UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

[Reports - Open file series] 76-786.

THE LISBURNE GROUP, A POTENTIAL MAJOR HYDROCARBON OBJECTIVE OF THE ARCTIC SLOPE, ALASKA

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ABSTRACT

The Lisburne Group, a thick carbonate rock unit of Mississippian and Pennsylvanian age, is one of the most widespread potential reservoir rock units in northern Alaska. A comprehensive review of the Lisburne in the subsurface of the eastern Arctic Slope indicates attractive reservoir characteristics in a favorable source and migration setting where numerous trapping mechanisms appear to be available. Evaluation of this group as a potential exploration objective is particularly timely in view of impending offshore sales in the Beaufort Sea and current exploration programs underway in the Prudhoe Bay area and the Naval Petroleum Reserve.

Dolomite and sandstone have been identified as reservoir rocks. Oolitic grainstone is a common rock type, but all observations to date indicate little reservoir potential owing to complete void filling by calcite cement. The most important reservoir rock as judged by thickness, areal extent, and predictability is microsucrosic (10-30μ) dolomite of intertidal to supratidal origin. It is present throughout the Lisburne

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This paper has benefited from reviews and suggestions by W. P. Brosgé, P. W. Choquette, C. G. Mull, and R. D. Carter. We are grateful for their help.

and is most abundant near the middle of the sequence. Northward it decreases in thickness from 1,000 feet (300 m) to less than 100 feet (30 m). Porosity of the dolomite as determined in selected wells averages between 10 and 15 percent and attains a maximum of slightly more than 25 percent. Net thickness of reservoir rocks (i.e., rocks with greater than 5 percent porosity) varies in these wells from 140 feet (40 m) to 390 feet (120 m). Oil shows are common, and drill-stem tests have yielded as much as 1,600 bbls/day oil and 22 MMcf/day gas in the Lisburne pool of the Prudhoe Bay Field and as much as 2,057 bbls/day saltwater outside the field area. The occurrence of dolomite over such a large area makes its presence in the offshore Beaufort Sea and adjacent Naval Petroleum Reserve No. 4 fairly certain. The occurrence of sandstone as thick as 140 feet (40 m) in the middle and upper part of the Lisburne in two coastal wells suggests that larger areas of sandstone may be found to the north in offshore areas. Shows of oil and gas and a saltwater flow of 1,470 bbls/day have been recorded from this sandstone facies.

Shales of Permian and Cretaceous age unconformably overlie the Lisburne, providing adequate sealing beds above potential reservoirs. Impermeable limestone (completely cemented grainstone) and thin beds of shale may serve as seals within the Lisburne, but the possibility of fractures in these units may negate their sealing capability.

The most favorable source rock for Lisburne hydrocarbons appears to be Cretaceous shale that unconformably overlies the Lisburne east of Prudhoe Bay. This shale is reported by Morgridge and Smith (1972) to be a rich source rock and is the most likely source for the entire Prudhoe Bay Field. A source within the Lisburne or within the underlying Kayak Shale is postulated to explain oil shows in the southernmost Lisburne wells. This postulated source may be in a more basinal facies of the Lisburne and may be similar to dark shale in the upper Lisburne found in thrust slices in the Brooks Range. Coal in the underlying Endicott Group is a possible source for dry gas. It is inferred that at the present time much of this coal is in a gas-generating regime downdip from the Prudhoe Bay Field area.

Stratigraphic traps involving the Lisburne Group may exist as a result of widespread Permian and Cretaceous unconformities. Structural traps related to normal faulting may occur along the trend of the Barrow Arch, and faulted anticlines are numerous in the foothills of the Brooks Range. Combination traps are possible along the trend of the Barrow Arch at places where both stratigraphic and structural trap might exist.

INTRODUCTION

The Lisburne Group in the subsurface of the eastern Arctic Slope, Alaska, consists of a thick sequence of Mississippian and Pennsylvanian shallow marine carbonate rocks. In the Prudhoe Bay Field, the Lisburne is one of five major petroleum-bearing reservoirs. Because it is one of the most widespread rock units in northern Alaska and because subsurface tests here are relatively few, the Lisburne is considered to be a large, but generally undocumented potential reservoir.

The purpose of this paper is to point out the petroleum potential of the Lisburne of the eastern Arctic Slope and to speculate on the occurrence of the Lisburne northward in the offshore and westward in Naval Petroleum Reserve No. 4. Evaluation of the petroleum potential of the Lisburne is particularly timely in view of impending offshore lease sales in the Beaufort Sea and the current exploration programs in the Prudhoe Bay area and the Naval Petroleum Reserve (Fig. 1).

Throughout the history of petroleum exploration in northern Alaska, the Lisburne has been considered to have "petroleum potential". Initially the Lisburne was considered to be an "extremely problematic" source for oil, and chances were considered slight for trapping oil in significant amounts because of the high degree of deformation observed in the Brooks Range (Smith and Mertie, 1930). Later the Lisburne was considered a potential reservoir, but it was not penetrated by any of the 36 test wells drilled by the U.S. Navy during the period 1944-1953 (Reed, 1958). The Lisburne was not encountered in the subsurface until 1966 with the drilling of the Union Kookpuk No. 1 and the Sinclair Colville No. 1

just east of NPR 4 (Fig. 2). In these wells the Lisburne had both porosity and oil shows. The next well drilled in this region was the Arco-Humble Prudhoe Bay No. 1, the discovery well for the Prudhoe Bay Field. Since the discovery of this field in 1968, numerous additional wells have penetrated the Lisburne. Well records and samples from 46 penetrations of the Lisburne are now publicly available (Fig. 2); very few of these data have been incorporated in earlier Lisburne studies.

Results presented here are preliminary and are part of an ongoing project by Bird. This study is based on a network of correlated wells established by electric log, lithologic, and paleontologic correlations. Samples and thin sections from seven wells were studied in detail and the results extrapolated to nearby wells. A total of 22 complete Lisburne penetrations and 24 partial penetrations were available for study. Rock samples and petrographic thin sections were studied at the State of Alaska Division of Oil and Gas, Anchorage, Alaska and at the U.S. Geological Survey, Menlo Park, California.

For providing access to samples, thin section, and well records, the authors thank the State of Alaska Division of Oil and Gas, Atlantic Richfield Oil Company, B. P. Alaska, Continental Oil Company, and Standard Oil Company of California.

The Lisburne Group has been studied extensively in the Brooks Range and has been the subject of numerous reports, primarily by U.S. Geological Survey personnel. A. K. Armstrong, the senior author of many of these reports, has summarized previous studies and has presented interpretations of the Lisburne's regional paleogeography, lithofacies, and porosity trends (Armstrong and Mamet, 1970; Armstrong et al., 1970; Armstrong, 1974; Armstrong and Bird, 1976) and diagenesis (Wood and Armstrong, 1975). The regional setting and general stratigraphy of the Prudhoe Bay Field have been described by Rickwood (1970) and by Morgridge and Smith (1972). The regional tectonic setting and depositional history of the North Slope and adjacent areas have been summarized most recently by Lerand (1973) and Grantz et al. (1975).

The following brief summary of the geologic history and setting is included to show the relation of the Lisburne Group to the tectonic framework of the North Slope and to illustrate the similarities of the Lisburne to other major oil-bearing reservoirs at Prudhoe Bay.

GEOLOGIC HISTORY AND SETTING

The Lisburne Group of the eastern Arctic Slope is the northern subsurface continuation of rocks exposed in the Brooks Range that extend from the Yukon Territory, Canada, 750 miles (1250 km) westward to Cape Lisburne (Fig. 1). The Lisburne is part of a belt of clastic and carbonate rocks of Carboniferous age extending nearly the entire length of the North American Cordillera and probably westward beneath the Chukchi Sea at least to Wrangel Island (Grantz et al., 1975; Bogdanov and Tilman, 1964). The irregular northern edge of the Lisburne (Fig. 1), formed by erosional and depositional thinning, follows the trend of the Mesozoic Barrow Arch. From its northern margin at a depth of about 9000 feet (3000 m), the Lisburne slopes gradually southward as depth of burial increases to more than 25,000 feet (8000 m) along the axis of the Mesozoic Colville Trough (Rickwood, 1970). The Lisburne in the central and western Brooks Range has been thrust relatively northward hundreds of kilometers to a position nearly over the axis of the Colville Trough (Martin, 1970; Tailleur and Snelson, 1968). In the northeastern Brooks Range, displacements are much smaller than in the western part of the range and the Lisburne is thought to be more nearly autochthonous (Fig. 1).

The Lisburne is part of an Upper Devonian to lowermost Cretaceous assemblage of clastic and carbonate rocks deposited in a southward-deepening basin with a source for sediments to the north. This assemblage, the Ellesmerian sequence of Lerand (1973), includes four of the five major reservoirs in the Prudhoe Bay Field.

Major tectonism in Late Jurassic and Early Cretaceous time in northern Alaska resulted in the replacing of northern landmasses by southern ones. This tectonic event, probably the most significant in the history of northern Alaska, resulted in the formation of the ancestral Brooks Range, the opening of the Arctic Ocean, and the formation of the trap at Prudhoe Bay (Rickwood, 1970). At that time the once continuous, smoothly sloping continental mass that formed the northern source area and shelf for the Ellesmerian sequence was rifted apart. The uplifted edge of the rift valley was eroded, and northeast of Prudhoe Bay much of the Ellesmerian sequence was removed. Later the newly formed continental margin of northern Alaska subsided and tilted in the direction of the newly opened Arctic Ocean, thereby forming the Barrow Arch. This positive feature was onlapped by younger strata, and the truncated rocks of the Ellesmerian sequence were sealed by Barremian and younger Cretaceous shales. These shales, rich in organic matter, are the presumed source rocks for Prudhoe Bay hydrocarbons (Morgridge and Smith, 1972).

Continued subsidence in the north and uplift in the south together produced northeastward-migrating foredeeps, which were filled by a series of clastic wedges. The Barrow Arch was onlapped and overstepped by these clastic wedges in Late Cretaceous and Tertiary time. It was the fortuitous combination of excellent reservoir rocks located on a major structure; the truncation, overlapping, and sealing of these reservoir rocks by rich source beds; and their subsequent burial that resulted in the Prudhoe Bay Field, the largest petroleum accumulation in North America.

STRATIGRAPHY

The Lisburne in the subsurface of the eastern Arctic Slope of Alaska is part of a genetically related sequence of Mississippian and Pennsylvanian rocks bounded at the top and base by major unconformities (Fig. 3). This sequence can conveniently be divided into a lower part composed primarily of clastic rocks, assigned to the upper part of the Endicott Group (Tailleur et al., 1967), and an upper part composed primarily of carbonate rocks, the Lisburne Group (Bowsher and Dutro, 1957). The Endicott Group in this area includes the Kekiktuk Conglomerate, the Kayak Shale, and the Itkilyariak Formation, whereas the Lisburne Group consists of three informal lithologic units: a lower limestone, a medial dolomite, and an upper limestone.

The vertical succession of rock types, similar to that previously described in the northeastern Brooks Range by Brosgé et al. (1962) and by Mull and Mangus (1972), indicates a progressive change upward from nonmarine to marine depositional environments, i.e., an overall transgression. Regional stratigraphic synthesis by Armstrong (1974) indicates that deposition took place in an east-trending basin and that the transgression proceeded from south to north. The vertical sequence of rock types and their inferred environments of deposition suggest that the transgression was characterized initially by deposition of coarse- to fine-grained coal-bearing clastic sediments in an alluvial-deltaic environment adjacent to a shallow sea in which sand, mud, and argillaceous limestone were being deposited. Later the supply of clastic sediment was greatly reduced and carbonate sedimentation predominated.

The transgression was then characterized by limestone deposition in tidal flat and lagoonal environments adjacent to a broad, shallow carbonate shelf with oolite bars and tracts of bioclastic sand.

Isopachs of the Endicott Group (Fig. 4) and the Lisburne Group (Fig. 5) show generally similar patterns with truncation in the northeast by an Early Cretaceous unconformity. This similarity in thickness suggests that major topographic features persisted throughout Carboniferous time; lithologic changes across these highs and lows (discussed below in more detail) are consiste t with this interpretation. Subsurface correlations (Fig. 6) indicate that thinning of these strata from negative to positive areas was by three mechanisms: 1) onlap by basal clastic rocks of the Kekiktuk Conglomerate, 2) convergence of beds (internal thinning) in both the Endicott and Lisburne Groups, and 3) truncation at the top of the Lisburne. A stratigraphic cross section across the positive area in the northeastern Brooks Range by Armstrong and Bird (1976) shows similar relations.

A feature suggestive of a clastic wedge is present in the Endicott Group near the truncation edge, but its geometry is poorly defined, and the sediment grain size and proportion of sandstone to shale do not appear to differ significantly in nearby wells.

The following discussion of late Paleozoic stratigraphic units is presented to describe their lithologic characteristics and variations in the subsurface and to present the criteria used in distinguishing these formations.

Kekiktuk Conglomerate

A succession of gray shale and sandstone with minor amounts of limestone, conglomeratic sandstone, and coal rests on a pre-Upper Devonian basement of mildly metamorphosed, deformed, and eroded argillite. Because of their generally similar lithology and stratigraphic position, these sedimentary rocks are assigned to the Kekiktuk Conglomerate as defined by Brosgé et al. (1962) in the northeastern Brooks Range. In the Brooks Range the Kekiktuk is overlain with apparent conformity by the Kayak Shale, in the subsurface to the north, by the Itkilyariak Formation. The contact between the Kekiktuk and Itkilyariak appears to be gradational and is picked at the highest occurrence of a continuous sequence of carbonaceous sandstone and gray shale. In the area of the paleo high west of Prudhoe Bay (Fig. 4), the Kekiktuk Conglomerate is not distinguishable from the Itkilyariak Formation. These rocks consist of red and gray conglomerate, sandstone, and shale with minor amounts of limestone. Since no clear distinction can be made between the Kekiktuk and Itkilyariak Formations in this section, it is referred to as the Endicott Group undifferentiated (Fig. 6).

The greatest observed thickness of the Kekiktuk is slightly more than 1500 feet (450 m) in the Mobil Mikkelsen Bay No. 1 (Fig. 6). The formation thins southeastward to about 300 feet (100 m) at the type section in the northeastern Brooks Range. Westward from the Mikkelsen Bay well, the Kekiktuk thins, apparently by basement onlap and internal convergence (Fig. 6).

Relative to the type area, the Kekiktuk in the subsurface appears to contain more shale, coal, and limestone and less sandstone and conglomerate. These differences in lithology and thickness suggest that the Kekiktuk was deposited in a rapidly subsiding basin by low-gradient streams traversing a swampy lowland that was occasionally flooded by the sea. An eastern source area has been postulated for the type Kekiktuk (Reed, 1968; Donovan and Tailleur, 1975). A northern source area may be indicated by the relatively coarse-grained undifferentiated Endicott Group on the paleo high west of Prudhoe Bay (Figs. 4 and 6).

Kayak Shale

A sequence of dark-gray shale with varying amounts of sandstone and limestone lies gradationally between the Kekiktuk Conglomerate and the Itkilyariak Formation (Fig. 6). These rocks are assigned to the Kayak Shale (Bowsher and Dutro, 1957) on the basis of similar lithology. The stratigraphic position of the Kayak in the subsurface differs from that in the type section in the central Brooks Range, where the Kayak occurs disconformably beneath the Lisburne Group and above the Upper Devonian Kanayut Conglomerate (Bowsher and Dutro, 1957, p. 6). In the subsurface the Kayak is encountered most frequently in wells south and east of B.P. Sag Delta 31-10-16 (Fig. 6), where it consists predominantly of gray shale with minor amounts of limestone, sandstone, and thin red shale beds. Although facies relations are complex, it appears that the Kayak wedges out in a northwesterly direction toward Prudhoe Bay by lateral gradation into both the

Kekiktuk Conglomerate and the Itkilyariak Formation. The Kayak appears to represent a shallow marine, locally euxinic environment of deposition and perhaps indicates a minor transgressive pulse within the overall gently transgressive sequence (Fig. 3).

Itkilyariak Formation

A distinctive sequence of red and gray sedimentary rocks referred to the Itkilyariak Formation of Mull and Mangus (1972) underlies the Lisburne Group. In the subsurface this formation consists of shale, limestone, and sandstone with red the predominant color. Shale generally constitutes more than 60 percent of the sequence. Limestone that becomes more abundant in the upper part of the formation accounts for as much as 30 percent of the formation; sandstone contributes generally less than 10 percent. Nodules of anhydrite are common in the shale and limestone. Since thin beds of red shale occur locally throughout the Lisburne Group (e.g., B.P. Put River 9-11-13) and even in the overlying Sadlerochit Group (e.g., Sinclair-B.P. Colville No. 1), the basis for identifying the top of the Itkilyariak using "the top of the highest redbed" (Mull and Mangus, 1972, p. 1367) should be modified. In this study, we have picked the top of the Itkilyariak at the top of the highest occurrence of a continuous sequence of redbeds beneath a sequence composed predominantly of carbonate rocks.

The greatest observed thickness of the Itkilyariak Formation is 850 feet (260 m) penetrated in the Mobil Kadler No. 1 (Fig. 2). The contact with the underlying Kayak Shale appears to be gradational, as does the contact with the overlying Lisburne Group. Southeastward from the Arco-Humble Prudhoe Bay No. 1, interbeds of limestone and gray and green shale increase in abundance and suggest a lateral equivalency of the Itkilyariak with part of the Kayak. In the area of Sinclair-B.P. Colville No. 1 (Fig. 6), interbedded limestone is rare, and the section consists predominantly of sandstone, conglomerate, and shale. This interval, designated as the "Endicott Group undifferentiated", may be a red oxidized facies of the Kekiktuk Conglomerate or an unusually coarse-grained facies of the Itkilyariak Formation.

The Itkilyariak Formation is interpreted as having been deposited under arid, subaerial conditions on a coastal plain which was periodically flooded by the sea. This interpretation is based on the stratigraphic position of the formation, its red color, the interbedded limestone containing the same suite of fossil fragments as the Lisburne, and the presence of evaporite nodules.

Lisburne Group

The Lisburne Group consists of limestone and dolomite with varying amounts of shale, sandstone, replacement chert, and nodular anhydrite. Interbedded shale and sandstone increase in abundance northward from the Brooks Range but seldom make up more than about 20 percent of the total section. Accompanying this northward increase in siliciclastic rocks is a noticeable color change from shades of green and gray in the southern wells to red and gray in the northernmost wells (Fig. 6).

In the subsurface the Lisburne is the equivalent of the Alapah Limestone (Bowsher and Dutro, 1957) and the Wahoo Limestone (Brosgé et al., 1962) as defined in the Brooks Range. Because these formations are difficult to distinguish in the subsurface, the Lisburne Group is subdivided there into three informal lithologic units: 1) a lower limestone, 2) a medial dolomite, and 3) an upper limestone (Figs. 3 and 6). These three units are readily identifiable throughout the northern part of the subsurface area and are approximately the same as units used in the stratigraphic correlation sections of the Alaska Geologic Society (Fackler, 1971; Mangus and Pessel, 1972). Thickness trends of these informal units are similar to those for the entire Lisburne Group (Fig. 6). The presence of all three units in the areas of thinnest Lisburne suggests that these areas were paleo highs that were generally submerged during Lisburne deposition and were merely subsiding at a slower rate than surrounding areas.

The lower limestone unit consists of 70 to 80 percent medium- to dark-gray cherty limestone, minor amounts of dolomite, and 20 to 30 percent shale and sandstone. Limestone of the lower unit is typically darker and more argillaceous than the upper limestone unit. Grain-supported carbonate rock types are generally more abundant than mud-supported types. Bioclastic fragments, mainly bryozoa and pelmatozoa, are the most common particle types in the lower limestone unit; and oolites are rare. Foraminifers are common but not as abundant as in the upper limestone unit. Nodules or euhedral crystals of evaporite minerals (Plate 1E) are more common in the lower than in the upper limestone unit; anhydrite, barite, and celestite were reported by Wood and Armstrong (1975). The association of dark muddy carbonate rock types, reduced abundance of foraminifers, and the presence of evaporite minerals is consistent with a stratigraphic position immediately overlying the transitional marine to nonmarine Itkilyariak Formation. Together, these data suggest a shallow marine, inner-shelf environment of deposition with periodically fluctuating salinities and thus a continuation of the general overall Carboniferous transgression.

The dolomite unit, recognized as the middle part of the Lisburne Group where dolomite exceeds limestone in abundance, grades into adjacent limestone units mainly by means of a decreasing number of pure dolomite interbeds, rather than by gradation into dolomitic limestone that becomes less dolomitic. Associated lithologies include limestone, shale, and sandstone with varying amounts of pyrite, replacement chert, and evaporite minerals. The dolomite unit increases in thickness southward from Prudhoe Bay, where it becomes increasingly interbedded with limestone and thereby more difficult to identify as a distinct unit. Over the paleo high west of Prudhoe Bay (Fig. 5), the dolomite unit thins, but contains less interbedded limestone and is nearly all (about 90 percent) dolomite.

Crystal size is the best criterion for categorizing dolomite types in the Lisburne (Wood and Armstrong, 1975) and is one of several useful characteristics in distinguishing syngenetic from diagenetic dolomite. Following the usage of Illing _et al._ (1967), dolomite in the Lisburne is of two types: 1) _macrodolomite_ that has an average grain size greater than 30μ and 2) _microdolomite_ that has an average grain size less than 30μ. Dolomite in the subsurface Lisburne Group shows a range of crystal size from less than 5μ to more than 100μ. Although the variation of crystal size over short distances can be considerable and relations are commonly unclear, certain generalizations appear to obtain.

Macrodolomite with a crystal size greater than 50 μ is generally an accessory mineral in coarse-grained limestone where it preferentially replaces the lime mud matrix and not the grains (Plate 1B). It is present in all three lithologic units in the Lisburne Group but tends to be the more common dolomite type in the limestone units. The association of macrodolomite with open marine limestone and a general absence of features characterizing an intertidal or supratidal environment suggest that much of the macrodolomite is of relatively late diagenetic origin.

Microdolomite is most commonly represented by 10-30 μ crystals. Rocks consisting of microdolomite are usually completely dolomitized and display a unimodal crystal size distribution with a small standard deviation (i.e., "well sorted"). Common accessories in the microdolomite include sponge spicules and angular silt-size quartz grains (Plate 1C). Where microdolomite is an accessory, the limestone is usually a mudstone or wackestone with a sparse flora and fauna. Sedimentary structures observed include nodules of anhydrite, pseudomorphs of calcite after bladed gypsum, calcite-filled dessication cracks, and laminations interpreted to be algal mats (see Wood and Armstrong, 1975, pl. 11). Microdolomite occurs in all three lithologic units in the subsurface Lisburne Group but is most common in the medial dolomite unit. Considered together, the evidence presented here suggests that the microdolomite is of very early diagenetic (syngenetic) origin in an intertidal to supratidal (sabkha) environment. The dolomite unit therefore represents a period of regression in an overall transgressive trend (Fig. 3).

The upper limestone unit consists of light- to medium-gray cherty limestone with minor amounts of interbedded dolomite, shale, and sandstone. Grain-supported limestones (mainly bioclastic and oolitic grainstones) are the most common carbonate lithofacies (Plate 1A),

oolitic grainstones account for most of the upper limestone unit. Locally, where bioclasts are common, bryozoan and pelmatozoan fragments dominate the skeletal components. Foraminifers and algae are more abundant and more diverse in the upper limestone unit than in the other Lisburne units; locally they become very abundant and are the dominant rock-forming organisms. Evaporite minerals are very rare in the upper limestone unit.

Sandstone is generally a minor component of the upper limestone unit and seldom exceeds two percent of the total thickness. In the Hamilton Brothers Milne Point No. 1 (Fig. 6), this sandstone constitutes about 30 percent of a relatively thin Lisburne section. Although the informal lithologic units of the Lisburne are difficult to identify in this well, the sandstone is probably situated in both the dolomite and upper limestone units. The sandstone is light gray to buff colored and is composed of fine- to medium-grained, subangular, moderately sorted quartz and chert grains with varying amounts of silica and calcite cement (Plate 1F). The presence of fossil fragments and calcite cement is variable, and the full range in composition from sandy limestone to relatively pure sandstone has been observed. The sandstone is interbedded with minor amounts of shale, limestone, and dolomite.

The environment of deposition of the upper limestone unit is interpreted to be a relatively high energy open marine shelf with numerous oolite shoals; the evidence for this is the abundance of grainstone textures (many of which are oolitic), relative abundance of diverse foraminiferal and algal assemblages, and the general rarity of evaporite minerals and microdolomite. A nearby shoreline is suggested in the area of the Milne Point No. 1 by an abundance of sandstone and red shale and by a relatively thin Lisburne section here.

Overlying Beds

The Lisburne Group is unconformably overlain in most areas by the Echooka Formation (Fig. 3), the basal unit of the Sadlerochit Group as defined by Detterman et al. (1975). The Echooka in the subsurface generally consists of greenish-gray to dark-gray, argillaceous quartzose sandstone and shale with distinctive accessories including glauconite, siderite, dolomite, phosphate, and pyrite. The Echooka, which is the basal marine transgressive unit of the Sadlerochit Group, onlaps the Lisburne and wedges out northward from several hundred feet in the Brooks Range to zero near Prudhoe Bay (Detterman, 1970). North of this zero edge the Lisburne is overlain by silty shale of the Kavik Member of the Ivishak Formation. According to Detterman (1970) and Eckelmann et al. (1975), the Kavik represents a prodelta facies in a regressive sequence. Continued regression resulted in the southward progradation of a fluvial-deltaic sandstone facies, the main producing reservoir of the Sadlerochit Group in the Prudhoe Bay Field.

East of Prudhoe Bay the Lisburne is unconformably overlain by dark-gray, marine, carbonaceous shale of Cretaceous age. This shale records the time of overlap of this deeply eroded part of the Barrow Arch where the entire section of Jurassic through Mississippian rocks was removed.

PALEONTOLOGY AND AGE

The foraminiferal zonation scheme of Mamet as described and defined in Armstrong and Mamet (1970), Armstrong *et al*. (1970), and Mamet and Skipp (1970) was used in making correlations and age determination. The age determinations summarized in Figure 6 are based on studies of thin sections from both core and drill-cutting samples. These data indicate that the Lisburne Group in the subsurface includes foraminiferal zones 16 through 21, a range in age from Late Mississippian (Chesterian) to Middle Pennsylvanian (Atokan). The lower limestone unit and uppermost Itkilyariak Formation contain Foraminifera diagnostic of zones 16_i and 16_s; the dolomite unit, zone 17; and the upper limestone unit, zones 18 to 21. Age-diagnostic foraminifers have not yet been observed in the lower and middle parts of the Endicott Group. The age of this group in the subsurface based on regional stratigraphic relations (Armstrong, 1974) is probably Mississippian (Meramecian and older). The unconformity between the Lisburne and Sadlerochit Groups apparently represents the time interval from the late Middle Pennsylvanian through the Early Permian, a period of approximately 40 million years (Armstrong and Mamet, 1970).

Foraminifera and algae were found to occur most abundantly in skeletal grainstones and packstones and rarely in wackstones, lime mudstones, and oolitic grainstones; an exception to this is the rare occurrence of foraminifers and algae in bryozoa-rich packstones and grainstones. As discussed above, faunal abundance and diversity increase upward with a marked interruption in the trend through the dolomite unit. These observations are consistent with the interpretation based on lithologic evidence that the Lisburne represents an overall transgression interrupted by a regression in the middle of the sequence. These observed relations of microfauna to rock type are similar to those made by Armstrong and Mamet (1970) in the Lisburne of the Brooks Range.

Correlations based on paleontology substantiate the nature of Lisburne thinning by convergence and truncation and agree with electric log and lithologic correlations. Where other means of correlation are not possible because of rapidly changing thickness or facies, the foraminiferal zonation has proved invaluable. An example with far reaching implications is the correlation between the Union Kalubik Creek No. 1 and the Gulf-B.P. Colville Delta No. 1 (Fig. 7). Here electric log and lithologic correlations could not be made, and the dolomite unit appears to be anomalously thin or missing in the Colville Delta well. Foraminifera and algae indicate that the entire Lisburne penetrated at the Colville Delta well is Pennsylvanian (zones 20 and 21), whereas the Lisburne in the Kalubik Creek well is Pennsylvanian in the upper few feet and Mississippian (Chesterian) below. By these data, at least the Pennsylvanian portion of the upper limestone unit thickens northwestward from the Kalubik Creek well and that strata equivalent in age to the dolomite unit (foraminiferal zone 17) were not penetrated in the Colville Delta well. A similar rapid thickening of the upper limestone unit takes place in the Arco Itkillik No. 1 (Fig. 6), where the dolomite unit was penetrated. Considering the widespread occurrence and persistance of the dolomite unit, it appears likely that it is also present in the area of the Colville Delta well, and therefore lies undrilled beneath the bottom of the well. It also appears likely that the dolomite unit is present farther north offshore and to the west in NPR 4.

DEPOSITIONAL MODEL

A generalized depositional model (Fig. 8) based on observation of subsurface samples and well logs shows the distribution of rock types, biota, and inferred environments of deposition. Oolitic grainstones and microdolomite are interpreted to be environmentally diagnostic and to be indicative of shoal and tidal flat environments, respectively; in developing the model, all other rock types were arranged with respect to these two distinctive rock textures. Certainly, an understanding of modern carbonate environments aids in reconstructing these facies (Jordan, 1973). The Lisburne model is similar in many respects to models proposed by Armstrong (Armstrong and Mamet, 1970; Armstrong, 1974), but differs by having more interbedded siliciclastic and carbonate rocks reflecting more shoreward facies than exposed in the Brooks Range outcrops. As in the Brooks Range, no carbonates with reef-like characteristics have been encountered in the subsurface.

Deposition of the Lisburne is thought to have taken place on a shelf of very low gradient where small changes in sea level produced correspondingly large horizontal shifts in facies. Repeated interbedding of different carbonate rock types and interbedding of carbonate with non-carbonate sediments suggest that either intermittent uplift of the landmass to the north or numerous fluctuations of sea level caused lateral shifts in environments during the Late Mississippian and Early and Middle Pennsylvanian in this area. No sedimentary rocks representing basinal facies (Fig. 8) have been observed in wells studied to date. Greatest water depths in the subsurface Lisburne occurred in the southern part of the study area and are represented by the uniformly dark carbonate and gray shale present in the Forest Oil Company Kemik No. 1 (no. 18, Fig. 2). Basinal facies have been observed in the Brooks Range and are characterized by dark, argillaceous limestone, siliceous shale, and black chert that contains radiolaria and cephalopods in addition to the typical Lisburne fauna and flora (Armstrong and Bird, 1976).

Evidence of a sharp shelf margin has not been found in the subsurface Lisburne, but the southernmost wells penetrating the group have not yet been studied in detail. Common shelf margin characteristics (such as abrupt facies changes from thick light colored, coarse-grained carbonate rocks to relatively thin, dark, argillaceous carbonate rocks, chert, and shale) have not been observed. Seismic reflection records, which might show a change in interval thickness related to a shelf margin, were not available for study. The presence of widespread shallow marine carbonate rocks and gradual facies changes suggests an overall ramp configuration for the Lisburne Group in the subsurface, a model presented earlier by Armstrong and Bird (1976) in a regional summary of the Lisburne in the eastern Brooks Range.

RESERVOIR

The Lisburne Group has several potential reservoir facies. These include dolomite, oolitic grainstone, and sandstone.

The most favorable reservoir rock type, in terms of net thickness of reservoir, areal extent, and predictability is microdolomite with 10-30μ crystal size (Plates 1C and 1D). Porosity values as high as 23 percent have been measured in the laboratory and as high as 27 percent have been calculated from acoustic logs. Porosity is primarily intergranular but is enhanced by the presence of vugs generally a few millimeters in diameter (Plate 1D). Vertical fractures, some open and some calcite filled, have been observed in cores. These may provide some small increase in porosity, but most importantly they provide increased permeability. Estimates of porosity derived from acoustic logs and visual examination of samples made for selected wells (Table 1) suggest that an average porosity of 10 percent or greater may be expected in the subsurface. The relatively high average porosity of 15 percent in the Union Kookpuk No. 1 suggests that better porosity may be developed locally on paleo highs. Net thickness of reservoir with greater than 5 percent porosity appears to increase as the Lisburne Group increases in thickness. Actual footage corresponds fairly closely to the total thickness of dolomite (Fig. 9). Dolomite isopachs shown in this figure represent the thickness of dolomite from all units in the Lisburne, not from the medial dolomite unit only. These data are based on our study of samples available to the public in Anchorage and on detailed lithologic logs prepared by American Stratigraphic

Company in Denver. Because most of the data are from lithology logs, the dolomite thicknesses include both microdolomite and macrodolomite without regard to reservoir quality.

Grainstones are abundant in the Lisburne, and in the upper limestone unit most of the grainstones are oolitic (Fig. 6). Some of them still show open-framework packing (Plate 1A) indicative of high initial porosity. Unfortunately, these grainstones have always been found to be completely cemented by void-filling calcite. Nevertheless, the reservoir potential of this rock type could be considerable if conditions favorable for porosity development could be found. Such conditions could include areas where little or no void-filling cement occurred or where leaching has removed the calcite cement or grains.

Significant amounts of sandstone are present in the Hamilton Brothers Milne Point No. 1; somewhat lesser amounts occur in the PLAGHM Beechy Point No. 1 (Fig. 6). The components of quartz and chert are similar to those found in the Sadlerochit Group reservoir, although cementation appears to be complete in Lisburne sandstones (Plate 1F).

The areal extent of this Lisburne sandstone facies is unknown. There is relatively little sandstone in any of the surrounding wells. Regional analysis which indicates a persistent northern source area for Mississippian through Jurassic sedimentary rocks on the North Slope suggests that more sandstone is present to the north in the offshore. The presence of a sandstone facies in the Lisburne and the possibility of a greater areal extent offshore is critical in evaluating the petroleum potential of the Beaufort Sea. An optimistic speculation on the areal distribution of this sandstone facies, shown in Figure 9, is based on the concept that the sandstone represents a "nearshore fringe" of clastic sediment bordering the paleo landmass farther to the north.

Drill-stem tests have recovered both hydrocarbons and saltwater from the Lisburne. Significant test results are tabulated in Table 2 and are shown with respect to their geographic (Fig. 9) and stratigraphic positions in (Fig. 6). Hydrocarbons have been recovered from three wells within the Lisburne pool in the Prudhoe Bay Field (Prudhoe Bay No. 1, East Bay No. 1, and Put River 9-11-13) and from one well southeast of the field (Mikkelsen Bay No. 1). The rest of the wells tested produced saltwater from the Lisburne.

Oil and gas in the Arco-Humble Prudhoe Bay No. 1 are present in thin dolomite reservoir beds in the upper limestone unit; the dolomite unit is apparently below the oil-water contact. Inspection of the logs suggests that the dolomite unit has as much reservoir potential as dolomite beds in the upper limestone unit; therefore, it appears possible that Lisburne production from Prudhoe Bay No. 1 would be greatly increased if the medial dolomite unit also were within the oil column. Oil and gas in the dolomite unit per se have been encountered in only one well (Mobil Mikkelsen Bay No. 1); unfortunately, flow rates have not been disclosed. Flow rates to 2057 bbls/day saltwater have been recorded from dolomite beds and 1470 bbls/day from sandstone.

SEALING BEDS

Adequate seals at the top of the Lisburne Group are present throughout the subsurface. North and east of Prudhoe Bay, Lower Cretaceous shale seals the Lisburne where it has been truncated by the Early Cretaceous unconformity (Fig. 6). Elsewhere the Kavik Member, a shale in the Ivishak Formation, provides the seal. For example, in the Prudhoe Bay No. 1, drill-stem test results show that the Kavik shale separates Sadlerochit oil from Lisburne gas. Where the Echooka Formation is present, its sealing capacity is questionable; it displays some capacity as a reservoir and yielded gas in the Sinclair-B.P. Colville No. 1 (Fig. 2).

Shale up to 25 feet thick occurs within the Lisburne and may provide internal seals. In addition, impermeable limestone, especially common in the upper limestone unit, may also have sealing capabilities, but open fractures observed in some Lisburne core samples may possibly reduce the sealing effectiveness of the limestone.

SOURCE ROCKS

Fine-grained rocks with organic content, thermal history, and proximity to reservoir beds adequate for source rocks for Lisburne petroleum include shale in the overlying Cretaceous and possibly shale within the Lisburne Group and the Kayak Shale. Coal in the Kekiktuk Conglomerate may be a source for dry gas in the Lisburne.

Morgridge and Smith (1972, p. 500) concluded that both Jurassic and Cretaceous shales were capable of generating the petroleum for the Prudhoe Bay Field. This conclusion is based on measurements of the total organic content and C_{15+} hydrocarbon content for the entire sequence of Mississippian through Cretaceous rocks in the Prudhoe Bay area. They found a total organic content of 1.9 percent and 5.4 percent and a C_{15+} hydrocarbon content of 660 ppm and 3,000 ppm for the Jurassic and Cretaceous shale, respectively. They believe that the Cretaceous shale is the most likely source because it is in contact with each major petroleum-bearing reservoir in the Prudhoe Bay Field. Their geochemical analyses of pre-Jurassic rocks, including the Lisburne and Endicott Groups, indicate a low oil-generating potential.

Oil shows are common in wells outside of the Lisburne oil pool area. These shows consist of black tarry oil (pyrobitumen) and cut fluorescence (Plate 1D). In the northern wells, shows may be from the Cretaceous source rock. However, oil shows in a southern well, the Home Bush Federal No. 1 (no. 19, Fig. 2), 40 miles (70 km) south and 7,000 feet (2,100 m) structurally lower than similar horizons at Prudhoe Bay, probably did not come from Cretaceous source rocks. We suggest that source rocks may be present south and downdip from this well in a more basinal facies of the Lisburne or possibly in the Kayak Shale. These postulated source rocks may be similar to shale observed in thrust sheets cutting the Lisburne in the Brooks Range. Thick intervals of dark, highly organic shale and limestone are present in the upper part of the Lisburne in the central Brooks Range (Patton and Tailleur, 1964, p. 496), and a Lisburne shale from the western Brooks Range yielded 6.7 gallons of oil per ton (Tailleur, 1964). The Kayak Shale in the central Brooks Range consists of about 1,000 feet (300 m) of dark-gray shale, but no geochemical data are available on the source rock potential of this unit. The time of maturation of these potential source rocks can be estimated by using the time and temperature relation presented in Hood et al. (1975), wherein a combination of temperature and duration of heating (time) sufficient to produce a coal rank of high volatile B (LOM 9) corresponds to the principal stage of oil generation from a wide variety of source rocks. In this area, a geothermal gradient of 1.6°F/100 feet (2.92°C/100 m) (AAPG, 1973), and initial temperature of 40°F (4°C), and burial of 10,000 feet (300 m) would result in a formation temperature of 200°F (93°C). Maturation of source rocks could be achieved within 7 million years at this temperature (Hood et al., 1975, fig. 3). The Lisburne was buried to 10,000 feet (300 m) in Early Cretaceous time (Morgridge and Smith, 1972, fig. 2). The onset of maturity, 7 million years later, would have occurred in later Early Cretaceous time. And as the regional slope at this time was probably still up to the north, migration would proceed in that direction into any available traps. These postulated source rocks are now found at depths greater than 20,000 feet (6,100 m) and undoubtedly are overmature.

Coal in the Kekiktuk Conglomerate may be a source for methane. Coal is most common in the wells southeast of Prudhoe Bay, where it reaches an aggregate thickness of as much as 50 feet. Coal is a prolific source of methane when conditions of time and temperature are sufficient for the coal to attain the rank of high bituminous coal to anthracite which corresponds to 25 and 5 percent volatile matter, respectively (Lutz et al., 1975). Although no data are available on the Kekiktuk coal, the rank can be estimated from a knowledge of the present-day temperature and the duration of burial. The graphic summary of the relation of coal rank to temperature and coalification time by Karweil (1956 pl. 2) as modified by Bostick (1973) has been used to estimate the rank of the coal. Present-day temperature of the coal is estimated by using a geothermal gradient of 2.4°F/100 feet (4.37°C/100 m) (Alaska Division of Oil and Gas, 1974). Coal known to occur as shallow as 10,900 feet (3,590 m) and deeper than 15,800 feet (5,180 m) is estimated to be at temperatures of 212°F (100°C) to more than 330°F (165°C), respectively. Duration of heating (burial time) is variable. In the area south and west of the Lower Cretaceous truncation (Fig. 9), burial has been continuous since Late Permian, but burial to within about 1,000 feet (300 m) of maximum probably was not achieved until early Tertiary time (about 50 m.y. B.P.). Gas generation (volatile matter $<25\%$) is estimated to occur at depths greater than 12,800 feet

(3,900 m). East and north of the Early Cretaceous truncation, burial has been continuous since the late Early Cretaceous but maximum burial was probably not achieved until late Tertiary time (about 10 m.y. B.P.). In this area, gas generation is estimated to occur below depths of about 17,700 feet (5,400 m). These estimates suggest that the Kekiktuk coal has not been buried deep enough or long enough to generate gas in the immediate area of Prudhoe Bay Field but that down-dip conditions are more favorable.

TRAPS

Stratigraphic traps, structural traps, and combinations of both types may be present in the Lisburne. The most likely areas for each type of trap are shown on Figure 10.

Stratigraphic traps may be present at the top of the Lisburne in places where reservoir rocks are truncated by an unconformity. The Permian unconformity truncates progressively deeper in a north to northwesterly direction and is geographically the most widespread. The Cretaceous unconformity truncates the entire Lisburne and is present in a relatively narrow northwestward-trending band located north and east of Prudhoe Bay along the Barrow Arch.

Two types of structural traps may be present: 1) traps related to complex folds associated with high-angle reverse faults that formed in Tertiary time and may be present in the foothills of the Brooks Range and 2) traps related to broad, gentle folds associated with numerous normal faults that may occur along the trend of the Barrow Arch. According to Rickwood (1970), faulting is restricted to a single period of deformation during Early Cretaceous time (upper Neocomian to Barremian) and is related to the formation of the Barrow Arch.

Combination traps may be present. Rickwood (1970) and Morgridge and Smith (1972) have shown that the Sadlerochit pool in the Prudhoe Bay Field is located on a west-plunging anticlinal nose, faulted on the north and south, and truncated and sealed by an unconformity on the east. Presumably the Lisburne pool is trapped in a similar fashion.

CONCLUSIONS

The petroleum potential of the Lisburne Group in the subsurface of the eastern Arctic slope, Alaska, appears promising because of a favorable combination of reservoir, source rock, and trapping mechanisms. A continuous dolomite reservoir is present throughout the area, and a significant sandstone reservoir is present in two wells along the coast. It is fairly certain that the porous dolomite reservoir extends both westward into Naval Petroleum Reserve No. 4 and northward into the offshore. The sandstone reservoir may occur widely to the north in the offshore.

Lisburne reservoir rocks are in direct contact with documented Cretaceous source rocks east of Prudhoe Bay, and it is speculated that source rocks are present within the Lisburne south of the study area, perhaps beneath the Brooks Range. Coal beneath the Lisburne is a probable gas source. Estimated temperatures and burial history suggest that much of the coal is at this time mature to overmature.

Stratigraphic traps related to unconformities might be possible over a wide area; structural traps may be present in the foothills foldbelt of the Brooks Range and along the Barrow Arch. Combination stratigraphic-structural traps may be present along the Barrow Arch.

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CAPTIONS FOR ILLUSTRATIONS AND TABLES

Figure 1. Index map of northern Alaska showing location of study area, major tectonic features, and distribution of the Lisburne Group. Significant stratigraphic tests are numbered and include:

1) U.S.N. South Barrow No. 3
2) U.S.N. Topagoruk No. 1
3) U.S.N. Simpson No. 1
4) U.S.N. Cape Halkett No. 1
5) Gulf - B.P. Colville Delta No. 1
6) Arco-Humble Prudhoe Bay No. 1
7) Humble East Mikkelsen Bay No. 1

The Lisburne is presumed to be present in Cape Halkett No. 1 based on information released by the Navy. Well reported drilled to basement and found "non-commercial in the Triassic-Permian and lower zones" (Oil and Gas Jour., 1975, p. 47).

Figure 2. Index map of study area showing data points within the Lisburne Group. Wells referred to in the text numbered:

1) U.S.N. Cape Halkett No. 1
2) Gulf - B.P. Colville Delta No. 1
3) Arco Itkillik No. 1
4) Union Kookpuk No. 1
5) Sinclair - B.P. Colville No. 1
6) Union Kalubik Creek No. 1
7) Sinclair - B.P. Ugnu No. 1
8) Hamilton Bros. Milne Pt. No. 1
9) PLAGHM Beechy Pt. No. 1
10) Mobil Kuparuk No. 1
11) B.P. Put River 33-11-13
12) B.P. Put River 9-11-13
13) Arco-Humble Prudhoe Bay No. 1
14) Arco-Exxon East Bay No. 1
15) B.P. Sag Delta 31-10-16
16) Mobil Kadler No. 1
17) Mobil Mikkelsen Bay No. 1
18) Forest Kemik No. 1
19) Home Bush Federal No. 1

Figure 3. Generalized stratigraphic column and relative sea-level fluctuations for late Paleozoic rocks in the subsurface of the eastern Arctic Slope, Alaska. Width of band on the right represents an attempt to bracket the numerous oscillations in order to show major sea level trends. Vertical line indicates approximate position of shoreline. No vertical scale or relative scale of thickness is implied.

Figure 4. Isopachs of the Endicott Group in the subsurface of the eastern Arctic Slope, Alaska: Kekiktuk Conglomerate, Kayak Shale, and Itkilyariak Formation. Truncation of the group in the northeastern part of area result of Early Cretaceous erosion. Dashed isopachs indicate greater degree of uncertainty. Isopach trends in areas of no data are based on assumed similarity in thickness pattern between Endicott and Lisburne Group.

Figure 5. Isopachs of Lisburne Group in the subsurface of the eastern Arctic Slope, Alaska. Truncation of the group in the northeastern part result of Early Cretaceous erosion. Dashed isopachs indicate greater degree of uncertainity than solid isopachs.

Figure 6. Fence diagram of the Endicott and Lisburne Groups in the subsurface of the eastern Arctic Slope of Alaska showing gross lithology, stratigraphic relations, foraminiferal zones, and significant drill-stem test results. Abbreviations used are: BPD = barrels per day; BOPD = barrels of oil per day; MMCFPD = million cubic feet per day; O = oil; G = gas; M = mud; W = water; SW = saltwater; GCO = gas-cut oil; GCM = gas-cut mud; 17+ = foraminiferal zone determination, zone 17 or younger.

Figure 7. Correlation of the Lisburne Group in the Gulf - B.P. Colville Delta No. 1 and the Union Kalubik Creek No. 1 based on foraminifera. See Figure 6 for the age of foraminiferal zones. Pronounced thickening of the upper limestone unit in the Colville Delta well is similar to that observed in the Arco Itkillik No. 1 (Fig. 6) and suggests that the dolomite unit may be present beneath the Colville Delta well.

Figure 8. Depositional model for the Lisburne Group, subsurface eastern Arctic Slope, Alaska, showing inferred lithologic and faunal relationships after a period of progradation. A relative sea-level rise would result in a significant shoreward shift of facies followed by another depositional progradation. The Lisburne is made up of repeated fluctuations of this type. No horizontal or vertical scale or width or thickness trends of facies are implied. However, overall dimensions of model would have horizontal distances measured in tens of kilometers and thicknesses measured in a few meters.

Figure 9. Reservoir data summary for the Lisburne Group, subsurface eastern Arctic Slope, Alaska, showing dolomite isopachs, significant test results, and possible areal extent of sandstone reservoir facies. See Tables 1 and 2 for additional reservoir and test data. Abbreviations same as in Figure 6.

Figure 10. Summary of types of traps possible in the Lisburne Group, subsurface eastern Arctic Slope, Alaska. The belt of normal faulting is believed to be related to the formation of the Barrow Arch. Faults shown are adapted from the Alaska Division of Oil and Gas (1974) and believed to be typical of trends and density of faulting in this belt. The offshore trend and extent of truncation by Early Cretaceous unconformity are speculative.

Table 1. Summary of significant drill-stem test results in the Lisburne Group, eastern Arctic Slope, Alaska.

Table 2. Summary of porosity estimates for selected wells in the Lisburne Group, eastern Arctic Slope, Alaska. Porosity, estimated from acoustic and gamma-ray logs, is developed primarily in dolomite and dolomitic limestone. See Figure 2 for well locations. Use of this data is as follows: in the first well listed, there is a total of 388 feet of strata with porosities of 5 percent or greater; these strata have an average porosity of 10.3 percent.

Plate 1. Photomicrographs from the Lisburne Group, eastern Arctic Slope of Alaska; bar scale is 250 μ on each photograph.

A. Skeletal grainstone from the upper limestone unit. Grains consist of fragments of bryozoa, brachiopods, crinoids, tubular foraminifers, and kamaenid algae. All are tightly cemented by sparry calcite. Sample is from B.P. Put River 33-11-13, core at 10,053 feet.

B. Partially dolomitized bryozoan packstone from the upper limestone unit. Relatively large dolomite rhombs (50-100 μ) preferentially replace the matrix of lime mud. Sample is from B.P. Sag Delta 31-10-16, core at 10,336 feet.

C. Microcrystalline dolomite (10 μ rhombs) with sponge spicules and angular, 50 μ quartz grains. Sample is from the upper limestone unit in B.P. Sag Delta 31-10-16, core at 10,337 feet.

D. Vuggy dolomite with black tarry oil from the dolomite unit. Dolomite rhombs are 20-50 μ; vugs result from the leaching of fossil fragments. Sample is from B.P. Sag Delta 31-10-16, core at 11,814 feet.

E. Grainstone from the lower limestone unit consisting predominantly of fragments of bryozoa and crinoids. The greater degree of compaction relative to the grainstone in photograph A suggests that cementation occurred relatively late, i.e., after compaction. Also present are large prismatic crystals of anhydrite, scattered rhombs of dolomite, and irregular patches of replacement silica. Sample is from B.P. Sag Delta 31-10-16, core at 12,060 feet.

F. Sandstone from the upper part of the Lisburne Group consisting of quartz and chert grains. Note the high degree of compaction. Sample is from the Hamilton Bros. Milne Point No. 1, drill cuttings from the interval 10,120 to 10,140 feet.

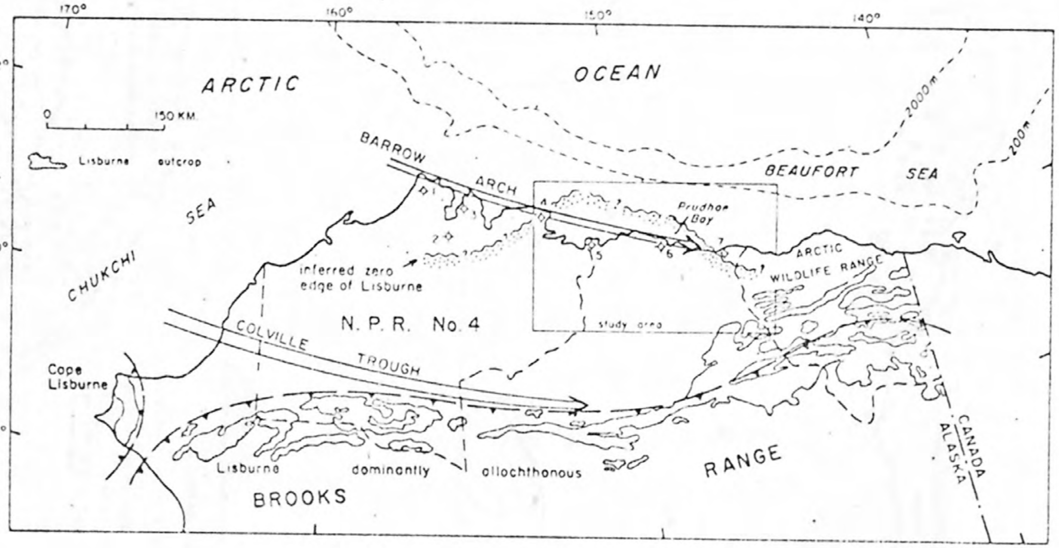

170°
160°
150°
140°
72°
70°
68°
ARCTIC
OCEAN
0
150 KM.
Lisburne outcrop
BARROW
ARCH
BEAUFORT
SEA
2000m
200m
SEA
CHUKCHI
Prudhoe Bay
ARCTIC
WILDLIFE RANGE
inferred zero edge of Lisburne
N. P. R. No. 4
study area
COLVILLE
TROUGH
Cape Lisburne
Lisburne
dominantly
allochthonous
RANGE
BROOKS
CANADA
ALASKA

Fig 1

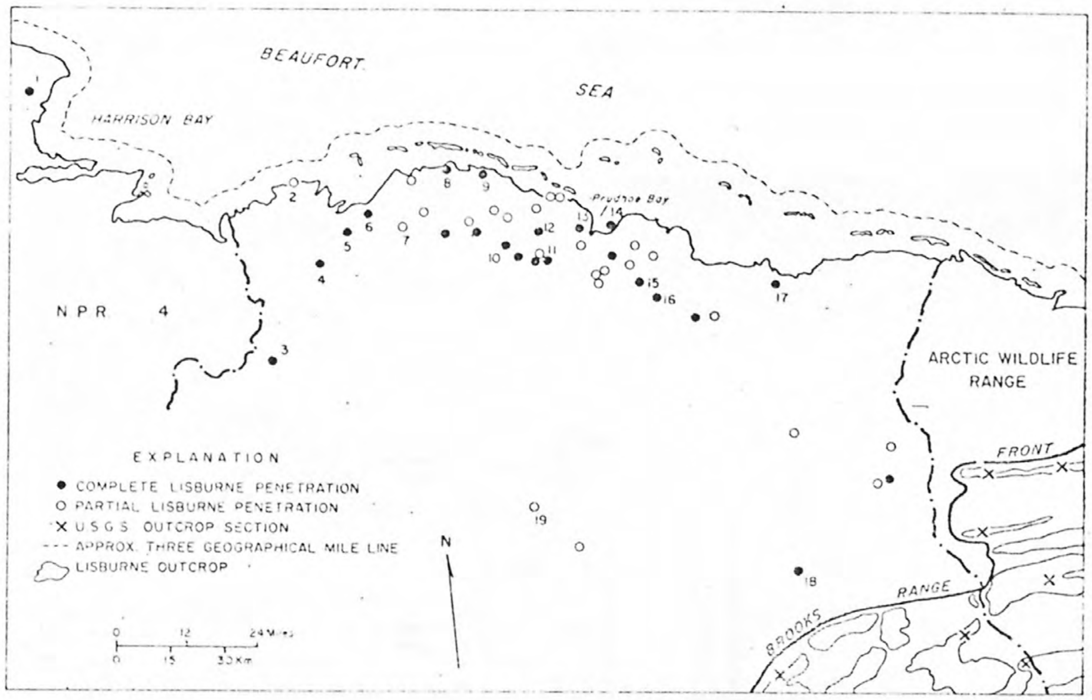

BEAUFORT
SEA
HARRISON BAY
Prudhoe Bay
N.P.R. 4
ARCTIC WILDLIFE
RANGE
FRONT
RANGE
BROOKS
EXPLANATION
COMPLETE LISBURNE PENETRATION
PARTIAL LISBURNE PENETRATION
U.S.G.S. OUTCROP SECTION
APPROX. THREE GEOGRAPHICAL MILE LINE
LISBURNE OUTCROP
N

Fig 2

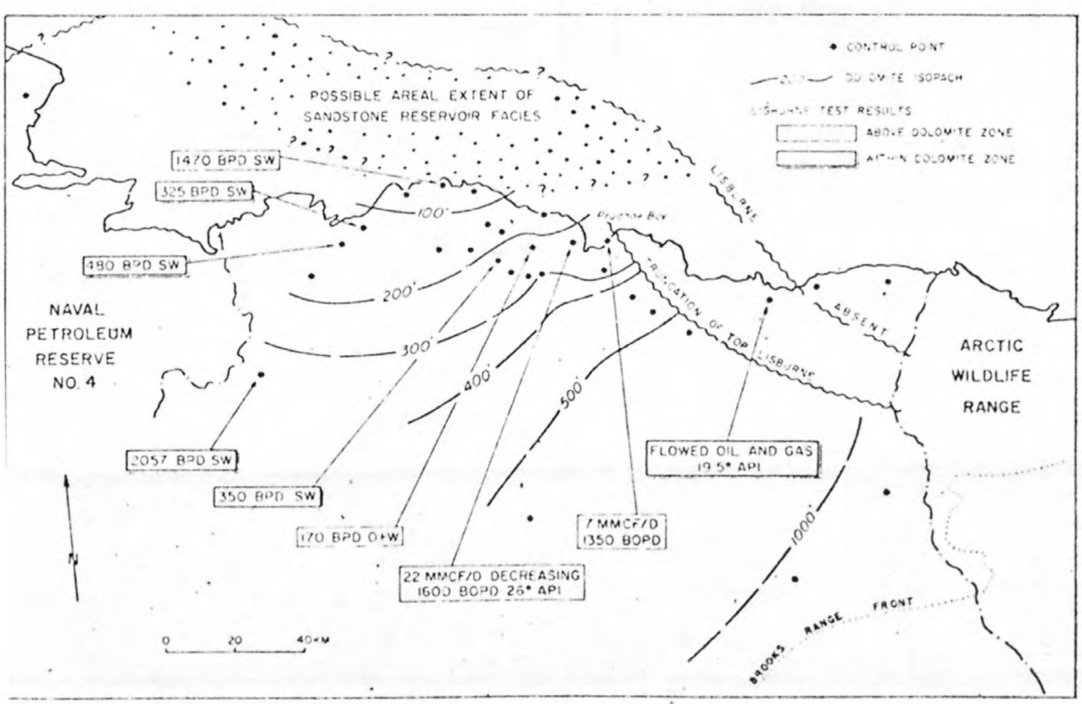

POSSIBLE AREAL EXTENT OF
SANDSTONE RESERVOIR FACIES
CONTROL POINT
DOLOMITE ISOPACH
LISBURNE TEST RESULTS
ABOVE DOLOMITE ZONE
WITHIN DOLOMITE ZONE
1470 BPD SW
325 BPD SW
480 BPD SW
Prudhoe Bay
LISBURNE
100'
200'
300'
400'
500'
1000'
TRUNCATION OF TOP LISBURNE
ABSENT
NAVAL
PETROLEUM
RESERVE
NO. 4
ARCTIC
WILDLIFE
RANGE
2057 BPD SW
350 BPD SW
170 BPD O+W
22 MMCF/D DECREASING
1600 BOPD 26° API
7 MMCF/D
1350 BOPD
FLOWED OIL AND GAS
19.5° API
N
0
20
40 KM
BROOKS RANGE FRONT

Fig 9

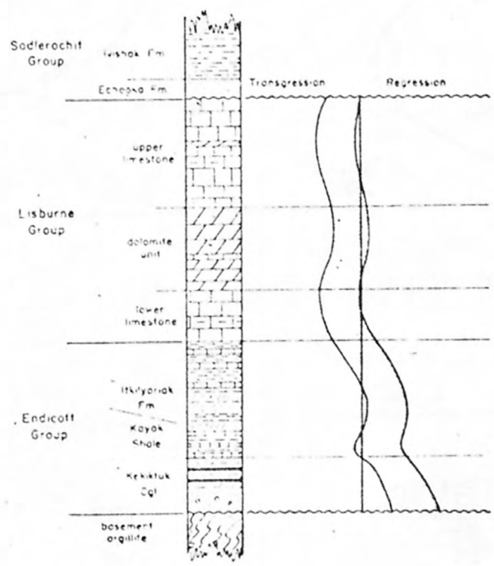

Sadlerochit Group
Ivishak Fm
Echooka Fm
Transgression
Regression
upper limestone
Lisburne Group
dolomite unit
lower limestone
Itkilyariak Fm
Endicott Group
Kayak Shale
Kekiktuk Cgl
basement argillite

Fig 3

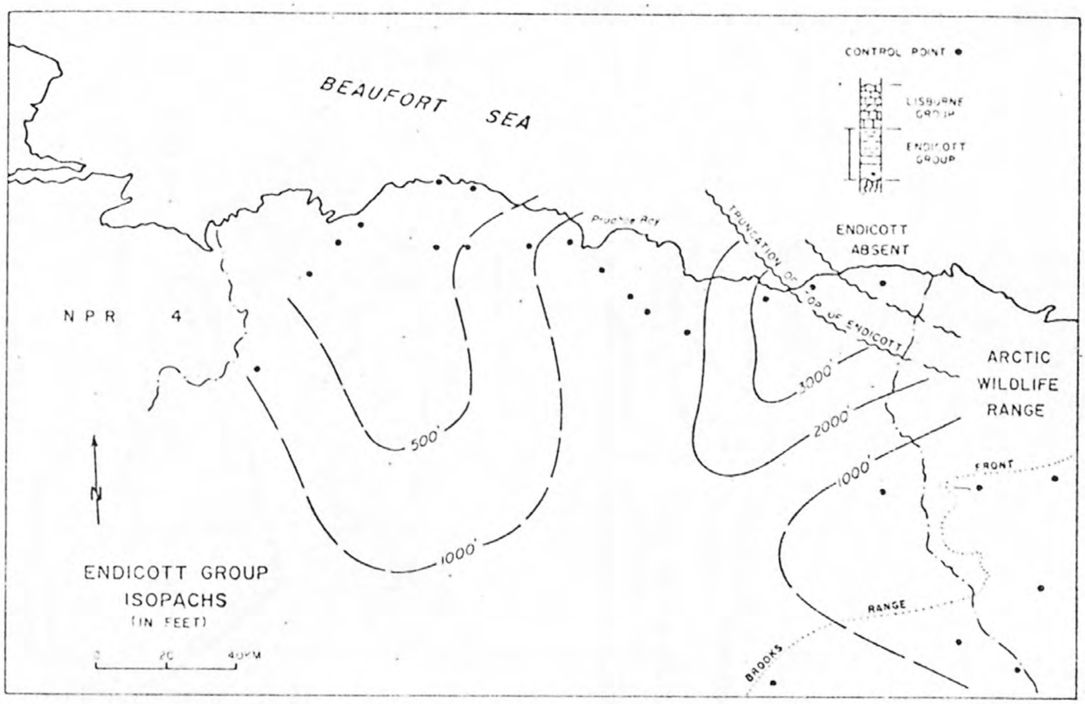

BEAUFORT SEA
CONTROL POINT
LISBURNE GROUP
ENDICOTT GROUP
Prudhoe Bay
TRUNCATION OF TOP OF ENDICOTT
ENDICOTT ABSENT
NPR 4
ARCTIC WILDLIFE RANGE
FRONT
RANGE
BROOKS
500'
1000'
2000'
3000'
N
ENDICOTT GROUP ISOPACHS
(IN FEET)
0 20 40 KM

Fig 4

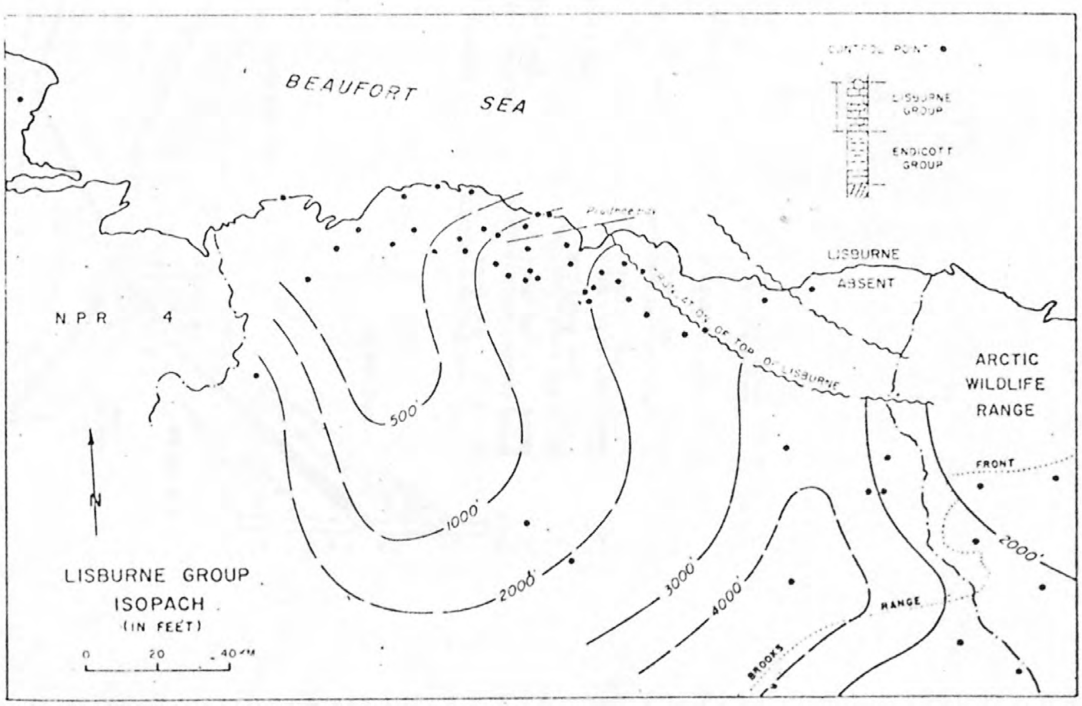
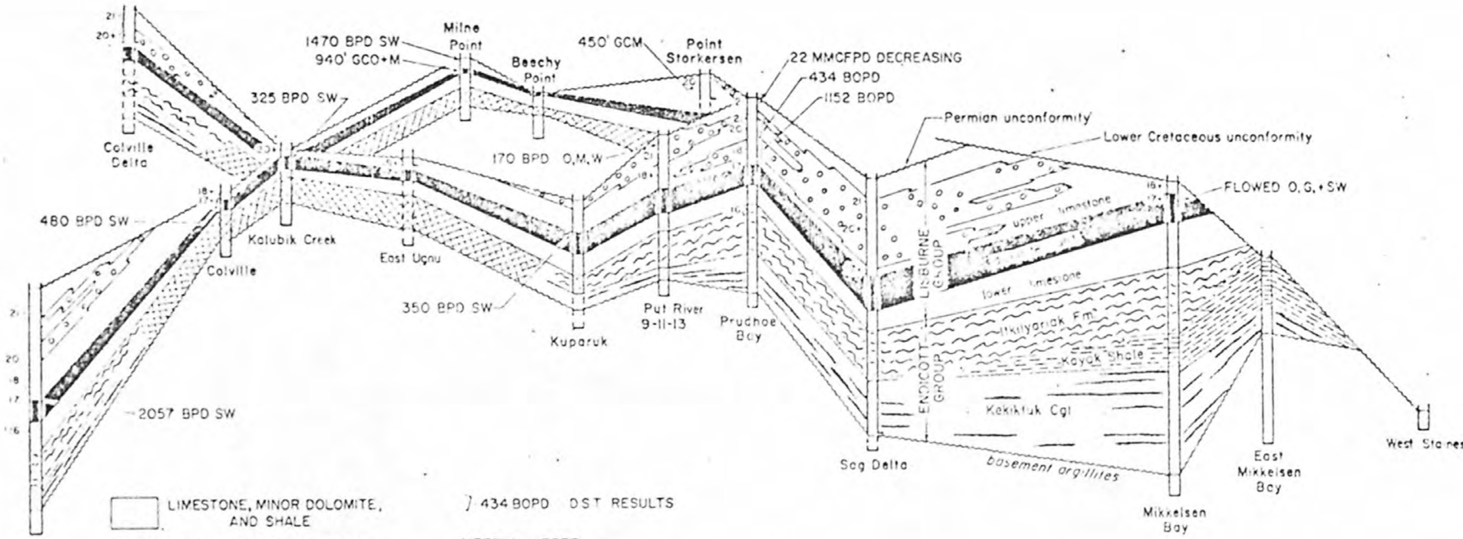
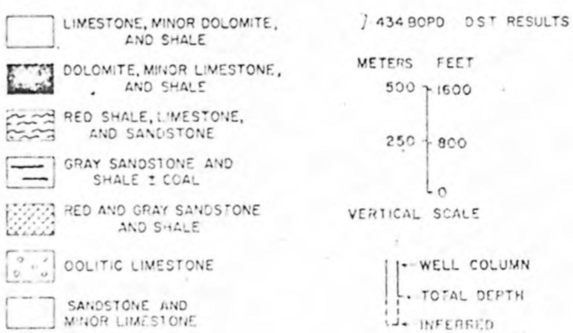

BEAUFORT SEA
CONTROL POINT
LISBURNE GROUP
ENDICOTT GROUP
Prudhoe Bay
TRUNCATION OF TOP OF LISBURNE
LISBURNE ABSENT
NPR 4
ARCTIC WILDLIFE RANGE
FRONT
RANGE
BROOKS
500'
1000'
2000'
3000'
4000'
N
LISBURNE GROUP ISOPACH
(IN FEET)
0 20 40 KM

Fig 5





MAMET'S FORAMINIFERAL ZONES

21	ATOKAN	MIDDLE PENN.
20	MORROWAN	LOWER PENN.
19 18 17 16s 16i	CHESTERIAN	UPPER MISSISSIPPIAN

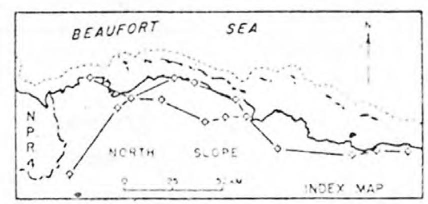


Fig 6

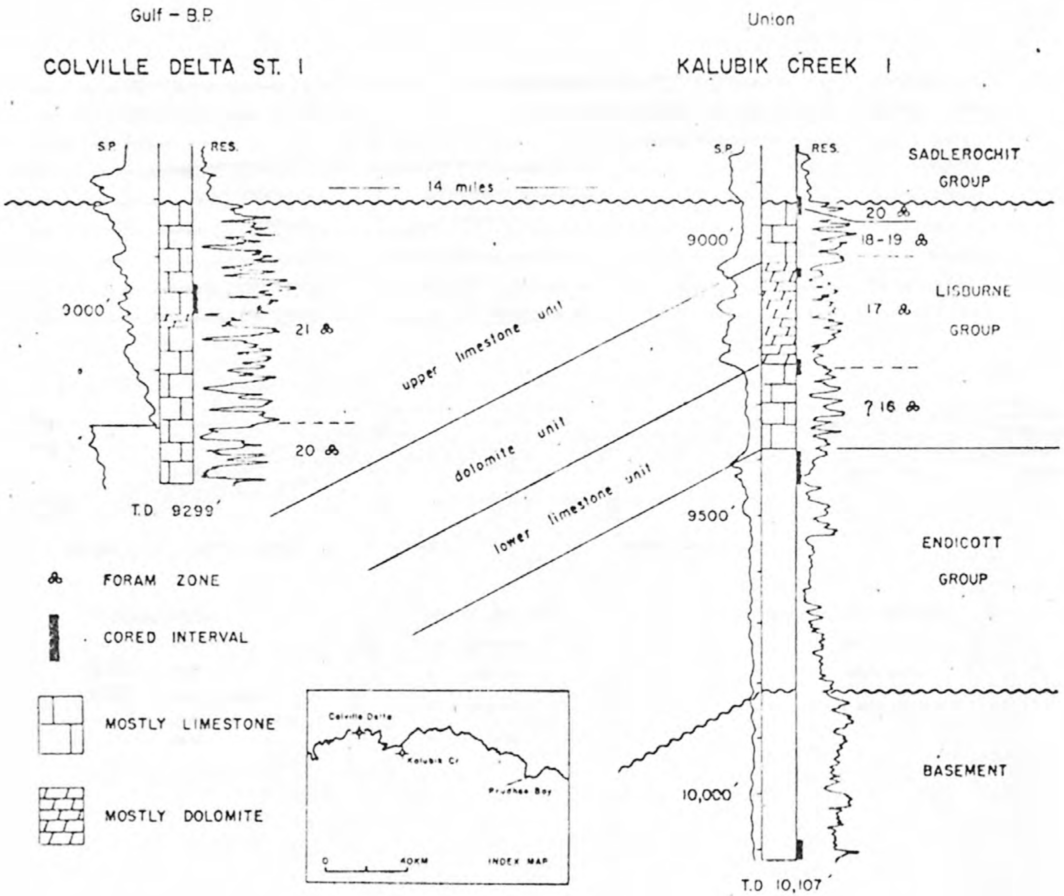
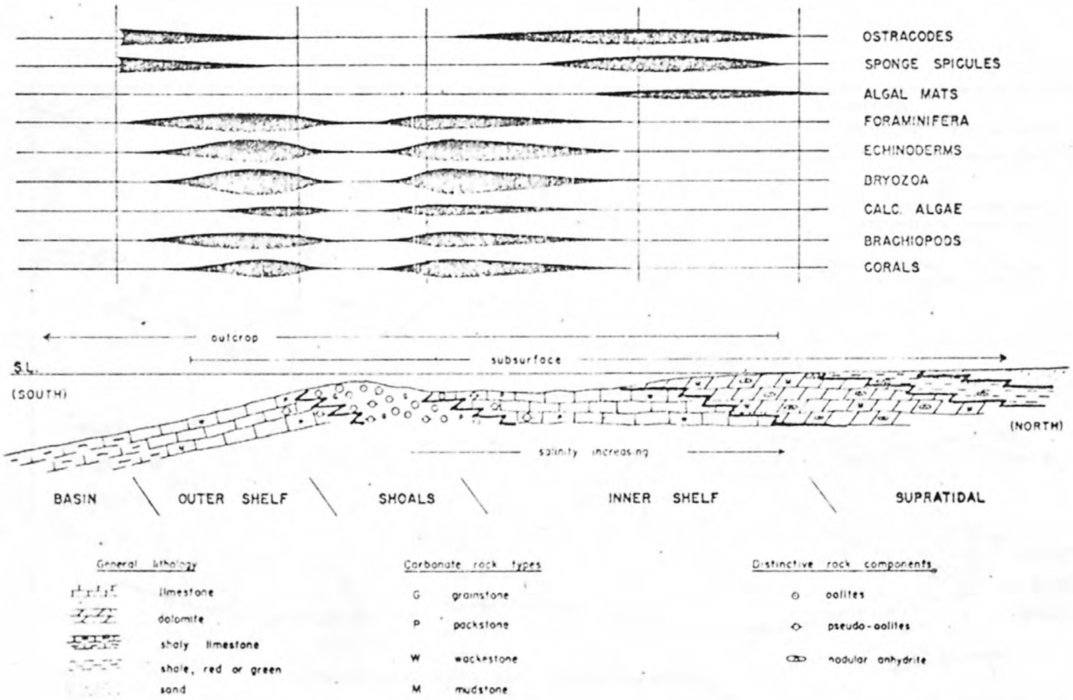

Gulf - B.P.
COLVILLE DELTA ST. I
Union
KALUBIK CREEK I
S.P.
RES.
14 miles
9000'
21
20
T.D. 9299'
upper limestone unit
dolomite unit
lower limestone unit
SADLEROCHIT GROUP
20
18-19
17
LISBURNE GROUP
? 16
9500'
ENDICOTT GROUP
BASEMENT
10,000'
T.D. 10,107'
FORAM ZONE
CORED INTERVAL
MOSTLY LIMESTONE
MOSTLY DOLOMITE
Colville Delta
Kalubik Cr
Prudhoe Bay
0
40KM
INDEX MAP

Fig 7



OSTRACODES
SPONGE SPICULES
ALGAL MATS
FORAMINIFERA
ECHINODERMS
BRYOZOA
CALC. ALGAE
BRACHIOPODS
CORALS
outcrop
subsurface
S.L.
(SOUTH)
(NORTH)
salinity increasing
BASIN
OUTER SHELF
SHOALS
INNER SHELF
SUPRATIDAL
General lithology
limestone
dolomite
shaly limestone
shale, red or green
sand
Carbonate rock types
G grainstone
P packstone
W wackestone
M mudstone
Distinctive rock components
oolites
pseudo-oolites
nodular anhydrite

Fig 8

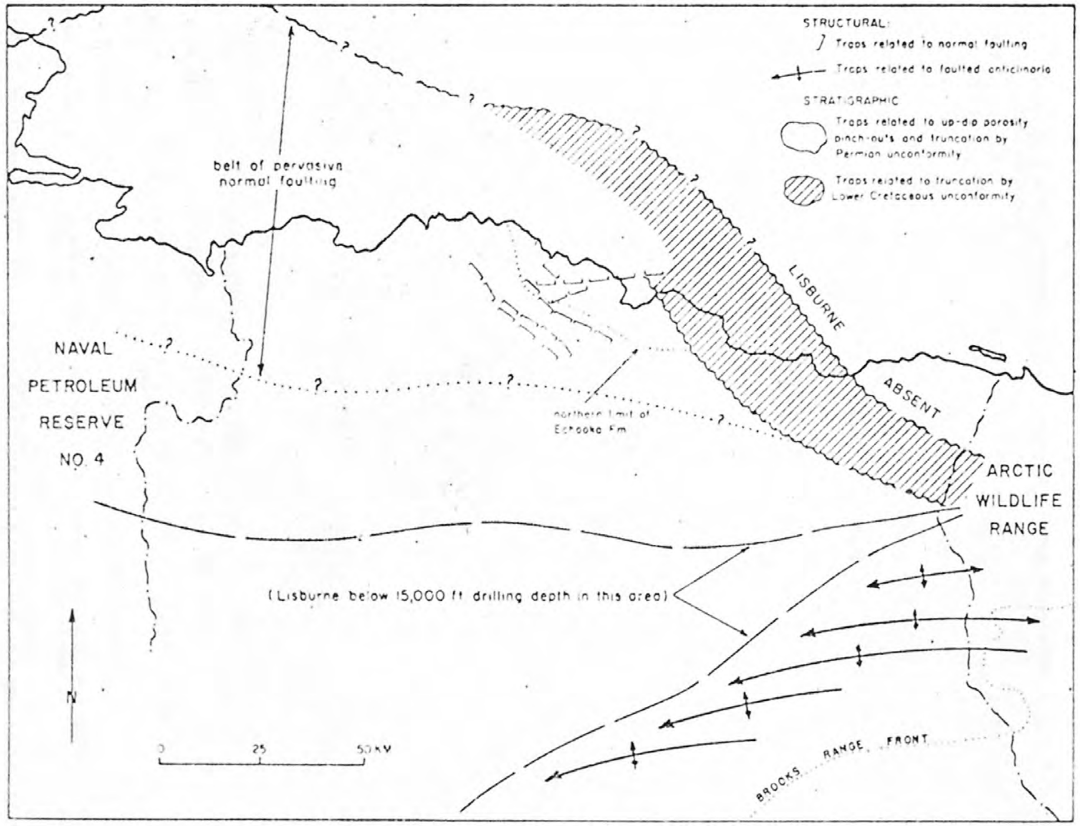

STRUCTURAL:
Traps related to normal faulting
Traps related to faulted anticlinoria
STRATIGRAPHIC
Traps related to up-dip porosity pinch-outs and truncation by Permian unconformity
Traps related to truncation by Lower Cretaceous unconformity
belt of pervasive normal faulting
NAVAL PETROLEUM RESERVE NO. 4
LISBURNE
ABSENT
northern limit of Echooka Fm
ARCTIC WILDLIFE RANGE
(Lisburne below 15,000 ft drilling depth in this area)
N
0 25 50 KM
BROOKS RANGE FRONT

Fig 10

Table 2

Well	Reservoir (Net feet with greater than 5% porosity)	Average Porosity (Average of net thickness)
B. P. Sag Delta 31-10-16	388	10.3
B. P. Put River 9-11-13	305	10.7
Union Kookpuk No. 1	218	14.6
Union Kalubik Creek No. 1	138	11.6
Sinclair - B. P. Ugnu No. 1	170	10.8

Table 1

	WELL	TEST INTERVAL	RESERVOIR	RESULTS
WITHIN DOLOMITE UNIT	Arco Itkillik No. 1	13,237-381	dolomite	2057 BPD saltwater
	Hamilton Bros. Milne Pt. No. 1	10,179-270	dolomite and sandstone	940 feet gas cut oil and mud
	Mobil Kuparuk St. No. 1	10,143-175	dolomite	350 BPD saltwater
	Mobil Mikkelsen Bay No. 1	11,870-12,200	dolomite	Flowed gas & oil (19.5° API) undisclosed rate
	Sinclair - B.P. Colville No. 1	9,023-73	dolomite	480 BPD saltwater
	Union Kalubik Creek No. 1	9,047-68	dolomite	325 BPD gassy sulphur water
ABOVE DOLOMITE UNIT	Arco Prudhoe Bay St. No. 1	8,750-883	dolomite	22 MMCFPD decreasing
	Arco Prudhoe Bay St. No. 1	9,200-410	dolomite	434 BOPD, 238 MCFPD, 26.2° API
	Arco Prudhoe Bay St. No. 1	9,505-825	dolomite	1152 BOPD, 1320 MCFPD, 26.9° API
	Arco East Bay St. No. 1	undisclosed	prob. dolomite	1350 BOPD, 7 MMCFPD
	B. P. Put River 9-11-13	9,304-600	limestone	170 BPD oil and water, 23.6° API
	Hamilton Bros. Milne Pt. 18-1	10,085-107	sandstone	1470 BPD saltwater