Chapter CC (Carboniferous and Older Carbonates)

CARBONIFEROUS AND OLDER CARBONATE ROCKS: LITHOFACIES, EXTENT, AND RESERVOIR QUALITY

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ABSTRACT

Carboniferous and older carbonate rocks are potential hydrocarbon reservoir facies for four plays in the 1002 area of the Arctic National Wildlife Refuge. These rocks include several units in the pre-Carboniferous basement and the Carboniferous Lisburne Group. Data from exploratory wells west of the 1002 area, outcrops south of the 1002 area, seismic lines, and well logs are synthesized herein to infer carbonate lithofacies, extent, and reservoir character beneath the northeastern Arctic coastal plain.

A chiefly shallow-water basement carbonate succession of Late Proterozoic through Early Devonian age (Katakturuk Dolomite, Nanook Limestone, and Mount Copleston Limestone) is interpreted to be present beneath much of the south-central 1002 area; it reaches 3,700 m thick in outcrop and is the primary reservoir for the Deformed Franklinian Play. A more heterogeneous lithologic assemblage of uncertain age forms basement in the northwestern part of the 1002 area; well data define three subunits that contain carbonate intervals 5- 50 m thick. These strata are prospective reservoirs for the Undeformed Franklinian Play and could also be reservoirs for the Niguanak-Aurora Play. Regional lithologic correlations suggest a Cambrian-Late Proterozoic(?) age for subunits one and two, and a slightly younger, later Cambrian-Silurian age for subunit three. Seismic and well data indicate that subunit one overlies subunit two and is overlain by subunit three. The Mississippian and Pennsylvanian Lisburne Group, a predominantly carbonate platform succession as much as 1 km thick, is projected beneath the southernmost part of the 1002 area and is a potential reservoir for the Ellesmerian Thrust-belt and Niguanak-Aurora Plays.

Carbonate rocks in the 1002 area probably retain little primary porosity but may have locally well developed secondary porosity. Measured reservoir parameters in basement carbonate strata are low (porosity generally ≤5%; permeability ≤0.2 md) but drill-stem tests found locally reasonable flow rates (4,220-4,800 bpd) and, in the Flaxman Island area, recovered gas and condensate from these rocks. The Lisburne Group has produced up to 50,000 bbl of oil/ day from the Lisburne field at Prudhoe Bay. Reservoir parameters of the Lisburne in northeastern Alaska range from low (porosities ≤5% in most limestones) to good (porosities average 6.5-10% in some dolostones). Reservoir quality in Carboniferous and older carbonate strata in the 1002 area should be greatest where these rocks are highly fractured and (or) truncated by the Lower Cretaceous Unconformity.

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INTRODUCTION

This section discusses the expected lithofacies, areal distribution, thickness, and reservoir character of Carboniferous and older carbonate rocks in the 1002 area of the Arctic National Wildlife Refuge (ANWR). These rocks consist of several units of pre-Carboniferous age and the Carboniferous Lisburne Group, and they provide potential reservoir facies for four of the plays described in this assessment. The data and inferences in this section derive chiefly from detailed examination of thin sections, core chips, cores, cuttings, and lithologic logs of 25 exploratory wells drilled northwest and west of the western border of the 1002 area (Fig. AO3, Tables CC1-CC6), integrated with previously published information on rocks exposed south of the 1002 area, and seismic and well log interpretations presented in other sections of this report (Grow and others, Chap. NA,Kelley, Chap. BR, Nelson and others, Chap.WL).

PRE-CARBONIFEROUS CARBONATE ROCKS

Carbonate rocks in several discrete units of pre-Carboniferous age are expected to occur in the 1002 area. Exposures in the mountain belt south of this area represent at least two pre-Carboniferous successions that differ in lithology, depositional environment, metamorphic grade, and structural complexity. Outcrops in the Shublik and Sadlerochit Mountains represent a coherent, unmetamorphosed, chiefly shallow-water carbonate platform sequence of Proterozoic through Early Devonian age (Dutro, 1970; Blodgett and others, 1986, 1988, 1992; Clough, 1989; Clough and others, 1988, 1990; Clough and Goldhammer, 1992; Clough and Robinson, 1994). Roughly coeval but more deformed, metamorphosed, and heterogeneous strata are exposed south and east of these mountains; these rocks have been variously interpreted as a conformable stratigraphic succession (e.g., Dutro and others, 1972; Norris, 1985; Kelley and others, 1994) or as an assemblage of fault-bounded tectonostratigraphic terranes (Moore and others, 1985). The pre-carboniferous rocks discussed in this chapter have been called the Franklinian sequence by some authors (but cf. Moore and others, 1994).

The chiefly platformal succession in the Shublik and Sadlerochit Mountains is at least 3,700 m thick and consists of the Katakturuk Dolomite (Upper Proterozoic), the Nanook Limestone (Upper Proterozoic and (or) Cambrian through Ordovician), and the Mount Copleston Limestone (Lower Devonian). This succession (herein called the "basement carbonate succession") was penetrated by the Canning River Unit A-1 well (Fig. AO3,

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Table CC1), is projected beneath the southcentral part of the 1002 area, and is the primary reservoir for the Deformed Franklinian Play.

The more heterogeneous pre-Carboniferous rocks southeast of the Shublik and Sadlerochit Mountains are largely unnamed; they have been less studied and have yielded fewer fossils than have rocks of the basement carbonate succession. Lithologies described include those characteristic of both shallow and deeper water settings; argillite, chert, various siliciclastic and carbonate metasedimentary rocks, and mafic to intermediate metavolcanic rocks have all been reported (Moore and others, 1994). "Basement complex" is an informal term that has been widely used for all rocks in the subsurface older than the Endicott Group (Bird, 1988); in this report, I use it to refer to all "basement" rocks with the exception of the "basement carbonate succession" defined above. Dolostone and limestone within the basement complex are known from exploratory wells in the Point Thomson-Flaxman Island area and the Mikkelsen Bay region to the west, are projected into the northwestern part of the 1002 area, and are the primary reservoirs for the Undeformed Franklinian Play; these rocks may also be reservoirs in the Niguanak-Aurora Play.

BASEMENT CARBONATE SUCCESSION

Lithofacies

In outcrops south of the 1002 area, the Upper Proterozoic Katakturuk Dolomite is as much as 2,500 m thick, consists of a variety of carbonate lithologies deposited chiefly in shallow subtidal to supratidal settings, includes abundant stromatolites and coated grains, and represents 5 second-order supersequences; 16 informal members, roughly equivalent to third-order depositional sequences, are recognized (Robinson and others, 1989; Clough, 1989; Clough and Goldhammer, 1992). The overlying Nanook Limestone is about 1,200 m thick and also contains a variety of shallow water lithofacies; the lower two-thirds of this formation are chiefly dolostone of Late Proterozoic and (or) Early and Middle(?) Cambrian age and the upper third is chiefly limestone (mainly peloidal pack-grainstone) of Late Cambrian and Ordovician age (Blodgett and others, 1986, 1988; Clough and others, 1988, 1990; Dumoulin and Harris, 1994, Fig. 26). In the Shublik Mountains, the Mount Copleston Limestone of Emsian (late Early Devonian) age disconformably overlies the Nanook; it is a maximum of 71 m thick and consists mostly of shallow-water lime mudstone with locally abundant brachiopods and stromatoporoids (Blodgett and others, 1992).

The Canning River Unit A-1 well, 10 km west of the western edge of the Sadlerochit Mountains (Fig. AO3; Table CC1), penetrated about 200 m (654 feet) of light gray, locally vuggy dolostone unconformably underlying the Endicott Group. This dolostone appears to be part of the basement carbonate succession; it has been interpreted as Katakturuk Dolomite (Bird and others, 1987) but could instead be the lower part of the Nanook Limestone. Core chips and cuttings of dolostone in the Canning A-1 well are homogenous, fine to medium grained (crystals 20-300 µm, mostly ≤100 µm), white to light gray to brown, and retain little or no primary texture; vugs and fractures (most quartz-filled) are locally abundant (Fig. CC1). The lower 700 m of the Nanook are quite similar to the Canning A-1 strata and consist largely of white to gray, fine- to medium-grained dolostone that lacks primary features but contains notable quartz-filled vugs and fractures (J.G. Clough, written commun., 1992). The Katakturuk Dolomite, in contrast, is characterized by well-preserved primary textures such as ooids, pisolites, and stromatolites (Clough, 1989), although parts of the formation lack such features and consist chiefly of 100- to 500-µm anhedral dolomite rhombs (Armstrong and Kelley, 1990; Kelley and others, 1992).

Extent and Thickness

The basement carbonate succession has been projected beneath the 1002 area on the basis of structural style seen in seismic data (Kelley, Chap. BR). In outcrop, the succession is cut by east-trending, mostly southward dipping thrust faults; a subsurface domain of faults similar to this extends from the range-front about 16 km north and is thought to reflect the areal extent of the basement carbonate succession (Kelley, Chap. BR). Thickness of these rocks in subsurface is assumed to be about 2000-4000 m, similar to that observed in outcrops south of the 1002 area; available seismic lines do not constrain this estimate.

Reservoir Quality

The reservoir quality of the basement carbonate succession is generally poor. Bird and others (1987) noted that most primary porosity in the basement rocks was destroyed during their long history of deep burial and deformation, but suggested that secondary porosity could be locally important.

Early dolomitization of the Katakturuk Dolomite has preserved much original fabric but has greatly reduced reservoir quality; dolomite rhombs 2-6 µm across replace framework grains, early cement, and micrite in many

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samples (Armstrong and Kelley, 1990; Kelley and others, 1992). The most recent porosity and permeability analyses of the Katakturuk are those in Clough (1995). He reports porosity data for 20 samples, taken from 10 of the 16 informal members of the Katakturuk and chosen to represent tidal flat, lagoon to shoal, and deep-water paleoenvironments; 12 of these samples contain visible primary (moldic, intraparticle, interparticle, and fenestral) and (or) secondary (fracture) porosity in hand sample. Measured porosities range from 0.5-8.6% with a mean value of 3.3%; the highest values (5 samples with ≥5%) come from peritidal mudstone (with visible fenestral porosity) and oolitic and pisolitic grainstones (some with visible moldic porosity, some with no porosity visible in hand specimen). Permeabilities of 15 samples analyzed are low and range from <0.1-1.19 md. Additional porosity and permeability data from the Katakturuk are given by Dutro (1970) and Bird and others (1987). Forty-three samples taken throughout the formation have porosities of 0.8-10.0%; all but two of the measured porosities are <4.5%, and most (35) are less than 2.5%. Permeabilities range from <0.1-1.6 md; most (29) are ≤0.1 md.

Few porosity/permeability values are available for the Nanook Limestone. Three samples--all dolostone from the lower half of the unit--have porosities of 1.2 to 1.9% and permeabilties of <0.1 to 0.2 md (Dutro, 1970; Bird and others, 1987). No porosities have been published for the Mount Copleston Limestone. According to Dutro (1970, p. M2) "porosities are generally low" throughout both units.

Core measurements and log interpretations indicate negligible primary porosity and permeability in the basement dolostone of the Canning A-1 well. Porosities of 9 samples from 2.5 m of core 200 m below the top of basement range from 0.3-1.1%; permeabilities are all <0.1 md (Bird and others, 1987). Neutron and density log values are near zero throughout the basement interval in this well (Nelson and Bird, Chap. FP).

Fractures--noted throughout the basement dolostone in the Canning A-1 well (this study; American Stratigraphic Company, 1976)--could improve reservoir quality (Bird and others, 1987; Armstrong and Kelley, 1990; Kelley and others, 1992). A 40-minute drill stem test through dolostone in this well recovered--apparently chiefly through fractures--fresh water at a flow rate of 4,800 barrels per day (Bird and others, 1987). Examination of laterolog-8 resistivity values suggests that about 20% of the basement dolostone in this well has enhanced (presumably fracture) porosity (Nelson and Bird, Chap. FP). Outcrop studies indicate that fractures in the basement carbonate succession formed chiefly during Tertiary concentric folding and

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thrust faulting (Kelley and others, 1992); fracture-related reservoir enhancement is probably greatest at the crests of anticlines where these rocks are thrust-ramped into place (Armstrong and Kelley, 1990).

Reservoir quality of the basement carbonate succession might also increase along subaerial exposure surfaces. Paleokarst features such as solution pipes, vertical cracks, and subhorizontal cavities are recognized in outcrop in nine members of the Katakturuk Dolomite; in the highest two members, these features may be tens of meters thick and of regional extent (Clough and Robinson, 1994). Most Katakturuk karst formed during sea-level lowstands that episodically interrupted its sedimentation, but features in the upper two members resulted from widespread uplift prior to deposition of the Nanook Limestone (Clough and Robinson, 1994). Karst features observed throughout the Katakturuk, however, are generally filled--with collapse breccias, speleothemic flowstone, and (or) cave popcorn (Clough and Robinson, 1994)--and do not preserve notable porosity.

In the Carboniferous Lisburne Group in the Lisburne field at Prudhoe Bay, reservoir quality is greatly improved beneath the Lower Cretaceous Unconformity (LCU) (Jameson, 1994; see further discussion below), and seismic data indicate that the LCU also truncates basement carbonate rocks in parts of the 1002 area [e.g., seismic line 14 in Kelley, Chap. BR]. LCU-related porosity in the Lisburne field is chiefly moldic, within limestones, and has "preferentially developed in micritic grains or parts of grains" such as peloids (Jameson, 1994, p. 1670). Peloidal limestones are common in the upper part of the Nanook Limestone; if similar rocks occur in the basement carbonate succession in the 1002 area, and are truncated by the LCU, porosity enhancement analogous to that described by Jameson (1994) may have occurred.

Thus, although measured reservoir parameters in the basement carbonate succession adjacent to the 1002 area are low, reservoir quality of these rocks within the 1002 area may have been enhanced by fracturing, karstification, and (or) diagenesis along the LCU.

BASEMENT COMPLEX

The pre-Carboniferous "basement complex" (as defined above) underlies the basement carbonate succession in the Sadlerochit Mountains and crops out south of the 1002 area. It also occurs in subsurface throughout much of northern Alaska and was penetrated by 17 exploratory wells drilled north and west of the 1002 area (Fig. AO3, Tables CC2-5).

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In exploratory wells along the northern coast of Alaska, two lithologically distinct metasedimentary successions make up the basement complex; one succession consists of interbedded carbonate and siliciclastic rocks and the other lacks appreciable carbonate (Banet and Scherr, 1994). The carbonate-siliciclastic succession was encountered in all offshore wells that were drilled into basement east of longitude 146° 40'; to the west, this succession is overlain by (and may laterally grade into) the noncarbonate succession, which comprises all basement penetrated offshore west of 148° (Banet and Scherr, 1994). Basement rocks in most, perhaps all, of the 17 wells noted above appear to belong to the carbonate-siliciclastic succession, and include three subunits that differ in lithology, distribution, and seismic character. All of these subunits could occur in the northern part of the 1002 area; all contain carbonate rocks that could provide reservoir facies. The age of these subunits, and their relation to the basement carbonate succession previously discussed, are uncertain; possible correlations with better dated basement rocks in northeastern Alaska are discussed below. All three subunits are considered "rocks of uncertain affinity" by Kelley (Chap. BR). The basement complex is described in more detail than other units in this report because little has been previously published on these enigmatic rocks.

Lithofacies, Deformation, and Correlation

Subunit One. Subunit one was penetrated in 5 offshore wells (Alaska Island 1, Challenge Island 1, and Alaska State F-1, D-1, and A-1) in the Flaxman Island area, with maximum penetration--about 390 m (1,286 ft)--in the Alaska State A-1 well (Fig. AO3, Fig. CC2). This subunit consists of locally abundant siltstone to fine-grained sandstone interbedded with dark shale and one or more distinctive intervals of dolostone and (or) limestone.

Siltstone and sandstone are especially abundant in the upper half of the subunit, where lithologic logs indicate that they make up 40-45% of the noncarbonate strata (e.g., Alaska State A-1 well, American Stratigraphic Company, 1978; Fig. CC2; Table CC2). A few continuous sandstone intervals are 5-10 m thick but most are less than 2 m (American Stratigraphic Company, 1978, 1984, 1985). Samples generally contain subequal amounts of quartz, feldspar, and carbonate; beds especially rich in quartz (Q=70-95% of all framework grains) are found near the top of the subunit in several wells. Staining indicates that the feldspar in most samples is plagioclase, but potassium and plagioclase feldspar occur together in samples from three wells (Fig. CC3A). Carbonate (chiefly dolomite) is a subordinate component of most subunit one sandstones but makes up 40% or

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more of some samples; staining indicates that the carbonate is locally iron rich. Elongate flakes of detrital white mica, biotite, tourmaline, and zircon are common accessory constituents in these rocks.

Carbonate rocks are found at or near the top of this subunit in all five wells and at two lower levels in Alaska State A-1 (American Stratigraphic Company, 1978; Fig. CC2). Similarities in thickness and log response suggest that the middle A-1 carbonate interval may correlate with carbonate near the top of basement in Alaska State F-1 and D-1 (Bird and others, 1987). Carbonate-rich intervals are 10 to 60 m thick; appreciable noncarbonate interbeds (shale) occur only in the lowest A-1 carbonate (Fig. CC2). Thin sections of core chips and cuttings reveal that most carbonate intervals are interbedded limestone and dolostone; only dolostone was observed in Challenge Island and Alaska State F-1.

Subunit one carbonate rocks are somewhat recrystallized but retain many relict features. Ooids, peloids, and micritic clasts are locally abundant; bioclasts (chiefly pelmatozoan and phosphatic brachiopod scraps) are rare (Figs. CC3B-E). Thin limestone beds in the lowest A-1 carbonate interval contain distinctive coarse fragments of pisoids, oncoids and (or) stromatolites. Rounded, medium- to very coarse grained detrital quartz is a notable feature of carbonate rocks throughout the subunit and makes up as much as 50% of some samples (Fig. CC3F). Carbonate clasts and cobbles in the overlying Thomson sand of Early Cretaceous age display striking textural similarities to, and appear to be derived from, subunit one carbonate rocks.

An apparent lack of deformation further distinguishes subunit one. Bed dips observed in core are low--0 to 15° (Bird and others, 1987). Primary structures such as burrows and cross-laminae are well preserved in thin section and hand sample. Grain boundaries in most sandstone samples are not recrystallized and fine-grained rocks lack slaty cleavage. Seismic data show continuity of reflections within this subunit and coherent, high-amplitude reflectors can be clearly recognized (Bird and others, 1987; Fisher and Bruns, 1987, Kelley, Chap. BR).

Composition and sedimentary structures suggest that the upper part of subunit one formed in a relatively shallow-water shelf or platform setting, but the lower part of the subunit (penetrated only in the Alaska State A-1 well) probably accumulated in deeper water. Abundant, thick beds of sandstone and carbonate (locally including ooid grainstone) characterize the upper strata, but the lower part of the subunit is mostly shale and siltstone

(Fig. CC2). Sandstone and limestone beds in these lower strata are rare and thin; core chips contain structures (grading, parallel and cross-laminae, scoured bed bottoms) characteristic of distal turbidites.

Fossil fragments indicate that at least the upper half of subunit one is Cambrian or younger. Carbonate beds contain phosphatic brachiopods in Alaska State F-1 (A.G. Harris, written commun., 1997) and pelmatozoan debris in all subunit one wells except Challenge Island (Table CC2). Samples from the lowest A-1 carbonate interval contain no definitive bioclasts, however, so these strata could be Proterozoic.

Carbonate textures and sandstone compositions in subunit one are similar to those reported from rocks assigned a Cambrian or Proterozoic age in outcrops south of the 1002 area. Ooids, oncoids, pisoids, peloids, and coarse, rounded quartz grains are abundant in several unnamed limestone units that overlie the Neruokpuk Quartzite (Proterozoic and (or) Cambrian) in the Demarcation Point quadrangle (Dutro and others, 1972; Reiser and others, 1980; Lane, 1991; Kelley and others, 1994; Lane and others, 1995). Fine- to coarse-grained, locally semischistose sandstones in the Neruokpuk Quartzite are quartz-rich but also contain 10-25% feldspar (plagioclase and perthitic microcline) (Sable, 1977); Kelley and others (1995) report abundant plagioclase and potassium feldspar (including microcline) in turbidite sandstones of the Neruokpuk.

Subunit Two. Four wells south and west of subunit one penetrated rocks herein assigned to subunit two of the basement complex: Point Thomson Unit 2 and Unit 3, West Staines 18-9-23, and W Mikkelsen Unit 2 (Fig. AO3; Table CC3). Maximum penetration is 305 m (1,002 ft) in Point Thomson Unit 2 (Fig. CC2). Subunit two is chiefly argillite with subordinate thin beds of siltstone to fine sandstone and--in Point Thompson Unit 2 only--limestone.

Sandstone in subunit two is less abundant than, but similar in composition to, sandstone in subunit one. Lithologic logs of subunit two show no discrete siltstone beds and only a single sandstone interval (<2 m thick) near the top of the subunit in W Mikkelsen Unit 2 (American Stratigraphic Company, 1972, 1983, 1984). Core chips, however, demonstrate that fine-grained sandstone to siltstone is present throughout the subunit as thin (<1 mm-1.5 cm) layers (Table CC3), many of which have parallel and (or) cross-laminae, grading, burrows, and (or) scoured bases. Most subunit two sandstone consists of subequal amounts of quartz, feldspar, and carbonate (Fig. CC4A), although a few beds in Point Thomson Unit 3 and W

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Mikkelsen Unit 2 contain ≥80% quartz. Staining indicates that all feldspar is plagioclase and most carbonate is iron-rich dolomite.

Variously recrystallized limestones, in intervals <1.5-15 m thick intercalated with argillite, make up 30% of the lower half of basement at Point Thomson Unit 2 (Fig. CC2; American Stratigraphic Company, 1984). Ooids and fragments of pisoids, oncoids and (or) stromatolites are extremely abundant in these limestones (Fig. CC4C, D); some coated grains have a black mud matrix. A few samples contain rare, poorly preserved bioclasts? (including possible pelmatozoan material).

Subunit two appears more deformed than subunit one. Vertical beds occur in cores from W Mikkelsen Unit 2 (this study) and Point Thomson Unit 2 (American Stratigraphic Company, 1984). Sedimentary structures in sandy layers are locally well preserved (especially in Point Thomson Unit 3 and W Mikkelsen Unit 2), but grain boundaries in many samples are recrystallized. Evidence of deformation and recrystallization are heterogeneously distributed throughout the subunit (Fig. CC4), but seem at least partly controlled by original lithology. The finest grained and (or) thinnest bedded rocks are most affected--they are generally cleaved and some have phyllitic or semischistose textures (Fig. CC4B). Sandstone and siltstone layers are typically less deformed than shales.

Most, perhaps all, of subunit two accumulated in a relatively deep water (off-shelf) setting. Sedimentary structures indicate that sandy layers found throughout this subunit are distal turbidites. Coated grains such as ooids form primarily in shallow water, but their occurrence in this subunit within thin, subordinate, locally muddy limestone beds intercalated with argillite implies that these grains were redeposited into deeper water, probably by turbidity currents.

Subunit two could be a coeval, deeper water facies of subunit one. Quartzo-feldspathic sandstone found in both subunits suggests a common provenance; lower parts of both subunits contain thin limestone beds with distinctive, coarse, coated grains. Deformational differences between the two subunits may reflect rheologic contrasts--subunit two lacks the thick carbonate and sandstone intervals that characterize subunit one.

Bioclasts are few and questionable in subunit two, and no age-diagnostic fossils have been recovered. A Proterozoic age is suggested for at least part of the subunit by a suite of radiometric (K-Ar) ages (547-584 Ma) obtained from graphitic phyllites in West Staines 18-9-23 that have been interpreted

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as dating the metamorphism of these rocks (Drummond, 1974, p. 802). The subunit could be Cambrian or younger, however, if the micas that yielded these ages are detrital. Seismic data (discussed below) suggest that subunit two could be older than subunit one.

Subunit Three. Subunit three was penetrated by three wells in the Mikkelsen Bay area (W Mikkelsen State 1, Mikkelsen Bay State 1, and E Mikkelsen Bay State 1; Fig. AO3; Table CC4). Greatest basement penetration in this group--511 m (1676 ft)--was in E Mikkelsen Bay (Fig. CC2), but the basal 150 m drilled in this well may be part of subunit one or two (see below). Argillite makes up most of subunit three, but is intercalated with thin beds of fine-grained sandstone to siltstone, limestone, and chert.

As in subunit two, sandstone and siltstone form rare, thin layers that are generally parallel- and cross-laminated and locally graded with scoured bases. Lithologic logs (American Stratigraphic Company, 1972, 1973, 1981) show only minor, m-thick beds of sandstone and siltstone, mainly in the uppermost basement in E Mikkelsen Bay, but cores and core chips from all three wells contain mm-thick sandy and silty layers (Table CC4). Subunit three sandstone contains little or no recognizable feldspar and consists mostly of quartz, sedimentary lithic clasts (chert and mudstone), dolomite, and calcite (Fig. CC5A).

Lithologic logs and core chips suggest that carbonate rocks--all limestone--make up 20-30% of this subunit overall and as much as 50% of some dm-thick intervals in E Mikkelsen Bay. Most limy intervals are <6 m thick and many are <1 m; three lithologies (all somewhat recrystallized) were noted. The first, found in all three wells, is micrite to fine-grained limestone containing sparse to abundant calcite- and (or) quartz-filled ovoids (most 50-250 µm) that are probably replaced and recrystallized radiolarian tests. A second lithology forms a bioturbated layer 15 cm thick in core from W Mikkelsen State; it consists of 0.5-7 mm limestone clasts, all ooids or fragments of oolitic grainstone, in a dark muddy matrix (Fig. CC5B). The third limestone type was seen only in core and cuttings from E Mikkelsen Bay. The upper 360 m of basement in this well contain limestone that is mainly very fine to fine-grained grainstone, locally graded, made up of peloids, unusually small ooids (50-150 µm diameter), and fossil fragments (Figs. CC5C, D); this lithology grades into, and appears to be interbedded with, the radiolarian-bearing limestone described above.

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Limestone, in intervals as much as 15 m thick, makes up about half of the lower 150 m of basement in E Mikkelsen Bay (American Stratigraphic Company, 1973; Fig. CC2). These beds contain coarser, more "typical" ooids (500 µm-1.5 mm in diameter), as well as possible bioclasts and rounded detrital quartz--features typical of limestones in subunits one, and to a lesser degree, two. Thus, carbonate textures suggest that these basal strata at E Mikkelsen Bay should not be included in subunit three.

Wells in the Mikkelsen Bay area also contain several distinctive noncarbonate lithologies. Chert with locally well-preserved radiolarians forms rare, thin (< 1m) beds in Mikkelsen Bay and E Mikkelsen Bay (American Stratigraphic Company, 1972, 1973) and chert clasts containing radiolarians were noted in sandstone from all subunit three wells. Cuttings from E Mikkelsen Bay include minor amounts of altered mafic to intermediate volcanic fragments, particularly in the basal 30 m of section.

The degree of deformation in subunit three appears intermediate between that in subunits one and two. Vertical beds occur in core from W Mikkelsen State and some fine-grained rocks throughout the subunit are cleaved. Grain boundaries, however, are not strongly recrystallized, phyllitic and semischistose textures are uncommon, and sedimentary structures are well-preserved.

A deep-water (off-platform) depositional setting is indicated for much or all of subunit three by lithologic and textural evidence. Limy and sandy beds are generally thin, subordinate, intercalated with argillite, and appear (based on sedimentary structures noted in core chips) to be distal turbidites. As in subunit two, ooids in subunit three probably formed in shallow water and were then redeposited into a deeper water environment. Radiolarians, seen in thin sections of core chips and cuttings from throughout this subunit, also suggest an off-platform setting.

No tightly age-diagnostic fossils have been identified in subunit three, but radiolarians and other bioclasts in these strata indicate that they are of post-Proterozoic age. Correlation with lithologically similar but better dated rocks elsewhere in northern Alaska suggests a Cambrian, Ordovician, and (or) Silurian age for this subunit. Argillite, locally interbedded with radiolarian chert, oolitic limestone, and calcareous and quartzose sandstone, crops out south of the 1002 area; fossils of Cambrian, Ordovician, and latest Silurian or earliest Devonian age are found in these rocks (Dutro and others, 1972; Reiser and others, 1980; Kelley and others, 1994). Argillite with subordinate interbeds of chert, siltstone, and sandstone also occurs in

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subsurface west of Mikkelsen Bay. At Prudhoe Bay and Barrow, these strata contain graptolites and chitinozoans of Ordovician and Silurian age (Carter and Laufield, 1975); in the Barrow area, they include interbeds of fine-grained sandstone that lack feldspar and consist mostly of quartz and subordinate chert (A. Grantz, written communs., 1985, 1998). Correlation of limestone lithologies suggests that at E Mikkelsen Bay, subunit three overlies rocks belonging to subunits one or (perhaps) two. If this contact is a stratigraphic and not a structural one, subunit three may be the youngest of the three subunits.

Alternative Correlation for Subunits One, Two, and Three. As detailed above, lithologic evidence suggests a Cambrian-Late Proterozoic(?) age for subunits one and two of the basement complex, and a slightly younger, later Cambrian-Silurian age for subunit three. An alternative correlation for these rocks, based largely on interpretation of seismic data, is outlined by Kelley (Chap. BR). He proposes that stratigraphic position and structural style of basement rocks in and west of the northern part of the 1002 area (including subunits one, two, and three of this report) are analogous to those of thick, chiefly Devonian clastic wedges that locally underlie Mississippian strata throughout northern Alaska. Such wedges crop out in the eastern, central, and western Brooks Range, and fill subsurface basins (e.g., Meade and Umiat basins) beneath the western and central Arctic coastal plain.

The Devonian clastic wedge closest to the 1002 area is that exposed along the continental divide in the northeastern Brooks Range; these rocks are thoroughly described by Anderson (1993) and Anderson and others (1994) and may be compared to the basement complex west of the 1002 area. The continental divide succession is as much as 600 m thick and comprises two informally named formations. Conglomerate, sandstone, siltstone, and mudstone, deposited in shallow-marine to alluvial-fan settings, make up the Middle-Upper(?) Devonian Ulungarat formation. The Upper Devonian and (or) Lower Mississippian Mangaqtaaq formation locally overlies the Ulungarat, consists of algal limestone, sandstone, and mudstone, and probably formed in a lacustrine or restricted marine environment.

Petrography of the continental divide succession differs notably from that of the basement complex. Clastic rocks in the Ulungarat and Mangaqtaaq formations consist mainly of chert and lesser quartz framework grains; Ulungarat samples point-counted by Anderson (1993) contain 60-98% chert clasts (>80% chert in 13 of the 16 samples) and no feldspar. Sandstones in basement complex subunits one and two, in contrast, are rich in feldspar but have few lithic clasts. Chert is present in sandstones of subunit three, but it

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is never the predominant constituent. Carbonate rocks in the continental divide succession are exclusively limestone and chiefly algal packstone and grainstone; they form intervals <10 (generally, <3) m thick and contain abundant oncoids (1-8 cm in diameter), minor bioclasts (gastropods, ostracods, worm tubes), and rare ooids. Carbonate rocks in basement complex subunits one, two, and three, however, contain abundant ooids, as well as bioclasts (pelmatozoan material) indicative (e.g., Wilson, 1975) of normal marine salinity. Subunit one also contains abundant dolostone. Comparative studies of Phanerozoic limestones (Wilkinson and others, 1985) demonstrate that ooids are strikingly abundant worldwide in rocks of Cambrian age but are relatively rare in Devonian sequences.

The composition of Devonian clastic wedges elsewhere in northern Alaska appears broadly similar to that of the continental divide succession, and unlike that of the basement complex adjacent to the 1002 area. In particular, these Devonian wedges consist chiefly of chert-rich sandstone and conglomerate with little or no interbedded limestone (Anderson, 1993; Moore and others, 1994; A. Grantz, written communs., 1985, 1998). These compositional data argue against interpretation of subunits one, two, and three as parts of a clastic wedge of Middle and (or) Late Devonian age.

The compositional data outlined above could be compatible with the seismic interpretations in Kelley (Chap. BR) if basement in the 1002 area contains clastic wedges of more than one age and origin. Seismic lines throughout the northern part of the 1002 area reveal features interpreted as basement clastic wedges, but available data do not prove that all of these features are connected. The wedge seen on line AN84-6/AN85-8 encompasses rocks drilled in the Flaxman Island area (subunit one of this report) but no drill data constrains the composition of the wedge(s) noted on lines extending further east (e.g., AN84-3). Thus, subunit one could be part of a small wedge made up chiefly of Cambrian (and Proterozoic?) strata, and the larger wedge underlying most of the northern part of the 1002 area could consist chiefly of Middle-Upper Devonian rocks compositionally similar to coeval strata elsewhere in northern Alaska. The interpretation of various basement wedge types is supported by contrasts in wedge structures across the 1002 area. The wedge on line AN84-6/AN85-8 differs from wedge(s) to the east in lacking step-faults and containing apparent compressional features (Kelley, Chap. BR). These structural distinctions could reflect compositional differences between the wedges.

Other basement complex rocks. Five exploratory wells (E De K Leffingwell 1, Point Thomson Unit 4 and Unit 1, West Staines State 2, and

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Alaska State C-1) drilled adjacent to the 1002 area encountered basement complex rocks that could not confidently be assigned to any of the three subunits described above (Fig. AO3; Table CC5). Basement penetrations in these wells are relatively thin (≤40 m) and consist of predominantly fine-grained rocks that are locally strongly deformed and recrystallized. No carbonate strata occur in these sections; sandy layers are rare, thin, and made up mostly of quartz and carbonate. Geographic position alone suggests that basement strata at Point Thomson Units 1 and 4, West Staines State 2, and Alaska State C-1 belong to subunit two; all of these wells are within 4-6 km of confirmed subunit two strata at Point Thomson Units 2 and 3 (Fig. AO3).

The Leffingwell well is 14 km south of West Staines 18-9-23 and 21 km southeast of E Mikkelsen Bay State 1--wells which contain basement strata of subunits two and three, respectively. Thin (1-4 mm) silt- to fine sand-sized layers occur in 75% of Leffingwell core chips; most layers contain 65-80% carbonate, at least some of which has replaced other framework clasts. Feldspar has not been identified in these samples, but may have been completely altered to carbonate ± sericite (Kelley, Chap. BR); chert clasts are locally abundant. Most Leffingwell basement samples are semischistose, but equally deformed and recrystallized rocks occur in subunits two and three, finely intercalated with much less deformed looking rocks (Fig. CC4; cf. B and C,D). Kelley (Chap. BR) considers basement strata at Leffingwell to be similar to, and possibly correlative with, more metamorphosed parts of the Neruokpuk Quartzite. He assigns these Leffingwell strata to his "second unit" but considers all other basement complex strata to be rocks of uncertain affinity. The presence of chert clasts in some Leffingwell samples suggests a possible affinity with subunit three of this report, but the lack of carbonate intervals and the high degree of alteration and deformation characteristic of this section precludes a definitive correlation.

Extent and Thickness

Lithologic heterogeneity and complex deformation within the basement complex obscures seismic recognition of lithostratigraphic packages. Only subunit one, with its coherent high-amplitude reflectors, can be confidently recognized on seismic lines; it parallels the apex of the Mikkelsen high and extends southeast along the coastline into the northwestern part of the 1002 area (Fig. 18-2, Fisher and Bruns, 1987; Figs. 5, 8, 17, and 18, Scherr and others, 1991). Although subunits two and three are less distinctive in seismic profiles, well data suggests that these subunits also form linear belts trending southeast toward the 1002 area. Plate BS4 (segments 4 and 5) in Houseknecht and Schenk (Chap. BS) (also Kelley, Chap. BR) shows a part

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of seismic line 85-8, which runs NNW a few km west of the Alaska State A-1 well. On this line, gently-dipping reflectors (subunit one) overlie a package of steep, north-dipping reflectors (subunit two?). This relationship suggests that subunit two is older than subunit one, but the contact could be a structural one.

Carbonate intervals cannot specifically be distinguished within any part of the basement complex on seismic lines, but well data indicates the expected thickness of carbonate in the northern 1002 area. Carbonate beds have a maximum aggregate thickness of 45-75 m in each of the three subunits; continuous carbonate intervals are thickest in subunit one (50 m) and much thinner (15 and 6 m, respectively) in subunits two and three.

Reservoir Quality

Log and petrographic data suggest that carbonate rocks in subunit one are the best potential reservoir in the basement complex; noncarbonate parts of this complex appear to have little or no reservoir potential. Expected reservoir quality throughout the basement complex is generally low. Direct measurements of porosity and permeability have not been published for basement complex rocks adjacent to the 1002 area, but well log response and thin section observations allow some estimates of these parameters. Well log readings imply average porosities of 0-3% in carbonate strata, with values of 10-25% for some thin intervals (Bird and others, 1987) [P. Nelson, written. communs., 1997, 1998]. The highest values were recorded in dolostone and limestone of subunit one. Porosities of 20-25% were calculated for low-resistivity dolostones in the upper carbonate interval at Alaska State A-1 (Bird and others, 1987), and values as high as 10% were estimated for some of the basal strata at E Mikkelsen, which may also be part of subunit one [P. Nelson, written. communs., 1997, 1998].

Thin section observations support the log interpretations; minor intercrystalline porosity was noted in samples of dolostone and oolitic and bioclastic limestone from subunit one (Alaska State A-1, D-1), but limestone samples from subunits two and three contain no visible porosity. Several other factors increase reservoir potential for carbonate strata in subunit one relative to the rest of the basement complex; carbonate intervals in subunit one are relatively thick and locally occur directly beneath the pre-Mississippian unconformity. Carbonate layers in subunits two and three form thin, isolated interbeds in predominantly argillite successions.

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In spite of the poor reservoir potential indicated by well log and petrographic studies, drill stem tests of carbonate strata at or near the top of subunit one recovered gas and condensate from the Alaska Island 1 and Alaska State F-1 wells, and salt water at a flow rate of 4,220 bpd from Alaska State A-1 (Bird and others, 1987). As noted above for the basement carbonate succession, fractures have presumably enhanced reservoir quality in these rocks.

CARBONIFEROUS LISBURNE GROUP

The Lisburne Group is a predominantly shallow-water carbonate platform succession of Carboniferous age; it occurs widely in outcrop and subsurface throughout northern Alaska, is as much as 1 km thick, and comprises a depositionally and diagenetically complex array of lithofacies. The Lisburne is part of the Ellesmerian sequence of Mississippian to Cretaceous age which formed on a south-facing, slowly subsiding continental margin. Up to 50,000 bbl oil/day have been produced from the Lisburne Group in the Lisburne field at Prudhoe Bay (Jameson, 1994). Ten exploratory wells drilled along the western boundary of the 1002 area penetrated the Lisburne (Fig. AO3, Table CC6) and it is extensively exposed throughout the ANWR south of the coastal plain. The Lisburne is a potential reservoir for the Ellesmerian Thrust-belt and Niguanak-Aurora Plays of this assessment.

Lithofacies

The Lisburne Group in northeastern Alaska consists chiefly of limestone, lesser dolostone, and minor shale and sandstone. It comprises both mud and grain-supported carbonates formed in supratidal to deep subtidal settings; grains include various bioclasts (particularly pelmatozoan and bryozoan fragments), peloids, ooids, and intraclasts (Armstrong, 1974; Armstrong and Mamet, 1974, 1975; Bird and Jordan, 1977; Watts and others, 1994; Jameson, 1994). Two formations--the Alapah Limestone and the overlying Wahoo Limestone--are generally recognized, and a number of informal members have been described (e.g., Bird, 1982; Watts and others, 1994; Jameson, 1994).

The Lisburne Group formed during a series of marine transgressions across an irregular topographic surface with considerable relief (Armstrong, 1974; Watts and others, 1994). Detailed configuration of the Lisburne carbonate platform has not yet been delineated, but much of the Lisburne in northeastern Alaska, particularly the Wahoo Limestone, appears to have been deposited on a south-facing, gently sloping, homoclinal ramp (Armstrong and Bird, 1976; Gruzlovic, 1991; Jameson, 1994; Watts and

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others, 1994). At least three large-scale transgressive-regressive cycles are documented in the Lisburne in outcrops south of the 1002 area (Watts and others, 1994); m-scale lithologic cycles also occur, in outcrop and subsurface, particularly in the uppermost Lisburne (upper Wahoo Limestone) (Watts and others, 1994; Jameson, 1994). The Lisburne is truncated by an erosional surface of Permian age or, locally, by the LCU.

Broad depositional continuity of the Lisburne Group across hundreds of kilometers has been suggested by many authors (e.g., Armstrong and Mamet, 1974; Jameson, 1994; Watts and others, 1994). But detailed lithofacies patterns in the Lisburne Group are complex and reflect a variety of structural, depositional, and diagenetic controls. Brookian deformation has considerably compressed Ellesmerian lithofacies; recent estimates of tectonic shortening for the Lisburne in the 1002 area range from 26% (Wallace, 1993) to 47% (Cole, Chap. SM). Depositional and diagenetic controls on Lisburne lithofacies include platfrom configuration, paleoclimate, relative changes in sea level, and burial history (Armstrong, 1974; Gruzlovic, 1991; Jameson, 1994; Watts and others, 1994; Carlson, 1995).

Several aspects of Lisburne Group lithofacies patterns particularly affect reservoir quality and are discussed here. Carlson (1995) suggested that two opposed porosity gradients may characterize the Lisburne carbonate platform: greater formation of secondary porosity in a landward direction, but greater preservation of primary porosity (due to decreased meteoric cementation) in a seaward direction. Most documented porosity in the Lisburne is secondary porosity within microcrystalline dolostone (Bird and others, 1987), but Lisburne cementation patterns imply that deeper water strata could preserve significant porosity (Carlson, 1995). Distribution patterns of dolostone and downslope facies within the Lisburne in northeastern Alaska are discussed below.

Dolostone

Lisburne Group outcrops south of the 1002 area contain dolostone chiefly at three stratigraphic levels: in the lowermost and uppermost parts of the Alapah Limestone, and in the upper part of the Wahoo Limestone. Lisburne lithofacies have recently been described and interpreted by Gruzlovic (1991), Watts and others (1994), and Carlson (1995); their data on dolostone distribution are summarized here. (1) Spiculitic dolostone at the base of the Alapah formed in restricted marine (lagoonal?) environments during initial transgression of the Lisburne sea; it is best developed to the south (e.g., in

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the Fourth Range), where it is associated with as many as 7 subaerial exposure surfaces. (2) Spiculitic dolostone and dolomitic lime mudstone in the upper part of the Alapah crop out widely south of the 1002 area and are more abundant to the north; they are associated with locally well-developed karst textures and 5 subaerial exposure surfaces in the Sadlerochit and Shublik Mountains. The upper Alapah accumulated during the maximum geographic extent of the Lisburne platform, which resulted in greatly restricted water circulation across the platform interior. (3) Shallowing-upward cycles characterize the upper part of the Wahoo and may have formed during glacioeustatic sea level fluctuations; dolomitic mudstone and cryptalgalaminate mark the tops of these cycles. Dolostone in the Wahoo is most abundant in the northeastern part of the outcrop belt and is associated with as many as 5 subaerial exposure surfaces in the Sadlerochit Mountains.

Thickness of these dolomitic intervals varies across the outcrop belt but can be considerable. Maximum thicknesses of 60-90 m and 40-120 m are reported for relatively continuous dolomitic horizons in the lower and upper Alapah, respectively; dolostone in the upper Wahoo is more irregularly distributed through some 100-235 m of section (Gruzlovic, 1991; Carlson, 1995).

In subsurface west of the 1002 area, dolostone is locally abundant in the middle part of the Lisburne Group. This interval is variously referred to as the dolomite unit (Bird, 1982) or the middle member of the Alapah (Jameson, 1994) and correlates with what is called the upper member of the Alapah Limestone in surface exposures (Watts and others, 1994). Lithologic logs of 10 wells that penetrated all or part of the Lisburne adjacent to the western boundary of the 1002 area (Fig. AO3, Table CC6) indicate considerable variation in abundance and distribution of dolostone from north to south (American Stratigraphic Company, 1972, 1974, 1975, 1976, 1977, 1981; Fig. 7.7 of Bird and others, 1987). In the Mikkelsen Bay area, the Lisburne is about 450-620 m thick; dolostone, in intervals as much as 25 m thick, makes up 30-60% of the upper third of the unit and 10-18% of the entire section. About 40 km to the south, 3 wells (West Kavik 1, Beli Unit 1, and Canning River Unit B-1) bottomed in the Lisburne after pentrating from 336-674 m of section; dolostone here occurs throughout the unit in intervals 1.5-6 m thick and makes up 8-12% of the section. Only 5 km farther south, however, in the Kavik 1 and Canning River Unit A-1 wells, complete sections of the Lisburne (983 and 703 m thick, respectively) contain about 45% dolostone, including some intervals as much as 40 m thick. Another 25 km to the south, dolostone is also abundant (25% of section) in the Kemik Unit 1 well. The Lisburne here is about 1,530 m thick

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but may have been structurally thickened; several intervals of breccia are recorded on the lithologic log (American Stratigraphic Company, 1974).

Downslope Facies

As noted above, the Lisburne Group formed on a south-facing ramp; in outcrops south of the 1002 area, deeper water, open marine facies increase in abundance and show less calcite cementation to the south (Gruzlovic, 1991; Carlson, 1995). This gradient suggests that downslope facies of the Lisburne should be relatively rare beneath the 1002 area. Intervals as much as 50 m thick comprised of carbonate clasts in a limy or shaly matrix and interpreted as turbidites are reported from several intervals in the Canning River Unit A-1 and Kemik Unit 1 wells (American Stratigraphic Company, 1974, 1976) but these intervals show little or no porosity, based on well log responses (Nelson and Bird, Chap. FP) and core observations (this study). Downslope facies of the Lisburne that preserve significant porosity have not been documented in outcrops or in subsurface adjacent to the 1002 area.

Extent and Thickness

Seismic data indicate that the Ellesmerian sequence is present in subsurface beneath the southern part of the 1002 area and may also occur in the Niguanak and Aurora highs (Grow and others, Chap. NA). In parts of the southern 1002 area, the Lisburne Group appears to make up most of the Ellesmerian package (Grow and others, Chap. P9). Several factors (discussed below) suggest that reservoir quality of these Lisburne strata could be relatively good. The Lisburne in subsurface adjacent to the southwestern boundary of the 1002 area is rich in dolostone, at least some of which is relatively porous. In addition, where the Lisburne is truncated by the LCU (e.g., sesimic line 84-5 [K. Bird, written commun., 1998]), reservoir enhancement may be expected.

Thickness of the Lisburne Group beneath the southern part of the 1002 area is probably on the order of 700-1000 m, similar to that seen in wells such as Kavik 1 and Canning River Unit A-1. As noted above, thickness of the Lisburne in the Kemik Unit 1 well (>1,500 m) may reflect structural complications.

Reservoir Quality

Primary porosity throughout the Lisburne Group in northeastern Alaska has been largely occluded by early calcite cement. Stratigraphic, chemical, and

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isotopic data suggest that most cementation in the Lisburne exposed south of the 1002 area occurred during Carboniferous and sub-Permian subaerial events (Carlson, 1995). Calcite cementation and extensive pressure solution have destroyed virtually all primary porosity in the Lisburne field (James, 1994).

Published porosity values support the interpretation that significant primary porosity in the Lisburne Group is rarely preserved. In subsurface west of the 1002 area, porosity is generally low in limestones of the Lisburne but fair to good in dolostones (Bird and Jordan, 1977; Bird and others, 1987). Dolostone porosity averages 6.5% (range 2-15%) in outcrops south of the coastal plain and 10% (range 7-19%) in three wells (Beli Unit 1, Canning River Units A-1, B-1) drilled west of 1002 boundary (Bird and others, 1987).

As noted above for pre-Carboniferous rocks, several factors may improve reservoir quality in the Lisburne Group. Porosity of both limestone and dolostone is greatly enhanced in the Lisburne field at Prudhoe Bay where the Wahoo Limestone is truncated by the LCU; a thorough description of porosity development in this field is provided by Jameson (1994) and is summarized here. The Lisburne field produces chiefly from the Wahoo; initial tests of the Alapah Limestone yielded high oil rates, but delineation of Alapah reservoirs has proved difficult. Reservoir behavior of the Wahoo in the Lisburne field is controlled chiefly by: 1) depositional stratification, 2) the SAZ, a fractured, permeable subunconformity alteration zone, 3) multiple episodes of porosity formation, and 4) faults. Roughly 60% of total porosity formed during Cretaceous-Tertiary burial and hydrocarbon maturation; the rest is in dolomite produced during localized (Pennsylvanian) and regional (Permian-Triassic) subaerial exposure, and subsequent shallow burial.

Jameson (1994) reports "common" porosities of 10-15% in the Lisburne field, with corresponding air permeabilities around 0.1 md (see also Nelson and Bird, Chap. FP). Highest porosity and permeability values (20-30% porosity, 30-100 md permeability) are generally found in dolostones made up of hypidiotopic 20-40 µm crystals, but rare limestones, near the LCU and along faults, have undergone extensive late dissolution and have porosities as high as 40-50% (Jameson, 1994).

Lisburne Group dolostones from wells adjacent to the 1002 area were examined for this study primarily at W Mikkelsen State 1 (Fig. AO3; Table CC6). About 40% of the upper third of the Lisburne section at W Mikkelsen was cored; the cores contain shallowing-upward cycles similar in style and

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thickness to those described by Jameson (1994) at Prudhoe Bay, 70 km to the west. W Mikkelsen cycles are generally about 8-12 m thick and represent evolution from open to restricted marine conditions; some cycles are capped by skeletal grainstone shoals. Most cycles have shale at the base and spiculitic dolostone at or near the top. The upper part of the Lisburne at W Mikkelsen differs from correlative rocks in the Lisburne field chiefly in containing much less grain-supported carbonate (<30% vs 80% of total section).

About 25% (15 m) of the Lisburne core from W Mikkelsen is heavily oil stained and has porosities of 15-25% and permeabilities of 2-100 md; an additional 15 m of core is somewhat stained and has slightly lower reservoir parameters (Table CC7). Stained zones occur throughout the cored intervals, chiefly in upper parts of the shallowing-upward cycles; reservoir quality does not diminish appreciably down core (cf. samples at 11,350 and 11,706 ft, Table CC7). About 70% of the core from W Mikkelsen is dolostone. Dolostones at or near the tops of cycles have the highest porosities and permeabilities of all lithologies tested; fabric (Fig. CC6) and reservoir quality of these rocks are comparable to those of the most porous dolostones at Prudhoe Bay (Jameson, 1994). Dolostones without oil stains at W Mikkelsen are relatively porous (8-9%) but impermeable (0.03-0.005 md); these strata are slightly finer crystalline than permeable dolostones and may contain patchy calcite cement. Limestones at W Mikkelsen generally lack oil stains and have negligible reservoir properties (1% porosity; 0.0001 md permeability). Chemical analyses indicate that oil recovered from core samples of Lisburne microdolostone at W Mikkelsen belongs to the Ellesmerian petroleum system (Magoon and others, Chap. PS).

The Lisburne Group in the Mikkelsen Bay State 1 well is similar to that at W Mikkelsen. Cores from Mikkelsen Bay also contain intervals of oil stained, finely crystalline, locally spiculitic dolostone with moldic, vuggy, and intercrystalline porosity. Free oil recovered from a drill stem test of a dolostone-rich interval near the top of the Lisburne at this well has chemical affinities with the Hue-Sagavanirktok petroleum system (Magoon and others, Chap. PS).

Little information is available concerning Lisburne Group lithofacies and diagenesis in other wells adjacent to the 1002 area. Dolostones occur in these wells (Table CC6) but were not cored. Lithologic logs report dead oil and (or) questionable or spotty oil stains in dolostones from the Canning River A-1, Kavik 1, W. Kavik, and Kemik 1 wells (American Stratigraphic Company, 1972, 1974, 1976).

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Reservoir quality of the Lisburne Group, like that of the pre-Carboniferous carbonate rocks previously discussed, is significantly enhanced by fractures. This is demonstrated by performance data from the Lisburne field: two wells that lack significant matrix porosity or permeability in core or log each produced >1.5 million bbl of oil in two years (Jameson, 1994). Natural fracture patterns in outcrop and subsurface sections of the Lisburne were studied by Hanks and others (1997). They investigated sections deformed in both compressional and extensional structural regimes and found that lithology is the primary control of fracture density in both settings. Dolomitic mudstone is generally the most densely fractured lithology and grainstone is the least, but structural position is an increasingly important control of fracture character and distribution as intensity of deformation increases.

Karst formation may locally enhance reservoir quality in the Lisburne Group. Cavernous porosity occurs at the Alapah/Wahoo boundary in the Sadlerochit and Shublik Mountains and at Wahoo Lake, 60 km south of the Fourth Range. Meter-scale solution pockets and spar-filled caves as large as 15 x 20 x 40 m are found along this horizon and apparently formed during late dissolution, perhaps concurrent with development of secondary porosity in the Lisburne field (Carlson, 1995).

CONCLUSIONS

Carboniferous and older carbonate rocks provide important potential reservoir facies in the 1002 area. These rocks comprise three units. 1) A basement carbonate succession as much as 3,700 m thick consists chiefly of shallow-water strata of Late Proterozoic-Early Devonian age. This succession is expected beneath the south-central part of the 1002 area and is the primary reservoir for the Deformed Franklinian Play. 2) A lithologically heterogeneous basement complex appears to underlie the northwestern part of the 1002 area. Three subunits in this complex contain dm-thick carbonate intervals that provide reservoirs for the Undeformed Franklinian and Niguanak-Aurora Plays. Regional correlations suggest that these previously little studied rocks are at least in part of Cambrian age. 3) The Carboniferous Lisburne Group, part of the Mississippian-Cretaceous Ellesmerian sequence, is a predominantly carbonate shallow-water succession as much as 1 km thick in northeastern Alaska. It is projected below the southernmost part of the 1002 area and is a potential reservoir for the Ellesmerian Thrust-belt and Niguanak-Aurora Plays. Dolostones that have been fractured and (or) truncated by the LCU should provide the best reservoirs in all three units.

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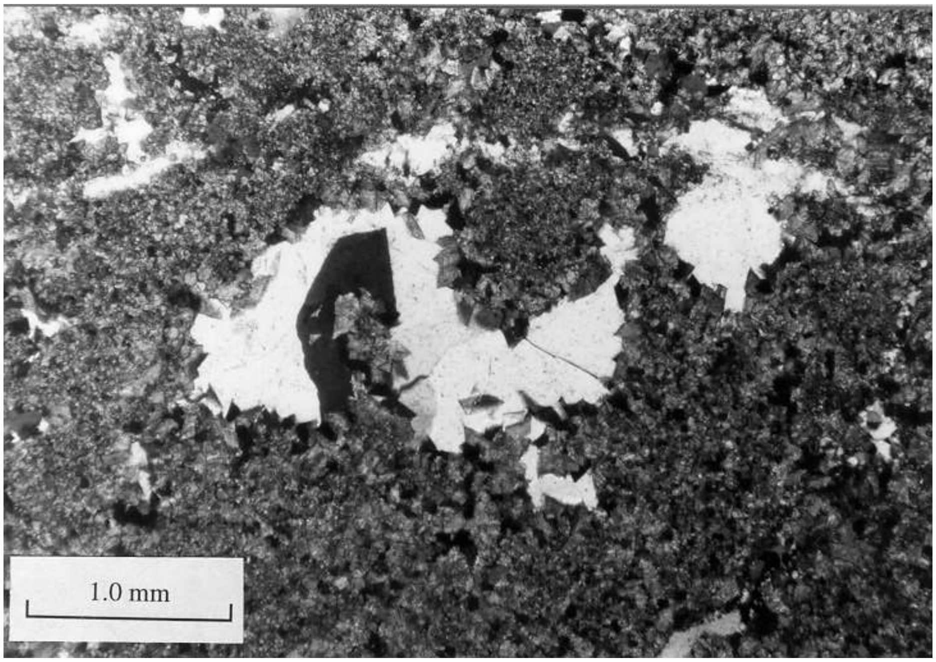

Fig. CC1. Photomicrograph of finely crystalline dolostone with quartz-filled vugs from pre-Carboniferous basement carbonate succession, Canning River A-1 well, core chip, 8,866-67 ft. Crossed nicols.

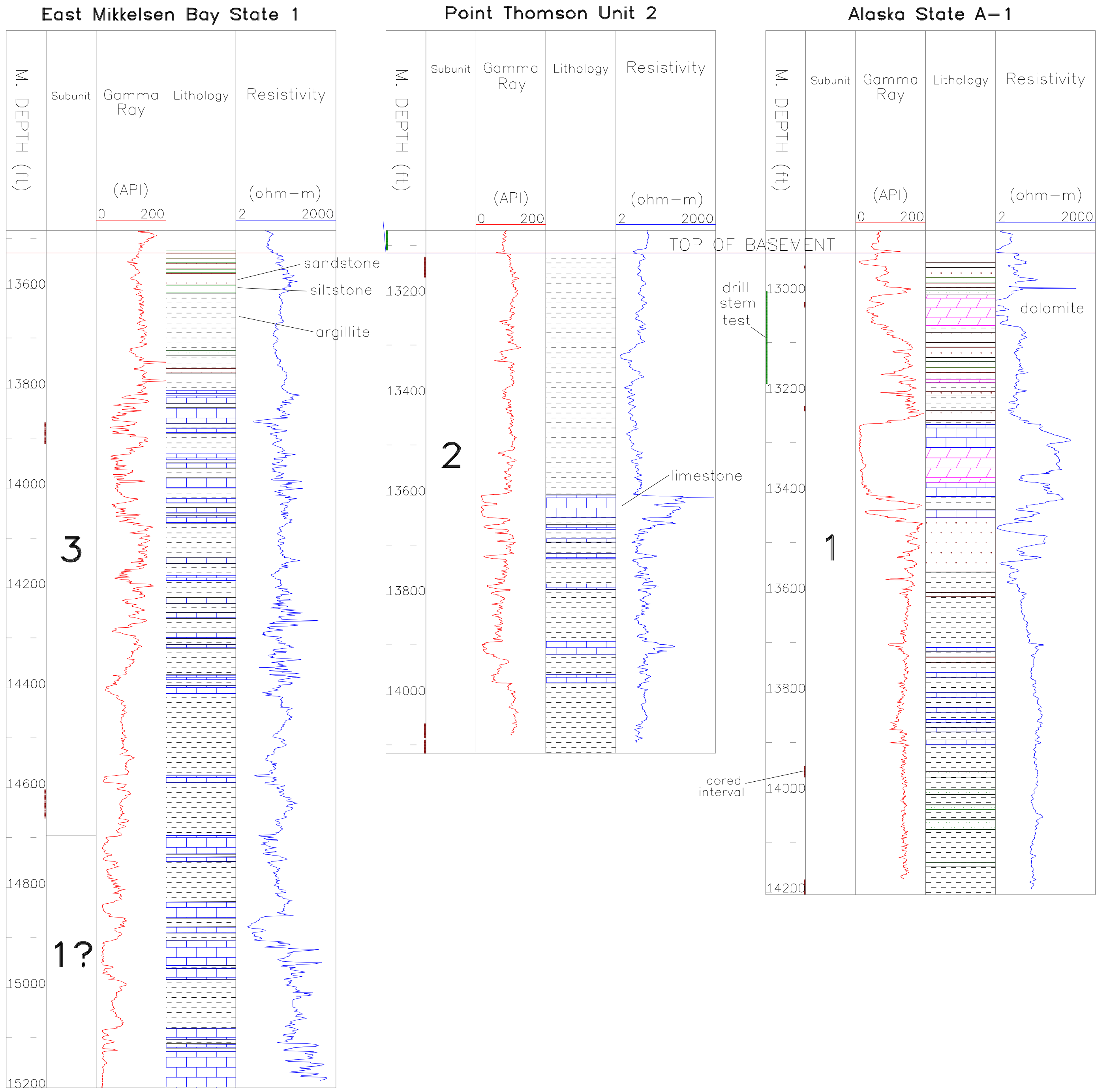

Fig. CC2. Pre–Carboniferous basement complex successions and well logs in the Alaska State A–1, Point Thomson Unit 2, and E Mikkelsen State 1 wells; subunits as defined in this report. Data from lithologic logs (American Stratigraphic Company, 1973, 1978, 1984) and thin sections of core chips and drill cuttings. Lithologic boundaries have been adjusted so that carbonates correspond to sections with low gamma–ray readings.

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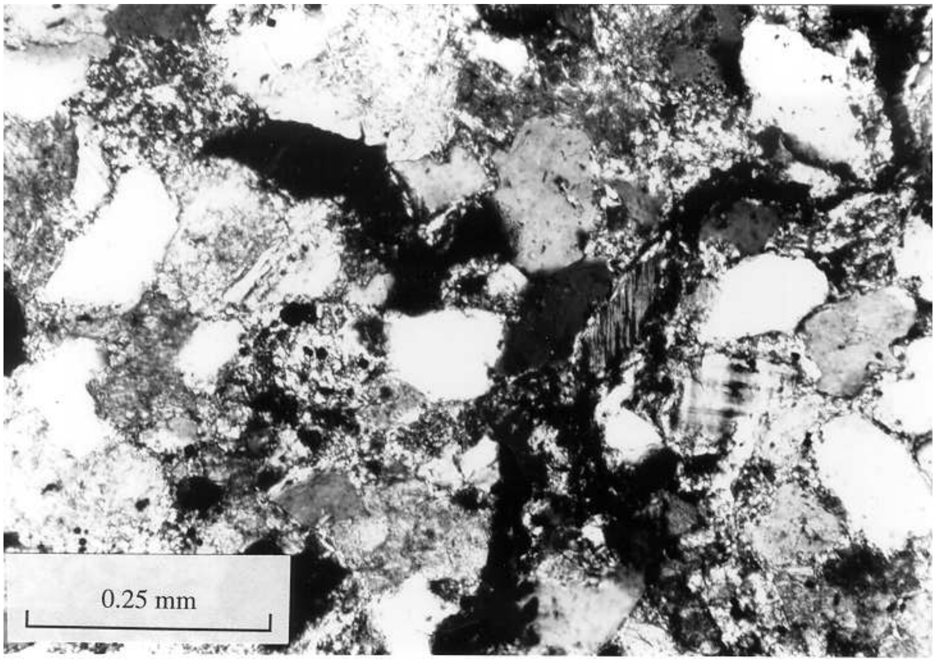

Fig. CC3A. Photomicrograph of pre-Carboniferous basement, subunit one. Fine-grained sandstone with abundant quartz, plagioclase, and potassium feldspar; note microcline grain in center right. Crossed nicols. Alaska State A-1 well; core chip, 13,237 ft.

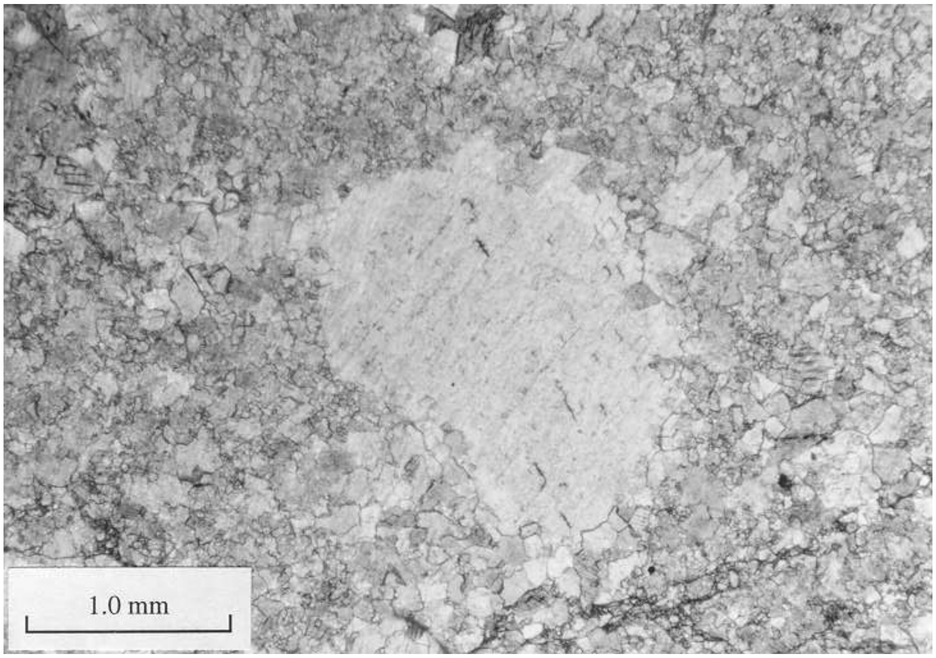

Fig. CC3B. Photomicrograph of pre-Carboniferous basement, subunit one. Pelmatozoan fragment in dolostone. Alaska State F-1 well, core chip, 13,836 ft.

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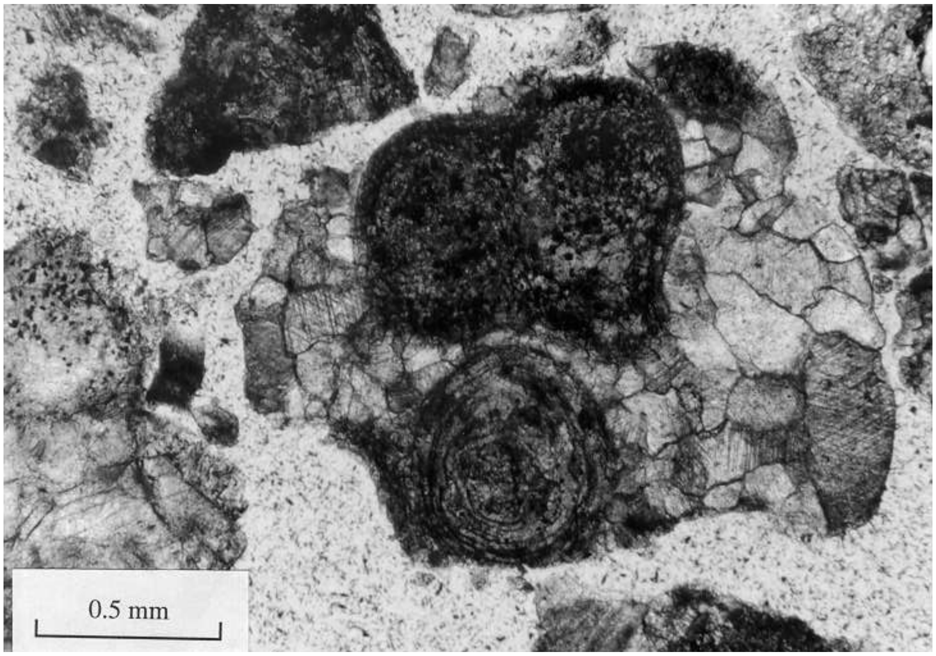

Fig. CC3C. Photomicrograph of pre-Carboniferous basement, subunit one. Variously preserved coated grains; cuttings from Alaska State D-1 well (12,810-900 ft).

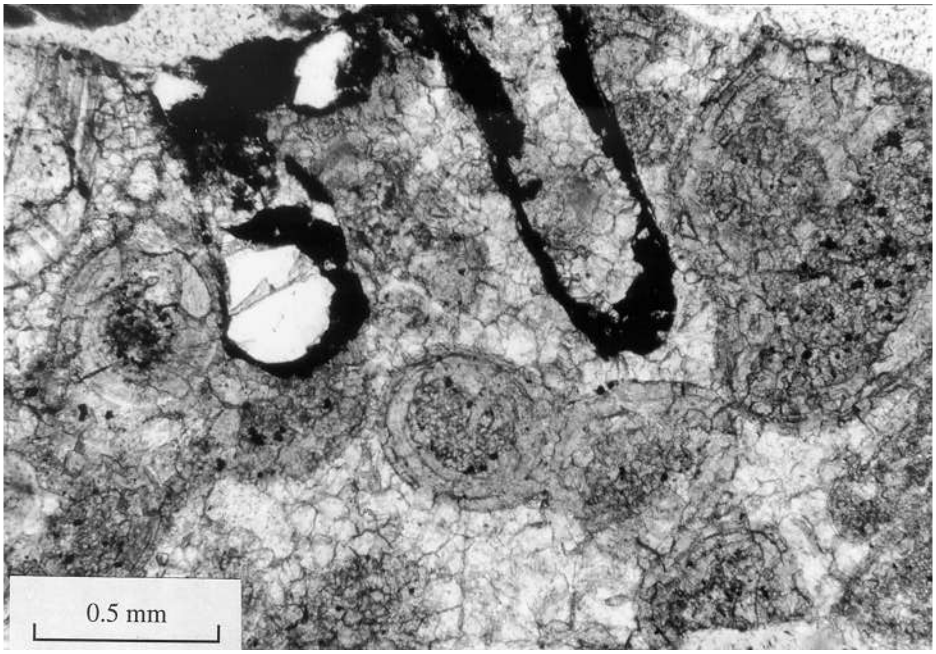

Fig. CC3D. Photomicrograph of pre-Carboniferous basement, subunit one. Variously preserved coated grains; cuttings from Alaska Island 1 well (15,030-60 ft).

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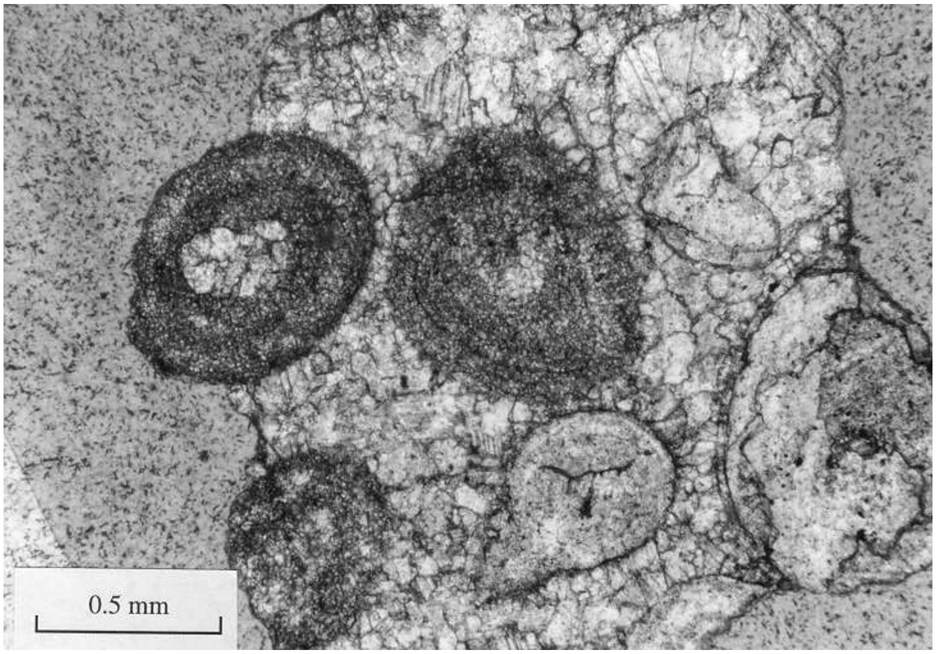

Fig. CC3E. Photomicrograph of pre-Carboniferous basement, subunit one. Variously preserved coated grains; cuttings from Alaska State A-1 well (13,370-80 ft).

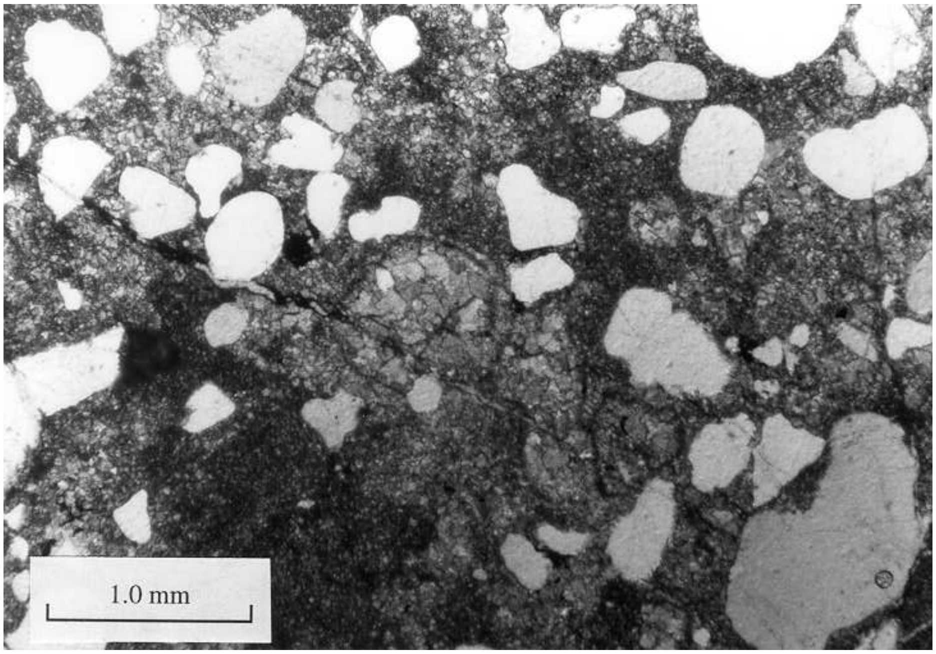

Fig. CC3F. Photomicrographs of pre-Carboniferous basement,subunit one. Dolostone with abundant rounded, medium to very coarse grains of detrital quartz. Alaska State F-1 well, core chip, 13,838 ft.

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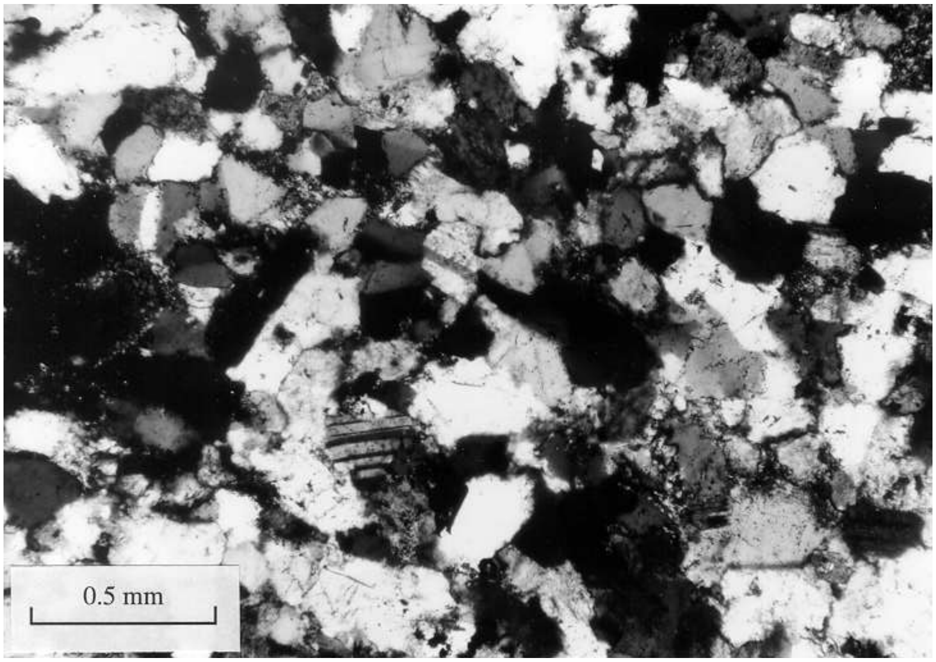

Fig. CC4A. Photomicrograph of pre-Carboniferous basement, subunit two. Fine-grained sandstone with abundant quartz and plagioclase; crossed nicols. West Staines 18-9-23 well, core chip, 13,120-21 ft.

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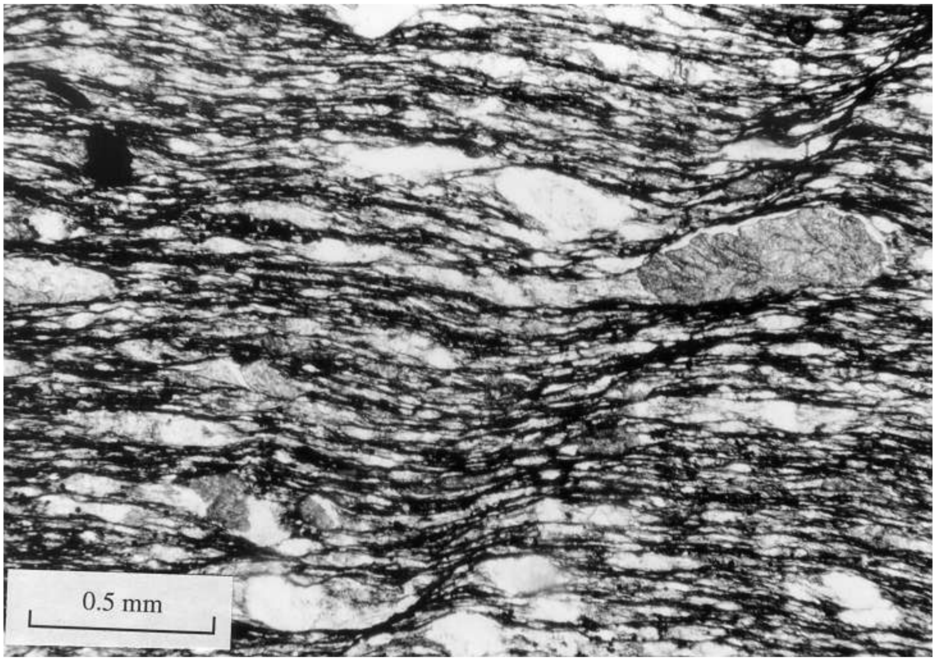

Fig. CC4B. Photomicrograph of pre-Carboniferous basement, subunit two. Semischist. Point Thomson Unit 2, core chip, 13,155 ft.

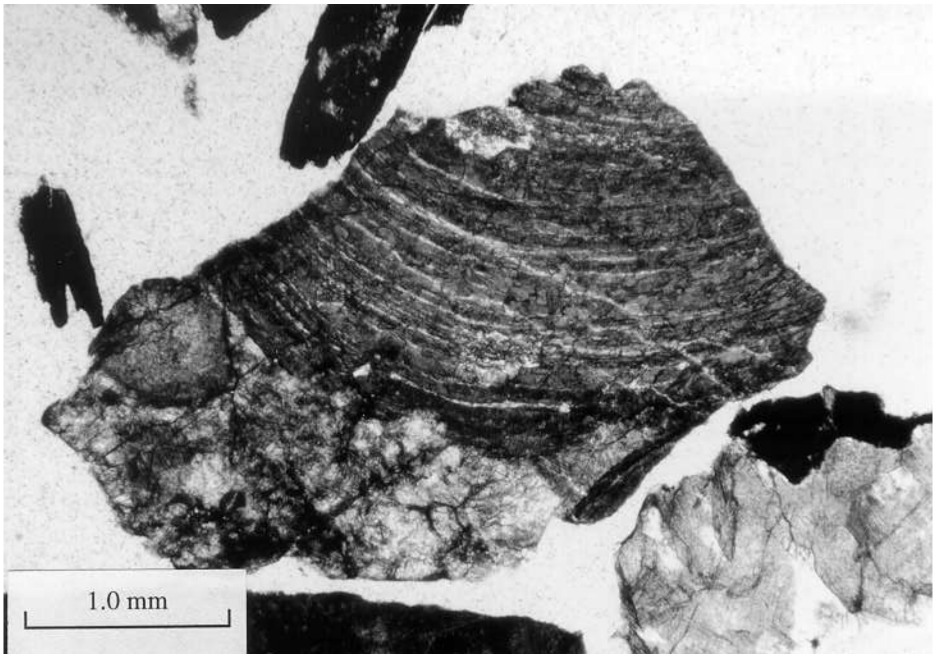

Fig. CC4C. Photomicrograph of pre-Carboniferous basement, subunit two. Pisoid fragment. Point Thomson Unit 2, cuttings, 14,100-17 ft.

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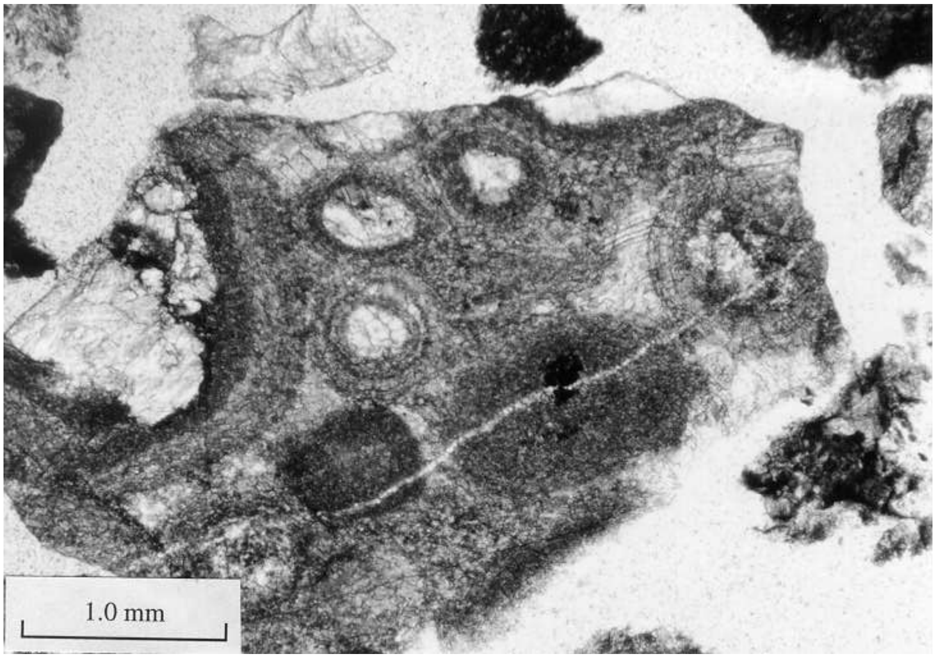

Fig. CC4D. Photomicrograph of pre-Carboniferous basement, subunit two. Variously preserved coated grains. Point Thomson Unit 2, cuttings, 13,620-50 ft.

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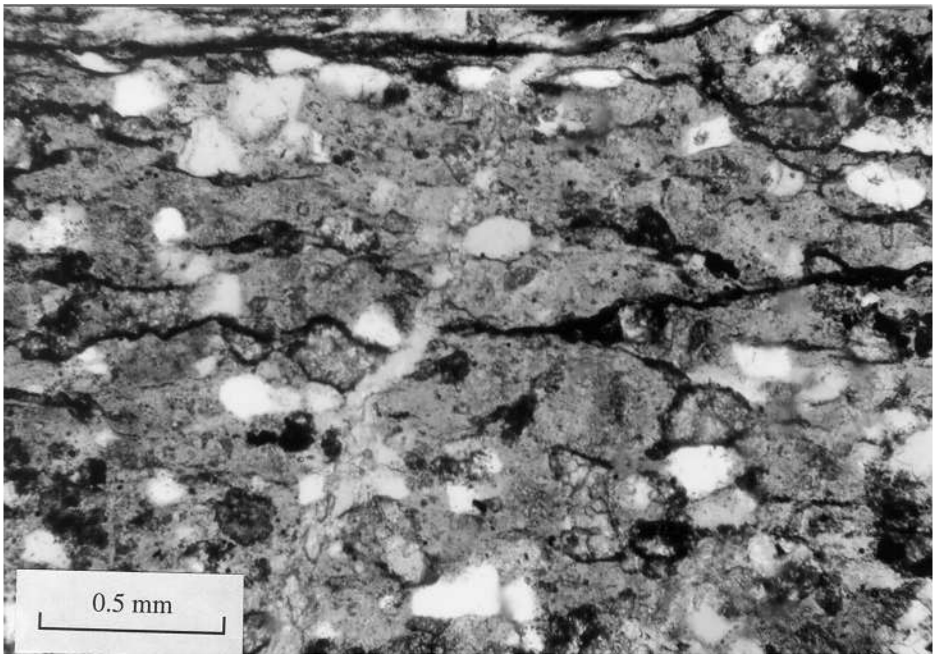

Fig. CC5A. Photomicrograph of pre-Carboniferous basement, subunit three.
Fine-grained sandstone rich in quartz and chert (dark grains).
E Mikkelsen Bay State 1, core chip, 14,630 ft

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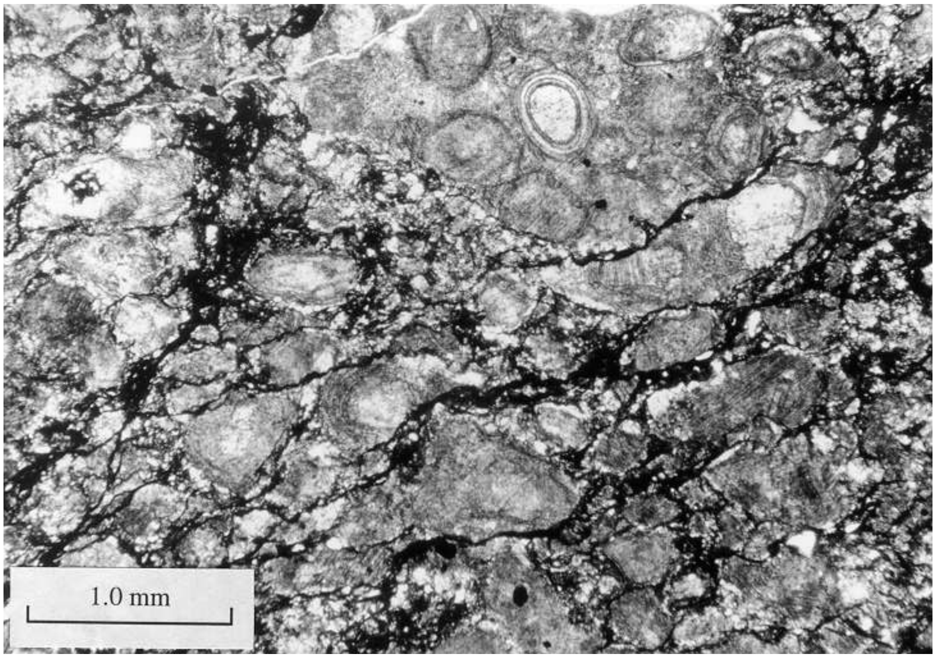

Fig. CC5B. Photomicrograph of pre-Carboniferous basement, subunit three. Fragments of oolitic grainstone in muddy matrix. W Mikkelsen State 1, core sample from 15,569 ft.

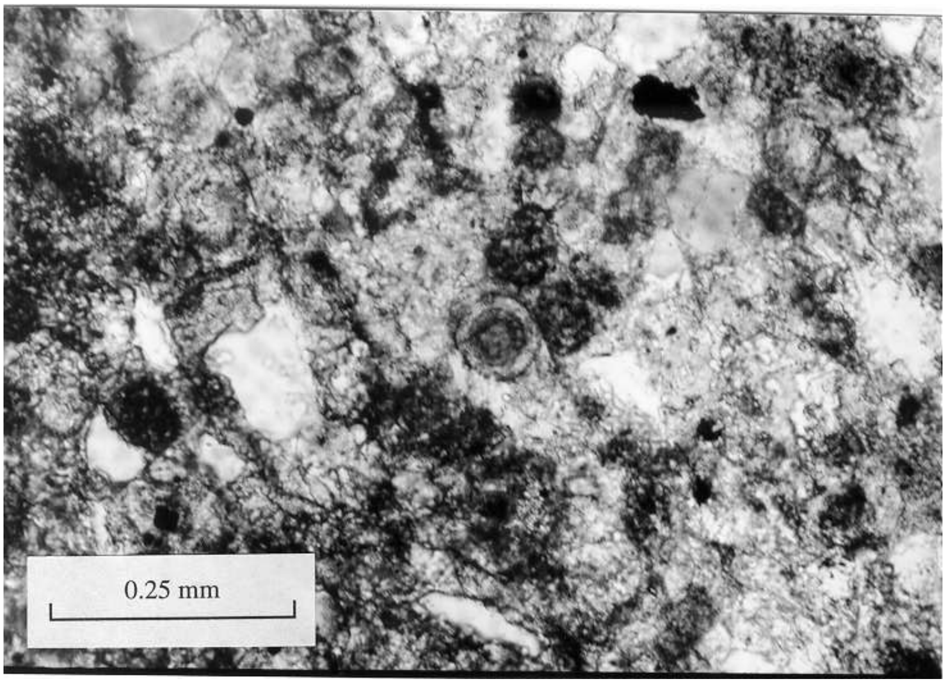

Fig. CC5C. Photomicrograph of pre-Carboniferous basement, subunit three
Recrystallized limestone with small coated grains, peloids, and possible bioclasts.
E Mikkelsen Bay State 1, core chip, 13,903 ft.

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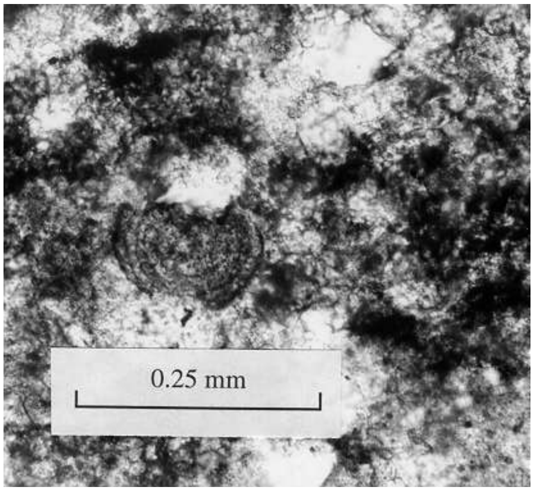

Fig. CC5D. Photomicrograph of pre-Carboniferous basement, subunit three.
Recrystallized limestone with small coated grains and possible bioclasts.
E Mikkelsen Bay State 1, core chip, 13,903 ft.

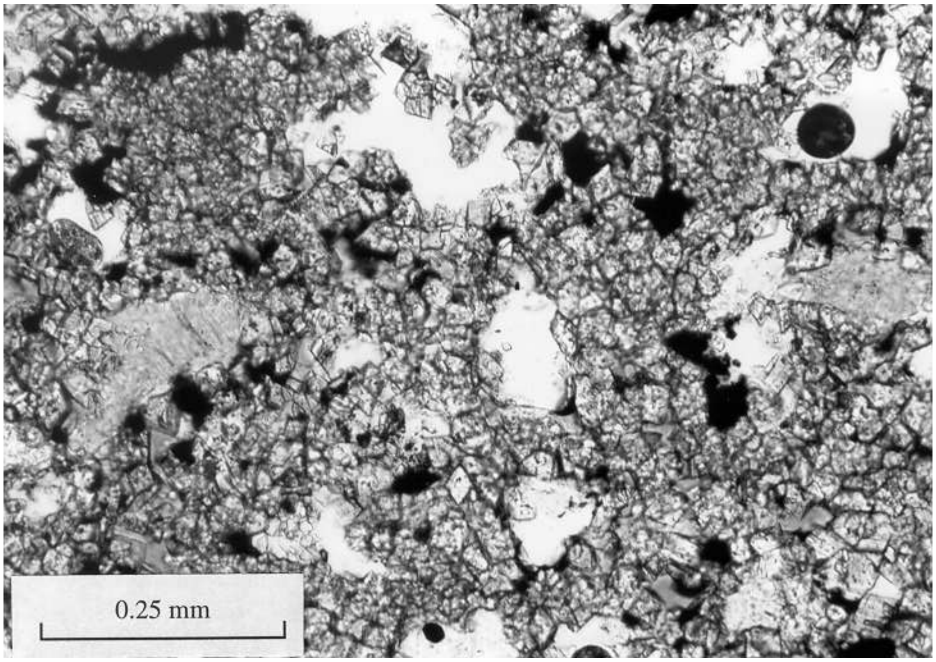

Fig. CC6. Photomicrograph of finely crystalline dolostone with good plug porosity (26.9%) and permeability (107 md), Carboniferous Lisburne Group. W Mikkelsen State 1 well, core sample, 11,350 ft. Fabric and reservoir quality of this sample are similar to those of porous dolostones in the Lisburne field described by Jameson (1994, cf. Fig. 14).

Table CC1. Exploratory well drilled west of the 1002 area that penetrated the pre-Carboniferous basement carbonate succession (as defined in this report); see Fig. AO3 for well location. Carbonate features: V, vugs. Carbonate thickness from lithologic log. Sources indicate types of materials examined for this report: CC, core chips; L, lithologic log (American Stratigraphic Company, 1976); T, thin section made from core chip; TC, thin section made from ditch sample of drill cuttings; for T and TC, number in parentheses is number of sections examined.

Well name	Measured depth (ft), penetration (ft, m)	Interval cored (ft)	Carbonate type, features, thickness (m)	Sources
Canning River Unit A-1	8,220-8,874 654 (200)	8,865-874	Dolostone V 200	CC, L, T (8), TC (11)

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Table CC2. Exploratory wells drilled west of the 1002 area that penetrated the pre-Carboniferous basement complex, subunit one (as defined in this report); see Fig. AO3 for well locations. *, true vertical penetration differs significantly from measured penetration in this deviated well and is listed below as TVP. Carbonate features: F, fossil (b, phosphatic brachiopod, p, pelmatozoan); O, ooid; P (pisoid, includes oncoids, possible stromatolite fragments), Pe, peloid (includes micritic clasts); Q, detrital quartz (mostly rounded, medium to very coarse grains). Carbonate thickness from lithologic logs. Sources are materials examined for this report: CC, core chips; L, lithologic log produced by American Stratigraphic Company (1978, 1984, 1985); T, thin section made from core chip; TC, thin section made from ditch sample of drill cuttings; for T and TC, number in parentheses is number of sections examined.

Well name	Measured depth (ft), penetration (ft, m)	Intervals cored (ft), % of core chips with ss, sltst layers	Carbonate type, features, and thickness (m)	Sources
Alaska Island 1	15,000-15,222 222 (68)	15,097-127 [66]	Limestone, dolostone F (p), O, Pe, Q 22	CC, L, T (11), TC (3)
Alaska State A-1	12,920-14206 1,286 (392)	12,946-951 13,019-029 13,228-237 [55] 13,948-970 [90] 14,175-205 [78]	Limestone, dolostone F (p?), O, P, Pe, Q 67	CC, L, T (23), TC (14)
Alaska State D-1	12,720-13,050 330 (101)	None	Limestone, dolostone F (p), O, Pe, Q 48	L, TC (8)
Alaska State F-1*	13,835-14,316 481 (147) TVP: 422 (129)	13,833-838	Dolostone F (b, p), O, Pe, Q 52 [TVP: 42]	CC, L, T (12), TC (15)
Challenge Island 1	13,490-13,587 97 (30)	13,487-516 [84]	Dolostone Pe, Q 9	CC, L, T (12)

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Table CC3. Exploratory wells drilled west of the 1002 area that penetrated the pre-Carboniferous basement complex, subunit two (as defined in this report); see Fig. AO3 for well locations. Carbonate features: F, fossil; O, ooid; P (pisoid, includes oncoids, possible stromatolite fragments). Carbonate thickness from lithologic logs. Sources are materials examined for this report: C, core; CC, core chips; L, lithologic log produced by American Stratigraphic Company (1972, 1983, 1984); T, thin section of core or core chip; TC, thin section made from ditch sample of drill cuttings; for T and TC, number in parentheses is number of sections examined.

Well name	Depth (ft), penetration (ft, m)	Intervals cored (ft), % of core chips with ss, sltst layers	Carbonate type, features, and thickness (m)	Sources
W Mikkelsen Unit 2	11,630-11,930 300 (92)	11,664-714 [72]	None	C, CC, L, T (10)
Point Thomson Unit 2	13,115-14117 1002 (306)	13,124-164 [40] 14,090-117 [18]	Limestone F?, O, P 44	CC, L, T (7), TC (6)
Point Thomson Unit 3	13,930-14,125 195 (60)	13,894-14,013 [65]	None	CC, L, T (16)
West Staines 18-9-23	13,122-13,329 207 (63)	13,122-153 [27] 13,153-178 [6] 13,178-202 [12] 13,271-309 [27] 13,309-329 [20]	None	CC, L, T (13)

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Table CC4. Exploratory wells drilled west of the 1002 area that penetrated the pre-Carboniferous basement complex, subunit three (as defined in this report); see Fig. AO3 for well locations. Carbonate features: F, fossil (p, pelmatozoan; r, radiolarian); O, ooid; P (pisoid, includes oncoids, possible stromatolite fragments), Pe, peloid (includes micritic clasts); Q, detrital quartz (mostly rounded, medium to very coarse grains). *, feature found only in basal 150 m at E Mikkelsen Bay; these strata may belong to subunit one or two. Carbonate thickness from lithologic logs; parenthetical values at E Mikkelsen Bay are thicknesses in upper part of section (first) and lower 150 m (second). Sources are materials examined for this report: C, core, CC, core chips; L, lithologic log produced by American Stratigraphic Company (1972, 1973, 1981); T, thin section made from core or core chip; TC, thin section made from ditch sample of drill cuttings; for T and TC, number in parentheses is number of sections examined.

Well name	Depth (ft), penetration (ft, m)	Intervals cored (ft), % of core chips with ss, sltst layers	Carbonate type, features, thickness (m)	Sources
Mikkelsen Bay State 1	16,543-16,596 53 (16)	16,542-572 16,572-596 [10]	Limestone F (r) 3	CC, L, T (15)
E Mikkelsen Bay State 1	13,529-15,205 1,676 (511)	13,868-912 [10] 14,604-662 [15]	Limestone F (p, r), O, Pe, P*, Q* 137 (62, 75)	CC, L, T (21), TC (16)
W Mikkelsen State 1	15,520-15,623 103 (31)	15,563-623 [80]	Limestone F (p, r), O 3	C, CC, L, T (15)

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Table CC5. Exploratory wells drilled west of the 1002 area that penetrated the pre-Carboniferous basement complex (as defined in this report); see Fig. AO3 for well locations. Strata in these wells were not assigned to a subunit; see text for discussion. C, carbonate; Q, quartz. Sources are materials examined for this report: CC, core chips; L, lithologic log produced by American Stratigraphic Company (1977, 1983, 1984); T, thin section made from core chip (number of sections examined).

Well name	Depth (ft), Penetration (ft, m)	Intervals cored (ft)	Basement lithology	Sources
Alaska State C-1	13,705-13,761 56 (17)	13,700-731	Mostly phyllite; minor QC semischist	CC, L, T (7)
E De K Leffingwell 1	14,717-14,824 107 (33)	14,794-824	Phyllite and QC semischist	CC, T (9)
Point Thomson Unit 1	13,160-13,298 138 (42)	13,158-163	Argillite, minor QC siltstone	CC, L, T (1)
Point Thomson Unit 4	14,983-15,074 91 (28)	14,973-15,010	Argillite/phyllite	L
West Staines State 2	13,155-13,171 16 (5)	None	Argillite/phyllite	L

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Table CC6. Exploratory wells drilled west of the 1002 area that penetrated the Lisburne Group (Carboniferous). *, well bottomed in Lisburne; +, value is penetration, not true unit thickness. #, thickness may have been increased by structural complications. Abundance and distribution of dolostone from lithologic logs. Sources indicate materials examined for this report: C, core; CC, core chips; L, lithologic log produced by American Stratigraphic Company (1972, 1974, 1975, 1976, 1977, 1981); T, thin section made from core or core chips (number of sections examined).

Well name	Depth (ft), thickness (ft, m)	Intervals cored (ft)	Dolostone abundance, distribution	Sources
Beli Unit 1*	12,421-14,632 2,211 (674) +	12,421-444	12%, throughout unit	CC, L, T (16)
Canning River Unit A-1	5,675-7,980 2,305 (703)		43%, throughout unit	L
Canning River Unit B-1*	9,700-10,803 1,003 (336) +		10%, throughout unit	L
Kavik 1	5,555-8,778 3,223 (983)		45%, throughout unit	L
Kavik Unit 2*	7,135-7,500 365 (111) +			L
West Kavik 1*	14,525-16,613 2,088 (637) +	14,558-570 14,570-586 14,886-908	8%, throughout unit	CC, L, T (22)
Kemik Unit 1	10,950-15,970 5020 (1,531) #	10,994-11,045	25%, throughout unit	C, CC, L, T (6)
Kemik Unit 2*	8,340-8,880 + 540 (165)			L
Mikkelsen Bay State 1	11,768-13,798 2,030 (619)	11,721-778 11,778-792 11,792-807 11,962-989 11,989-12,008 12,378-399	10%, upper part only, 34% of upper third	CC, L, T (13)
W Mikkelsen State 1	11,305-12,792 1,487 (454)	11,266-309 11,309-323 11,349-409 11,585-631 11,681-733	18%, upper part only, 60% of upper third	C, CC, L, T (75)

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Table CC7. Porosity and permeability of selected Lisburne Group lithologies from the W Mikkelsen State 1 well. Ls, limestone; Do, dolo. MICP, mercury injection capillary pressure. Perm, permeability. nd, not determined.

Measured sample depth (ft)	Lithology	Visible oil stain	Plug porosity (%)	MICP porosity (%)	Plug perm (md)	MICP perm (md)
11,305	Ls, skeletal packstone	None	1.1	0.81	nd	0.0001
11,350	Do, burrows, xtls 5-25 µm	Strong	26.9	22.4	107	90.2
11,374	Do, xtls 5-10 µm	None	7.7	8.13	0.02	0.005
11,392	Do, spiculitic, xtls 5-25 µm	Strong	23.4	20.4	2.3	2.52
11,402	Ls, mudstone	None	0.9	0.27	nd	0.0001
11,706	Do, spiculitic, xtls 5-80 µm	Strong	18.7	17.8	nd	15.3
11,717	Do, spiculitic, xtls 5-15	None	8.6	8.96	0.058	0.031

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