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MAP, CROSS SECTIONS, AND CHART SHOWING LATE QUATERNARY FAULTS, FOLDS, AND EARTHQUAKE EPICENTERS ON THE ALASKAN BEAUFORT SHELF

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INTRODUCTION

Geologically youthful structures are locally numerous on the Alaskan Beaufort shelf. These features can be grouped into provinces of (1) deep-reaching landslides and related listric normal faults near the shelf break, (2) apparently aseismic normal faults and related monoclines on the central and western shelf, and (3) broad folds, monoclines, and faults in a seismogenic zone on the eastern shelf. The distribution and geologic character of these near-surface structures provide insights into the deeper geologic structure of the Beaufort shelf and slope that may be useful to petroleum exploration. They also provide information on the mobility of the near-surface and surface materials that may constrain the safe development of the considerable oil and gas resources thought to underlie the area (Grantz and others, 1980). Preliminary assessment and overview of the environmental geology of the Alaskan Beaufort shelf, including late Quaternary folds, faults and earthquakes, are given in Grantz and Dinter (1980).

Surface movement along the faults or other apparently active structures discussed in this report could disrupt petroleum production and transportation facilities on the Beaufort shelf, possibly causing blowouts and spills of oil, gas, or formation water. The U.S. Bureau of Land Management (1979) has concluded that such accidents near shore between the Colville and Canning Rivers could have serious adverse ecologic consequences. This report indicates areas of the shelf subject to hazards of disruption of the seabed by tectonic movement. With a companion report (Dinter, 1982), it shows where thick unconsolidated sediment lies adjacent to tectonically active and seismogenic terranes. Such areas would be especially prone to strong ground motion and failure during earthquakes.

The distribution and character of youthful geologic structures of the Alaskan Beaufort shelf are presented on sheet 1. The data are shown on a new bathymetric map of the Beaufort Sea prepared by Greenberg and others (1981). Line drawings showing cross sections of typical structures as observed on both high- and low-frequency seismic reflection profiles are shown on sheet 2, and a chart depicting a tentative displacement history of the mapped faults and monoclines is presented on sheet 3.

DATA BASE AND ITS LIMITATIONS

Seismic-reflection data

High-resolution seismic-reflection profiles obtained in 1977 by the U.S. Geological Survey Research Vessel <u>S. P. Lee</u> (Grantz and Greenberg, 1981) were used to map and tentatively to date the movement history of near-surface geologic structures on the Alaskan Beaufort shelf. The profiles cover most of the middle and outer shelf between the 20- and 600-m isobaths. Six hundred meters is the maximum water depth at which the high-resolution seismic system obtained useful data. Most of the tracklines trend normal to the shelf break and are spaced 15 to 25 km apart (sheet 1). Tie lines are roughly parallel to the shelf break. Because of the grid spacing, fewer than half of the structures mapped on sheet 1 were crossed on more than one seismic profile. Strikes of structures crossed only once have been inferred from regional trends or from the trends of nearby local structures. Maximum uncertainties in position obtained by the integrated satellite-doppler sonar navigation system on the R/V <u>S. P. Lee</u> in 1977 are estimated to be about 1 km.

The Uniboom[1] seismic-reflection system used for the survey employs a hull-mounted transducer and a short single-channel streamer towed with an offset of 32 m. Amplifiers were filtered to pass signals in the 300- to 1,500-Hz range. Structural offsets as small as 1 m are discernible on the best profiles. Sub-bottom acoustic penetration was commonly 0.1 to 0.15 seconds of two-way seismic travel time, but, in especially favorable areas when seas were calm, penetration ranged to as much as 0.2 to 0.4 seconds. Offsets along near-surface geologic structures (sheets 1 and 3) were calculated assuming a sedimentary sound velocity of 1,500 m/s, a choice inferred from interval velocities derived from the processing of coincident multichannel seismic-reflection and sonobuoy refraction profiles.

The chief inhomogeneities in the data were introduced by sea state. Noise and strong motion of the streamer and the hull-mounted transducer during occasional storms strongly degraded the seismic profiles. At such times, indicated by a marked sinusoidal-like waviness of reflections on the high-resolution profiles, only strongly reflective shallow features were recorded. These effects, combined with water depth and local variations in acoustic properties of the shallow sedimentary deposits, created considerable variation in the depth to which the young geologic structures could be resolved.

Except on turns between the generally linear tracklines, low-frequency single-channel and multichannel seismic-reflection profiles were recorded coincidentally with most of the Uniboom profiles. All structures mapped from the high-resolution profiles were also examined on the low-frequency profiles in order to determine their deeper structural character, approximate dip, and relation to regional geologic structure.

[1]Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

Earthquake data

The epicenters shown on sheet 1 represent all earthquakes in the map area located by the northern and central Alaska seismographic networks of the Geophysical Institute (University of Alaska) and by the regional seismographic network of Canada during the period 1968-78. Earthquakes prior to 1968 were excluded because the data are too incomplete.

The Canadian locations are least-squares solutions for a one-layer, 36-km-thick crust having hypocentral depths constrained to mid-layer (18 km). A general estimate of errors in Canadian locations of epicenters is about $\pm$ 100 km (Basham and others, 1977). Locations determined by the Geophysical Institute are based on the weighted least-squares method of Lee and Lahr (1975). The P-wave velocity structure used is given by Biswas and others (1977). The hypocentral depths were constrained to 10 km. For most of these events the epicentral location errors are about $\pm$15 to 20 km.

The magnitude of the earthquakes shown ranges from about 0.5 to 5.3. The largest event (M = 5.3) occurred about 30 km off shore of Barter Island in 1968. Many events had magnitudes between 3.0 and 5.0, and a significant number of these were between M = 4.0 and M = 5.0.

The location of stations in the Geophysical Institute seismograph network in northeast Alaska (Biswas and Gedney, 1978) was such that all events greater than magnitude 3.0 in the northeast Brooks Range and the eastern part of the coastal plain to the west would have been recorded. Given the large number of events greater than M = 3.0 recorded by the network, and the fact that the network operated during parts of three years, the absence of epicenters from the coastal plain west of the mountain front and the Canning displacement zone (sheet 1) is thought to be tectonically significant.

GEOLOGIC FRAMEWORK

The regional extent and structural character of each of the three provinces of young, near-surface structures can be related to major features of the regional geology of the Alaskan Beaufort shelf and slope. In order to demonstrate the connection a synopsis of the regional geology, presented in greater detail by Grantz and others (1979), is included here.

The Atlantic-type continental margin off northern Alaska is postulated to have been created by rifting that separated the present North Slope of Alaska from the western Arctic Islands of Canada by sundering a formerly stable shelf, the Arctic platform. The Arctic platform was cut by erosion across mildly metamorphosed early Paleozoic bedded rocks during Late Devonian and Early Mississippian time and then covered by shelf-facies clastic and carbonate rocks during Mississippian to Triassic time. Breakup of the platform, and the beginning of drift, occurred about 120 m.y. B.P.

The geometry of the nascent rift divided the continental margin east of long 160° W. into two discrete structural sectors. This division has largely controlled the post-Triassic geologic development of the northern Alaskan continental margin. In the western, or Barrow, sector, which lies west of the Canning River, the edge of the rifted margin is thought to underlie the slope or upper rise, and a well-defined tectonic hinge line (sheet 1) underlies the middle and outer shelf. The hinge line is a flexure in the Arctic platform north of which the platform was heated, uplifted, and deeply eroded during the initial stages of rifting, and then cooled and subsided as the seafloor spreading center moved away from the margin. The eroded Arctic platform steepens in slope at the hinge line and descends northward through a transition zone to oceanic depths beneath the continental rise. As most of the shelf in the Barrow sector is underlain by the Arctic platform, the sector is characterized by relative tectonic stability. During Cretaceous and Tertiary time, clastic sedimentary materials derived from southerly (Brooks Range) sources prograded across the platform in the Barrow sector to form a thick and stratigraphically complex, but in general little-deformed, continental-terrace sedimentary prism. These sedimentary rocks are assigned to the Brookian sequence of Lerand (1973) as modified by Grantz and others (1979).

In the eastern, or Barter Island, sector of the continental margin, which lies east of the Canning River, the edge of the rifted margin is thought to lie beneath the shelf, and the hinge line lies shoreward of our seismic profiles, probably near the present coastline. The stable Arctic platform, which lies south of the hinge line, is therefore believed to be mostly absent beneath the shelf in this sector (Grantz and others, 1979). The Brookian sedimentary wedge beneath the shelf here is thicker than in the Barrow sector, and is thought to contain thick sections of Jurassic as well as Cretaceous and Tertiary strata. The Brookian sequence here is also much more complex structurally and contains deep subbasins. A few long, large-amplitude folds dominate the structure of the inner shelf in the Barter Island sector, and numerous smaller diapiric folds underlie the continental slope and rise. The folds in the eastern part of the sector are shale-cored structures of irregular shape and northwest strike. Those in the western part are detachment folds of more regular morphology and southwest strike.

The detachment folds of the eastern Beaufort shelf appear to be related spatially, and probably genetically, to a broad zone of uplift and distributed left-lateral displacement that follows the west face of the northeast Brooks Range (sheet 1). Because part of it follows the lower Canning River, the feature is here named the Canning displacement zone. The existence of a zone of "...either left- or right-lateral movement..." along the lower Canning River was postulated by Blanton (1970, p. K-14) on the basis of regional structural and stratigraphic trends. We read Blanton's brief note, which was not accompanied by maps, to suggest that the movement followed a subsurface disturbed zone that trended north from the Canning River at about 69°30' N. through the Marsh anticline. From near 69°30' N. the subsurface disturbed zone trends westerly and passes south of Umiat.

Evidence for the Canning displacement zone is physiographic, seismic, and structural, but the structural evidence is subtle, presumably because the zone is in an early stage of development. Physiographically, the zone is defined for much of its length by the northwest-facing, northeast-trending west front of the northeast Brooks Range (sheet 1). This front is at or near the west limit of major late Quaternary uplift in northeast Alaska (T. D. Hamilton, written commun., 1981). Seismically, the zone is marked by the west margin of a belt of teleseismic earthquake epicenters that trends southwest from Camden Bay toward the junction of the Yukon and Tanana Rivers (Meyers, 1976). Epicenters of the mainly smaller earthquakes shown on sheet 1, most of which were located by local and regional seismographic networks, also extend only as far west as the displacement zone. Structural evidence for the zone is of three kinds. First, Laramide structural trends are rotated counterclockwise in a broad zone across the mountain front. The geometry of the rotation suggests that the eastern Brooks Range moved about 25 to 50 km northward along the displacement zone with respect to the aseismic terrane to the west (Grantz and others, 1979, p. 284). Second, late Paleozoic and early Mesozoic strata are folded in the northeast

Brooks Range, whereas the same beds are generally flat beneath the lowland to the west. Third, the detachment folds and associated earthquake epicenters of the Camden Bay area of the Beaufort shelf, and apparently the Marsh anticline of the Arctic coastal plain near Camden Bay, terminate near the projection of the displacement zone. Taken together, these physiographic, seismic, and structural features suggest that the Canning displacement zone is a young, active, mainly strike-slip zone of displacement along which the northeast Brooks Range is moving northward, but also upward, with respect to the lowland to the west. The detachment character of the folds near Camden Bay suggests two structural models for their origin. The folds may be the structural front of an active, low angle thrust fault system that dips beneath the northeast Brooks Range and is bounded on the west by the Canning displacement zone. Alternatively, the folds may be developed in one or more gravity slides underlain by listric detachment faults that rise to the surface between the folds and the front of the northeast Brooks Range. The gradient for sliding could have been created by the observed uplift and northward translation of these mountains. Nearshore and onshore seismic data will be required to test these models.

DATING METHODS AND LATE QUATERNARY STRATIGRAPHY

The faults and monoclines mapped on sheet 1 displace seismic reflectors that correspond either to bedding or to disconformities within approximately the uppermost 300 m of sediment on the Alaskan Beaufort shelf. The age ranges of young movements assigned to the faults and monoclines (sheets 1 and 3) are based solely on a tentative interpretation of the ages of the involved strata and contacts as observed on the high-resolution seismic-reflection profiles. From an environmental or engineering-geologic standpoint, the most important structures are those which are presently, or were recently, active--that is, those faults that displace upper Pleistocene deposits, Holocene deposits, or the seabed. Fortunately, these deposits can be dated with relatively little ambiguity from stratigraphic relations observed on the high-resolution profiles. Activity along faults and monoclines that displace older strata is dated with less confidence, and the ages of movement reported for these beds are probably more useful in establishing a relative, rather than an absolute, chronology of faulting and monoclinal folding on the Beaufort shelf.

Faults and monoclines reported to show evidence of Holocene activity offset either the seabed or bedding internal to a late Wisconsin/Holocene stratum called unit A by Dinter (1982). For emphasis, these structural features are marked with a ball on sheet 1. Because much of unit A is probably older than the Pleistocene-Holocene boundary arbitrarily defined at roughly 10,000 years B.P. by Hopkins (1975), faults and monoclines that displace unit A may be latest pre-Holocene. As explained below, even the oldest beds at the base of unit A beneath the outer shelf postdate the maximum development of the latest Wisconsin glaciation, and none exceed 17,000 years in age. For convenience, because there is no presently recognized stratigraphic feature that defines the 10,000 year isochron in unit A, we arbitrarily refer all features which displace any part of unit A to the Holocene even though most parts of the unit may be older than 10,000 years. In doing so, we do not intend a revision of the definition of the Pleistocene-Holocene boundary at 10,000 years B.P. (Hopkins, 1975).

Unit A is a stratum that apparently represents nearly continuous marine deposition during the early phases of the rise in sea level following subaerial exposure of the shelf during the final Wisconsin eustatic sea level minimum. The stratum is bounded at its base by a disconformity and is underlain, in places, by a thin nonmarine or shallow-marine stratum, unit B of Dinter (1982). This unit is thought to represent subaerial exposure of the shelf during the late Wisconsin glaciation, which culminated about 17,000 years ago when sea level was approximately 100 m lower than at present (Dillon and Oldale, 1978). The age interpretation of these strata is corroborated by the fact that the disconformity at the base of unit A becomes indistinct and dies out seaward at a depth of 97 to 115 m below sea level, roughly the same depth as the late Wisconsin sea-level minimum. The uppermost sedimentary deposits seaward of the termination of the disconformity show vague but continuous bedding at least as deep as 150 to 200 m beneath the sea floor and probably represent intermittent marine deposition from at least middle Wisconsin through early Holocene time.

Beneath much of the middle and outer Beaufort shelf, units A and B are underlain by at least four marine strata separated by prominent disconformities and, in places, by thin layers similar in reflection character to unit B. The penetration limit of the Uniboom high-resolution system is such that no more than four underlying marine layers can be interpreted with confidence, and record quality is variable enough that not all four layers are penetrated on every line, nor can these layers be uniformly correlated from line to line, as is possible with units A and B.

On the presumption that each worldwide high stand of sea level would be accompanied by the accumulation of sediment on the outer Beaufort shelf, each interpreted marine stratum has been tentatively correlated (sheet 3) with an odd-numbered oxygen-isotope stage of Shackleton and Opdyke (1973). These authors suggest that the odd-numbered stages correspond closely to low ice volumes in the northern hemisphere and relatively high stands of worldwide sea level. Conversely, each disconformity or interpreted nonmarine or shallow-marine stratum separating two marine units on the Beaufort shelf has been tentatively correlated with an even-numbered oxygen-isotope stage. Even-numbered stages are believed to correspond to periods of high ice volume in the northern hemisphere and relatively low stands of worldwide sea level during which erosion or nonmarine and shallow-marine deposition might occur on continental shelves. The timing of activity derived for each of the mapped structures is based entirely on these provisional correlations and on the absolute ages tentatively assigned to the oxygen-isotope stage boundaries by Shackleton and Opdyke (1973). Wherever a fault offsets the base of a stratum but not its top, or offsets the top less than the base, movement is inferred to have occurred during the oxygen-isotope stage assigned to that stratum. The incremental and cumulative offsets during each stage for each mapped fault and monocline are presented in a correlation chart (sheet 3).

Only the correlations of units A and B with isotope stages 1 and 2 are strictly defensible. The older units have not been dated with certainty within the study area. However, the tentative correlations and age assignments are useful (1) as a framework for establishing a relative chronology of structural activity within and between shelf provinces and (2) in providing a best estimate of the absolute chronology of deformation from the available data.

LATE QUATERNARY STRUCTURES

Listric normal faults and related structures at the head of the continental slope

Character

Northwest of Smith Bay, and between the Colville Delta and the Canadian border, the upper continental slope is underlain by features interpreted to be large slumps that moved seaward on moderate- to shallow-dipping slip surfaces morphologically resembling listric normal faults (feature 45 on sheet 1; figs. 9 and 10 on sheet 2). Relatively steep bathymetric gradients suggest that slumping also shaped the upper slope west of the Colville Delta. However, only one of the few profiles that crosses the upper slope in that area shows a listric fault and slump masses. The length of the listric fault and slump terrane, measured parallel to the slope, exceeds 380 km. Its width, from head to toe, locally exceeds 35 km.

The slip surfaces at the base of the large slumps dip between roughly 15° and 40° (commonly 20°) seaward near slide headwalls, and flatten to between 1° and 6° down slope, where they are planar and subparallel to the seabed. These structural dips are approximate, having been measured from single-channel and unmigrated multichannel seismic profiles and corrected only for apparent dip. Upper surfaces of the slump masses are hummocky on a large scale, with bathymetric relief locally exceeding 400 m. Slump-mass thicknesses are commonly 200 to 300 m and rarely exceed 1,000 m (figs. 9 and 10, sheet 2). Vertical displacements at slide headwalls, observed on low-frequency seismic profiles, range from 70 to 700 m (average about 400 m) at the seabed or in the uppermost sedimentary strata. In general, thicker slump masses are structurally more coherent than thinner ones and have greater bathymetric relief, steeper headwall slip surfaces, and larger displacements at the headwall.

Four near-surface structures beneath the outer shelf (features 41-44 on sheets 1 and 3; figs. 6 and 7 on sheet 2) are closely related to the slump terrane. One (feature 41) is a deep-reaching monocline with no observable faulting at depth. The others are a monocline and two synclines developed over pull-apart zones at the heads of low-angle block glides. The block glides range from approximately 350 to 1,000 m in thickness. Their bounding slip surfaces are low-angle listric normal faults. Down-to-the-basin displacements as great as 70 m in upper Pleistocene sedimentary deposits and 30 m in Holocene materials were measured at these features.

Age

Dating of the listric normal features is uncertain. They appear morphologically young on low-frequency seismic reflection profiles and offset beds that are probably correlative with sedimentary deposits on the outer shelf inferred by Dinter (1982) to be upper Pleistocene and Holocene. The faults and slumps are, therefore, presumed to be late Pleistocene or Holocene in age. The related monoclines and synclines that overlie incipient listric faults and block glides on the outer shelf cut Holocene sedimentary materials and, at one locality, the seabed. Large-scale slumping has been a persistent process on the upper continental slope, as indicated by the many buried, inactive slump masses observed on low-frequency seismic records.

Faults that show late Quaternary and, in particular, Holocene displacement, and are still subject to the tectonic conditions that produced that displacement, are considered active (Slemmons and McKinney, 1977). By these criteria subsidiary faults in the headwall region of the listric-normal-fault province and most of the related structures are potentially subject to renewed motion.

Origin and relation to regional framework

The listric normal faults and slumps and related outer-shelf structures represent tensional failure under gravitational stresses of the thick and probably poorly consolidated upper part of the outer-shelf sedimentary prism toward the adjacent, relatively steep, free face of the continental slope. The listric normal faults and related slides are largely responsible for the structural contrast between the orderly strata of the continental shelf and the structurally and stratigraphically more chaotic strata of the continental slope and upper rise. The four subsidiary structures (features 41-44) are early stages in the extension of the slump terrane of the slope into the continental shelf. All represent failures toward steepened slopes at the headwalls of the main slide terrane. The deep-reaching monocline (feature 41) is inferred to be an incipient or arrested listric normal fault that may fail and form a large, deep slump. The other structures overlie the listric heads of low-angle normal faults that bound deep block glides. The blocks have moved only a relatively short distance, and the grabens behind them are largely filled with sediment. Renewed displacement that reactivated the deep-reaching monocline or moved the glide blocks onto the slope could collapse these parts of the outer shelf and shift the shelf break several kilometers shoreward of its present position. Collapse could occur suddenly or by slow creep, but in either case is judged to be an infrequent event.

Normal faults and monoclines beneath the shelf

Character

Down-to-the-basin normal faults and monoclines underlie the Beaufort shelf between Camden and Prudhoe Bays and from Harrison Bay to the west edge of the map area (features 1 to 35 on sheets 1 and 3; figs. 1, 3, 4, and 8 on sheet 2). Most of these structures consist of northerly dipping faults, many of them growth faults, that pass upward from bedrock into faults or monoclines with the same sense of stratigraphic displacement in Quaternary deposits. This morphology suggests that monoclinal warping in the Quaternary deposits may foreshadow future normal-fault displacement. All but a few of the monoclines can be traced downward into faults in the seismic profiles.

Dips of the normal faults, roughly estimated from unmigrated multichannel seismic profiles, commonly fall between 55° and 75°, averaging about 65° near the surface; and between 40° and 65°, averaging about 55° at depths of 1.5 to 2.4 km below the sea floor. These estimates are corrected only for apparent dip. Owing to the prevailing down-to-the-basin sense of displacement, moderate dip, and common structural growth on the faults, their movement is inferred to be dominantly or entirely dip slip.

The highest stratigraphic level of faulting at each structure mapped on sheet 1 is indicated on sheet 3. Observed stratigraphic displacements at the normal faults and associated monoclines range from 2 to 3 m at the seabed to more than 118 m in beds of Pleistocene age 150 m or more beneath the seabed. The limited penetration of the Uniboom profiling system and a lack of means for dating the older Quaternary section preclude the determination of maximum Pleistocene offset.

Age

Eight of the thirty-five structures assigned to the normal-fault province are considered active because they offset Holocene deposits or the seabed (sheet 2). These structures are marked with a dot on sheet 1. Another 18 structures are considered possibly active because they offset strata tentatively dated as latest Pleistocene. The remaining structures displace only strata thought to be older than latest Pleistocene and are therefore presumed young, but inactive.

We are most confident of the age of offset on structural features in the eastern and central parts of the Alaskan Beaufort shelf where the late Quaternary deposits are best known. The displacement history of these features is shown by heavy vertical lines on sheet 3. Because a number of the near-surface normal faults can be traced down dip into large bedrock growth faults, the growth process must be still active on the Beaufort shelf. Except near Camden Bay, no earthquakes have been recorded from the normal-fault province on the Canadian or northeast Alaska seismograph networks. Either the young faults of the province are aseismic or their recurrence intervals are too long, or these tensional features produce earthquakes too small to be detected by the seismographic networks.

Origin and relation to regional framework

Down-to-the-basin normal faults and related monoclines of the Alaskan Beaufort shelf are extensional failures in Brookian sedimentary rocks. They are found near and seaward of the tectonic hinge line in the Arctic platform of the Beaufort shelf (sheet 1). The steepened slope of the platform and the thickened sedimentary wedge that overlies it seaward of the hinge line have apparently localized the faults. The dips of the largest and deepest-reaching faults are observed on low-frequency seismic profiles to flatten as they descend from shallow depths in the vicinity of the hinge line to merge with the seaward-sloping surface of the eroded Arctic platform to the north.

Faulting was presumably favored by the weight of the thickened Brookian section, the steepened slope of the base of the Brookian sedimentary prism seaward of the tectonic hinge line, and by the proximity of the relatively steep free face of the continental slope. In the case of the growth faults, differentially greater sedimentary loading of the hanging wall by deposition after displacement events provided an additional driving mechanism.

The apparent absence of young normal faults on the shelf between the Colville and Canning Rivers (sheet 1) may be due to the fact that the tectonic hinge line there is close to the shelf break. The thickened sedimentary prism that is found seaward of the hinge line, and in which normal faults are well developed to the east and west, is thus narrow or absent in this area. Seaward of the shelf break, any young normal faults that may be present are obscured on the seismic records by slumps and other structures of the listric-normal-fault terrane. The paucity of mapped young normal faults west of Barrow Sea Valley, where the hinge line lies about 50 km south of the shelf break, is probably due to the wide spacing of profiles in that area.

A cluster of young faults and monoclines near Camden Bay (features 20-35, sheet 1) marks the east termination of the normal-fault province. The termination is abrupt and lies at the transition zone between the tectonically stable Barrow sector of the continental margin to the west and the folded Barter Island sector to the east. It also lies along the projection of the Canning River shear zone. The transition zone is characterized by a sharp westward decrease in amplitude of Neogene folds, a swing in strike of Neogene and Quaternary fold axes from southwest to west, and a westward decrease in the density and magnitude of earthquakes (sheet 1). Although both the north and south limbs of the short west-trending west ends of the broad Neogene and Quaternary folds are cut by the young faults and monoclines of the transition zone, the dip of these faults and monoclines, where determinable, is consistently northeast. For this reason, it is believed that the faults and folds had different origins.

The relative abundance of young faults in the transition zone may be due to reactivation of preexisting faults in this area. Such faults would have formed originally in a setting similar to that of the normal faults which presently lie near and north of the tectonic hinge line in the Barrow sector. Renewed movement along these preexisting faults in the transition zone might have arisen from the stresses that produced the Neogene detachment folds in the adjacent west part of the Barter Island sector. If the strike of the young faults in the transition zone is correctly interpreted, renewed displacement initiated by such stresses would be normal and(or) strike slip, depending on the precise orientation of the stresses involved.

The normal faults and monoclines west of the transition zone (features 1-19) are thought to be simple gravity failures, where the hanging wall moves and the footwall is stable. The character of the normal faults of the transition zone (features 20-25) is less clear. Their structural setting suggests that they could also be gravity faults, but as noted above they may have been reactivated by compressive stresses related to Neogene and Quaternary folding. Thus, at least their young history may have involved actual as well as relative motion of the footwalls, and they may not be simple gravity faults.

Structural features near Camden Bay

The inner shelf off Camden Bay and Barter Island is unusual in that it is seismically active (sheet 1) even though it is part of a passive continental margin. Recorded earthquakes range in magnitude from 3 to 5.3 and occur in greatest concentration in the area of broad late Quaternary folds that overlie the Neogene detachment folds near Camden Bay, in the western part of the Barter Island tectonic sector. The Neogene detachment folds underlie the inner and middle shelf and terminate on the west near the Barrow-Barter Island sector boundary. A horst-like ridge (feature 38-39), a monocline (feature 40), and two normal faults (features 36 and 37), all showing evidence of late Quaternary activity, were found within the area of the broad late Quaternary folds.

Folds

Late Quaternary deformation has occurred along many of the large Neogene folds of the Barter Island tectonic sector but has been strongest near Camden Bay, where anomalously thin Holocene deposits delineate a broad, low-amplitude late Quaternary structural high about 30 km wide and at least 60 km long. The northeast-trending structural high comprises three broad folds expressed in late Quaternary sedimentary deposits. Flank dips on these folds do not exceed 0.5^{o} to 1.5^{o}. Their axes are roughly coincident with northeast-striking detachment folds of much higher amplitude developed in the underlying Neogene sedimentary rocks (sheet 1).

East of the late Quaternary folds, recorded earthquakes are sparse and evidence of late Quaternary deformation is more subtle. In places, however, folding possibly has extended into late Quaternary time. The axis of one of the northwest-striking shale-cored Neogene anticlines east of Barter Island is marked by a slight elevation of the sea floor, and a large Neogene syncline in the area is overlain by slightly thickened late Quaternary sediment and by a slight depression of the sea floor.

The pattern of late Quaternary activity along structures that originally developed in Neogene time may extend on shore. Marsh anticline, for instance, a 60-km-long southwest-striking Neogene detachment(?) fold lying a few kilometers south of Camden Bay, must have been active during late Quaternary time. Dips in

Pliocene strata near the axis of the fold reach 60° and Pleistocene beds on its flanks dip as much as 18° (Morris, 1954; Reiser and others, 1971). D. M. Hopkins (oral commun., 1980) reports that probable outwash gravels exposed on the north flank of Marsh anticline in Carter Creek are underlain by marine clays containing fossils probably restricted to middle Pleistocene and younger deposits. The extensive outwash gravels exposed on the flanks of the structure are thus also probably of middle Pleistocene or younger age, and the time of their deformation younger still. The extent of folding on the anticline since deposition of the gravels can be estimated by making the assumption that the surface upon which the gravels were deposited had relatively low relief. The present structural relief of the basal surface, then, provides an estimate of growth on the fold since deposition of the gravels. Mapping by Morris (1954) indicates that structural relief on the base of the Pleistocene gravels presently exceeds 50 m on the south flank and 100 m on the north flank of Marsh anticline.

Geomorphic features along the plunging northeast end of the anticline may also indicate late Quaternary folding. Carter Creek and Marsh Creek cross the fold axis in valleys that are narrower and deeper than their headwaters. They may thus be antecedent streams that maintained their course through an area of active uplift. In addition, several small streams curve around the northeast-plunging nose of the fold. Some of these streams lie in shallow valleys in areas of low topographic gradient, and their curvature may partly result from late Quaternary tilting.

Faults and monoclines

Only a few faults and monoclines are associated with the shallow earthquakes and broad late Quaternary folds near Camden Bay (features 36-40, sheets 1-3; see also figs 2 and 5, sheet 2). Faults and monoclines are also sparse or absent on the shelf east of Camden Bay, even though Holocene folding and several recent earthquakes have occurred there.

In contrast to the normal faults of the Barrow sector and the listric normal faults of the continental slope, which dip uniformly seaward, some of the young faults in the zone of seismicity near Camden Bay dip southward (features 38-40, sheets 1-3). The faults in this zone also dip relatively steeply, about 60° to 90°, whereas the normal faults elsewhere dip at average angles of 55° to 65°. Maximum stratigraphic displacement observed on faults and monoclines of the seismogenic province is 7 m at the seabed and 21 m in the upper Pleistocene section (sheet 3).

Two normal faults (features 36 and 37) in the seismogenic province formed in response to extension near the axis of a large Neogene to late Quaternary detachment anticline. In contrast, what appears to be a shallow fault-block (feature 38-39) may have resulted from compression. This small, surficial, horst-like structure has bathymetric expression and occupies a structurally low position on the flank of a large Neogene and Quaternary fold (sheet 1).

If we assume that its bounding faults are parallel or subparallel, the horst-like structure forms a low ridge 300 m or less in width that has been uplifted as much as 7 m above the adjacent seabed along steeply dipping faults. The heights of the bounding scarps are unequal, and the ridgetop between them slopes a little more steeply than the surrounding seabed. The sea bed north of the structure lies about 5 m higher than the seabed to the south. The deepest reflector, inferred to be upper Pleistocene, that can be seen on our Uniboom profiles to be displaced at the bounding faults is offset 13 m.

The high-resolution record is of insufficient quality to determine precisely the nature of the faults that bound the horst-like structure, but offsets of Quaternary strata suggest that they may be a high-angle reverse fault/normal fault pair. In contrast to the normal faults to the west, which clearly continue downward into deep bedrock faults, the faults bounding the horst-like structure are obscure on the coincident multichannel profile. Possibly the horst-like structure is a near-surface failure formed in response to compression in a synclinal region of the underlying large Neogene to late Quaternary folds.

Age

The concentration of shallow earthquakes near Camden Bay demonstrates that the area is tectonically active. Furthermore, four of the five faults and monoclines within the seismic province are considered active because they offset the seabed, and the remaining one may be active because it offsets upper Pleistocene deposits (sheet 3). Recent tectonic activity on the shelf east of Camden Bay is indicated by broad, low-amplitude folds that involve late Quaternary sedimentary deposits, and by a few shallow earthquakes (sheet 1).

Origin and relation to regional framework

The cluster of young faults, monoclines, broad folds, and earthquakes near Camden Bay overlies the detachment folds in the western part of the Barter Island tectonic sector. The spatial association of these features suggests a continuation of Neogene tectonism into Holocene and modern time. Late Quaternary warping roughly coincident and congruent with one of the shale-cored anticlines and an adjacent syncline of the area east of Barter Island suggests that some tectonic activity may have extended east to the Canadian border. However, the absence of observed Quaternary faults and monoclines in this area, the small amplitude of the late Quaternary warps there as compared to those near Camden Bay, and the scarcity of earthquakes indicate that the area is less active than is the zone of seismicity near Camden Bay. Perhaps the activity in the eastern part of the Barter Island sector represents a late phase of the diapiric deformation that produced the large, probably shale-cored anticlines and flanking synclines of the Beaufort shelf east of Barter Island (sheet 1). A seismogenic zone that includes the active area near Camden Bay and extends eastward to connect with the Richardson-Mackenzie Mountains seismogenic belt of northwest Canada has been delineated by Thenhaus and others (1979).

Sheet 1 shows the relation between the Neogene and late Quaternary folds, the seismic and aseismic areas of northern Alaska (including the active seismogenic zone near Camden Bay), and the Canning left-lateral strike-slip displacement zone. Strong Holocene tectonism and seismicity may occur off Camden Bay because the area is the structural front of the belt of late Cenozoic compressional folds that lies east of the displacement zone. As discussed above, uplift and northward movement of the northeast Brooks Range along the displacement zone may have produced the detachment folds in the Brookian strata of the coastal plain and shelf by thrusting or gravity sliding. Their geometry implies that the displacement zone and the detachment folds were structurally linked and structural linkage and synchroneity are also suggested by the regional distribution of earthquake epicenters. These are clustered in the northeast Brooks Range and the continental shelf as far north as the northern structures of the fold belt but are sparse or absent from the shelf to the north and the lowland and continental shelf to the west. The fact that the displacement zone projects into the area off Camden Bay where both the Neogene folds and the seismogenic zone terminate on the west also suggests synchroneity. However, outcrop data for the age of the displacement zone have not been reported from onshore northern Alaska. If the displacement zone is indeed active and linked geometrically to the fold belt, it may be capable of generating earthquakes comparable in magnitude to the M = 5.3 event that occurred in the fold belt off Barter Island in 1968.

ENVIRONMENTAL GEOLOGIC SIGNIFICANCE

The active geologic structures of the Alaskan Beaufort shelf have the potential for surface movements that could disrupt petroleum production facilities and pipelines that may, in the future, be installed there. Because the line spacing of the data analyzed in the present report are such that many individual geologic structures were probably missed, detailed high-resolution surveys of possible construction sites on the shelf are desirable. The areas of greatest potential hazard are those where faulting or folding has displaced upper Quaternary sedimentary deposits or the sea floor. These areas include (1) the zone of large late Pleistocene and Holocene slumps and related listric normal faults on the upper slope and outer shelf, (2) the zone of shallow earthquakes and Holocene deformation near Camden Bay, and (3) the province of normal faults that offset late Pleistocene beds, Holocene beds, or the seabed west from Camden Bay. The absence of recorded earthquakes near the listric and normal faults is not evidence that these features are quiescent. Areas of the Beaufort shelf underlain by thick, fine-grained unconsolidated late Pleistocene and Holocene sedimentary deposits (Dinter, 1982) that are within or near tectonically active areas are also hazardous because fault movements or earthquakes might trigger failures in these weak sedimentary materials.

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