CD15 zone, which is dated at 2.5 Ma (Lagoe and Thompson, 1988). Therefore, horizon O probably is no younger than 2.5 Ma. Horizon R represents the lowest occurrence of abundant dropstones in the three wells studied. Strata just below horizon R, penetrated in the Exxon Y-0080 No. 1 (2,154 to 2,425 m) and ARCO Y-0007 No. 1 (3,190 to 3,425 m) wells, which have no dropstones, are interpreted as having been deposited within a mid-Pliocene warm event (Lagoe et al., 1993) lasting from 3.5 to 4.2 M. This places a maximum age of 3.5 Ma on horizon R. Basal Yakataga strata in the Exxon OCS Y-0800 No. 1

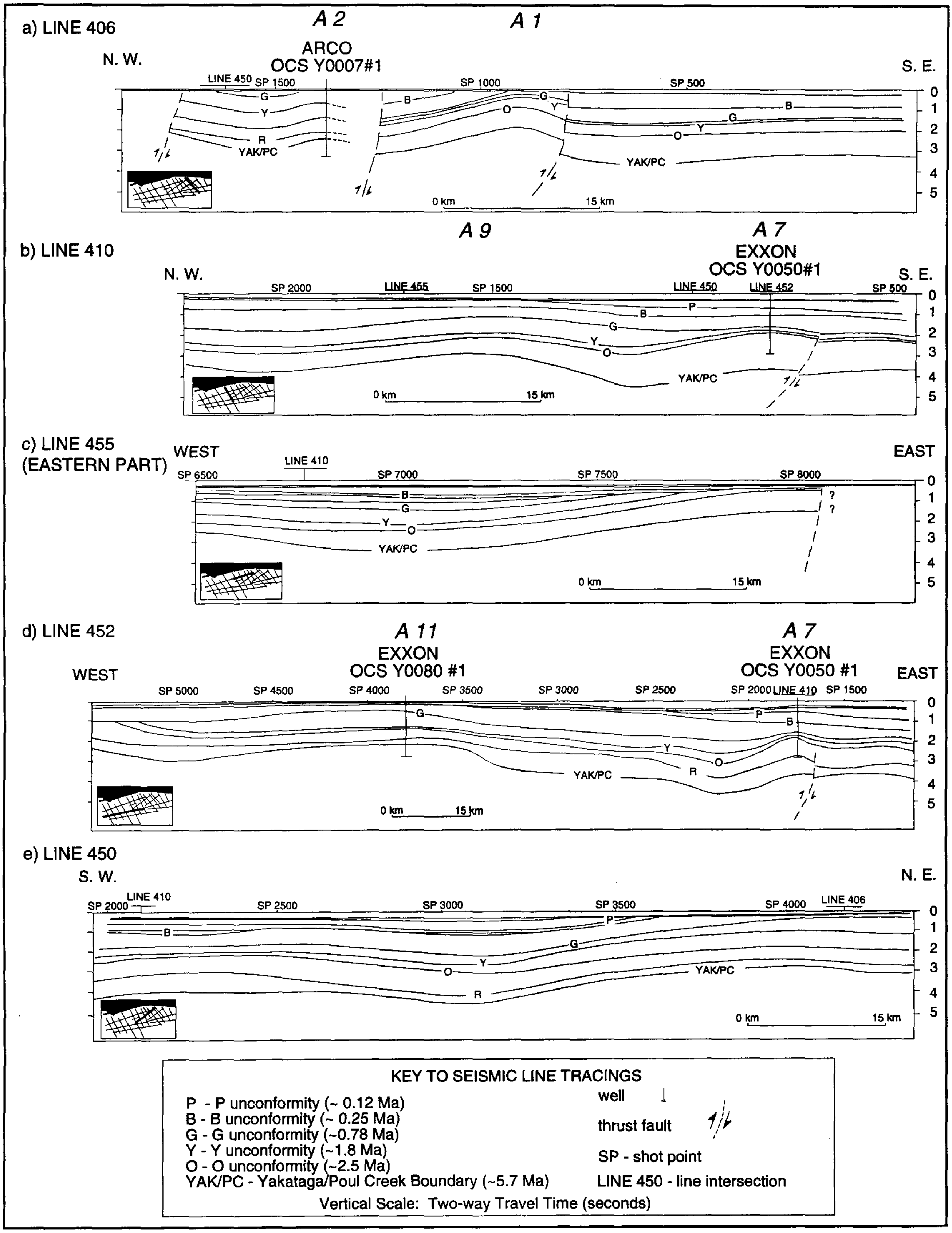

Fig. 3. Line tracings of selected seismic lines showing the unconformities and horizons mapped, showing well locations, and illustrating the geometries of the seismic sequences. Original seismic data for lines 406 and 410 are displayed in Bruns and Schwab (1983).

and ARCO OCS Y-0007 No. 1 wells contain a few dropstones. These sediments may be correlative with the lowermost diamictites at Yakataga Reef (Lagoe et al., 1993) and hence may represent initiation of tidewater glaciation along this margin. Sequence Yak/PC to O ranges in age from 5.7 to 2.5 Ma.

Sequence O to Y

Sequence O to Y is more than 1,000 m thick in the northeastern part of the study area near anticline A2 and thins to less than 150 m near anticlines A7 and A11 (Fig.3) due to uplift on these anticlines. Horizon Y is an unconformity that truncates older strata in the central part of the area (Fig.3d,e). The lowermost strata of this sequence onlap horizon O (Fig.3e).

In the western and central part of the area, sequence O to Y consists of interbedded muddy sandstones and sandy mudstones with a few dropstones. At the ARCO Y-0007 No. 1 well, the thickest part of this sequence contains interbedded muddy sandstones with dropstones and sandy mudstones with no dropstones, suggesting intermittent normal and glacial-marine conditions.

Paleobathymetry within this sequence ranges from outer neritic to uppermost bathyal (Fig.2). Paleobathymetry is variable in the west and the east; however, there is an overall decrease in water depth in the center of the area at the Exxon OCS Y-0050 No. 1 well as a result of continued uplift of anticline A7.

Sequence O to Y contains sparse right-coiling *N. pachyderma* and *N. asanoi* assemblages. The minimum age of the top of this sequence is considered to be 1.8 Ma, which is the extinction of *N. asanoi* (Lagoe and Thompson, 1988). The maximum age is constrained by the age of horizon O, which is discussed above. This sequence ranges in age from 2.5 to 1.8 Ma.

Sequence Y to G

Sequence Y to G varies in thickness from over 1,000 m in the west to less than 150 m to the southeast (Fig.3). It is eroded at anticline A2. Horizon G is a major unconformity that truncates uplifted strata at anticline A7 and near the Kayak Island platform to the west.

Lithologies in this sequence are mainly muddy sandstones with thin interbeds of sandy mudstone and increasing abundance of dropstones. Unlike the underlying unit, the sandy mudstones and muddy sandstones both contain dropstones, which indicates more continuous glacial-marine conditions.

In the central part of the study area, an outer neritic environment existed within sequence Y to G (Fig.2). To the west, paleobathymetries fluctuate from outer neritic to middle bathyal.

The age of horizon G is difficult to determine but probably is older than 0.25 Ma, which is the maximum date assigned by diatoms in the ARCO COST No. 1 well for horizon B (Minerals Management Service, pers. commun., 1992), and younger than 1.3 Ma due to the dominantly left-coiling populations of *N. pachyderma* within sequence Y to G (Fig.2). Therefore, the age for horizon G ranges from >0.25 to <1.3 Ma, with a midpoint of 0.78; and the age for sequence Y to G ranges from approximately 1.8 to 0.78 Ma.

Sequence G to B

The G to B sequence ranges in thickness from 800 to 2,000 m in the central and southeast parts of the study area, but it is absent due to erosion in the west and northeast (Fig.3). The sequence is bounded at the top by horizon B, a major unconformity that truncates older sequences toward the shoreline in the northern part of the area (Fig.3). Within this sequence is an additional unconformity associated with the final uplift of anticline A7 (Fig.3d); however, the unconformity has not yet been mapped throughout the study area.

Of the wells studied, lithologic and paleontologic information for sequence G to B is available only from the Exxon OCS Y-0050 No. 1 well. This sequence does, however, occur at the top of anticline A11 at the Exxon OCS Y-0080 No. 1 well; but no ditch samples were retrieved at well depths of less than 500 m. Sandy mudstones are dominant at the base of this sequence and muddy sandstones occur at the top. Dropstones are common throughout the sequence.

Locally, the base of the sequence G to B shows a deepening from an outer neritic to middle bathyal environment. Throughout the rest of the sequence, paleoenvironments range from uppermost bathyal through middle bathyal (Fig.2).

As stated above, the age of horizon B is considered to be no older than 0.25 Ma, suggesting a range in age of 0.78 to 0.25 Ma for sequence G to B.

Sequences B to P and P to Sea Floor

Sequence B to P, which occurs only in the central part of the study area, is about 500 m thick at anticline A7 (Fig.3b,d). The sequence thickens seaward and thins toward the northeast and the west. Horizon P truncates strata in the central part of the shelf (Fig.3d,e). The age of horizon P is not well constrained but is estimated at 0.12 Ma based on the midpoint between the ages of the sea floor and B (0 to 0.25 Ma). Lithologies are similar to the underlying sequence and also represent fluctuating paleobathymetries ranging from outer neritic to middle bathyal.

DISCUSSION

The complex geometries of the six stratigraphic sequences are the result of deposition, deformation, and erosion along this glaciated, active continental margin. The major sequence boundaries are unconformities that truncate strata uplifted at anticlines (Fig.3a,b,d) or platforms (Fig.3c,e). In addition, several of these unconformities also form large incised valleys that erode older strata (horizon B, shotpoints 2000-2500; horizon P, shotpoints 2700-3500; Fig.3e) and are in turn filled with younger deposits. The unconformities may be formed by subaerial, submarine, or glacial erosion. There is no evidence to support regional subaerial erosion of the offshore Yakataga section; with the exception of a few samples containing only inner neritic taxa (~10 m water depth) (Fig.2), the shallowest paleoenvironments are in the outer neritic zone (> 66 m). The incised valleys may be due then to either submarine erosion or erosion by glacial ice. The troughs and valleys that intersect the present-day Gulf of Alaska margin are considered to be glacially eroded, because they are incised into more lithified units, are U-shaped, have concave logitudinal profiles, and contain glacial deposits in their fill (Carlson et al., 1982).

The varying thicknesses of the sequences can be explained by erosion, increases in sediment-accumulation rates, localized uplifts, and the shifting of depocenters along the margin through time. Sediment accumulation rates for the Yakataga Fm. were high and increased over time. Uncorrected for compaction, accumulation rates are estimated to be in the hundreds, thousands, and several thousands of meters per million years in the lower, middle, and upper parts of the formation, respectively (Zellers, 1993; Lagoe et al., 1993). Changing thicknesses within the sequences also may be the result of lateral changes in the position of the major depocenter or changes in subsidence along the margin through time.

Paleobathymetric fluctuations in the offshore Yakataga Fm. probably are largely a function of local processes (uplift, subsidence, and sediment loading), and less a function of eustatic sea-level changes. A prominent deepening of more than 500 m at the base of sequence G to B (Fig.2 - Exxon OCS Y-0050 No. 1) corresponds with a major cooling of surface waters, as suggested by the shift to left-coiling *N. pachyderma.* Large relative sea-level changes such as this argue for a strong tectonic control on deposition along this margin. Changes greater than the range of eustatic changes (ca. < 130 m) argue against the simple linkage between regional climate change, glacial-marine sedimentation, and relative sea level (i.e., regional glaciation corresponds with lowered sea level).

CONCLUSIONS

Six stratigraphic sequences within the offshore Yakataga Fm. are recognized on the basis of integrated biostratigraphic, paleoenvironmental, well log, and seismic stratigraphic analyses. The geometries of these stratigraphic sequences are complex and are the result of the interplay between tectonics, sedimentation, sea level, and glacial processes affecting this margin.

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