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Devonian-Mississippian Carbonate Sequence in the Maiyumerak Mountains, Western Brooks Range, Alaska

by

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT

Virtually continuous, dominantly carbonate sedimentation occurred from at least Middle Devonian through early Late Mississippian time in the area that is now the Maiyumerak Mountains, western Brooks Range. Conodonts and megafossils throughout the Maiyumerak sequence indicate that any hiatus is less than a stage in duration, and there is no apparent physical evidence of an unconformity within the succession. The sequence is best exposed northwest of the Eli River, where Eifelian-Givetian dolostone (Baird Group) is conformably overlain by Givetian-Famennian argillaceous limestone (Eli Limestone). These rocks, in turn, are overlain conformably by Kinderhookian-Osagean quartzose limestone (Utukok Formation) and Osagean-Meramecian cherty dolomitic limestone (Kogruk Formation) of the Lisburne Group. Sedimentary structures and conodont species assemblages indicate deposition in a range of shallow-water, middle to inner shelf environments; the shallowest and most restricted depositional regimes prevailed during late Middle Devonian time.

The Maiyumerak sequence is in striking contrast to Paleozoic successions in adjacent fault slices in northwestern Alaska, in the eastern Brooks Range, and in the subsurface across northern Alaska. Other successions contain thick intervals of Upper Devonian-Mississippian siliciclastic rocks, condensed basinal Carboniferous facies, or an unconformity which spans much or all of Devonian and Early Mississippian time. Sedimentologic and biostratigraphic data support correlation of the Maiyumerak sequence with sequences of the Kelly River allochthon to the north and west, and suggest that these sequences were deposited contiguously on a single geographic high, the Kelly platform. Terrigenous material in the Maiyumerak sequence matches the Endicott Group in age and composition, and probably derived from a common source. This conclusion implies that the Kelly platform and the Endicott delta were at least partly adjacent during Late Devonian-Early Mississipian time, and offers a new constraint for paleogeographic reconstructions of the western Brooks Range. Inundation of the Kelly platform in the late Meramecian was probably due largely to tectonic factors, such as northward drift of northern Alaska, abetted by short-term eustatic shifts.

ACKNOWLEDGMENTS

This study was part of a survey of the geology and mineral resources of the Baird Mountains 1 x 3 degree quadrangle, conducted by the U.S. Geological Survey under the auspices of the Alaska Mineral Resource Assessment Program (AMRAP). We gratefully acknowledge the assistance of William Thompson and Inyo Ellersieck in the field, and thank all our AMRAP colleagues for logistical support and useful geologic discussions, particularly Susan M. Karl, Jeanine M. Schmidt, and Alison B. Till.

INTRODUCTION

The Maiyumerak Mountains are in the southwestern part of the Brooks Range in northwestern Alaska, and are made up of a diverse assemblage of Paleozoic and Mesozoic sedimentary and igneous rocks (Fig. 1; Karl and others, 1989). The Devonian-Mississippian carbonate rocks described in this report comprise a northeast-trending, fault-bounded sequence that is exposed for at least 75 km along the southeast flank of the Maiyumerak Mountains; this study concentrates on the northeastern exposures of this sequence in the Baird Mountains quadrangle.

In order to facilitate correlation with previous geologic studies of northern Alaska, the term "sequence" is used here in the sense of Mayfield and others (1988) and not as it has been employed in seismic stratigraphy. Mayfield and others (1988, p. 146) considered the thrust sheets of northwestern Alaska to be made up of "structurally overlapping sequences....composed of sedimentary,

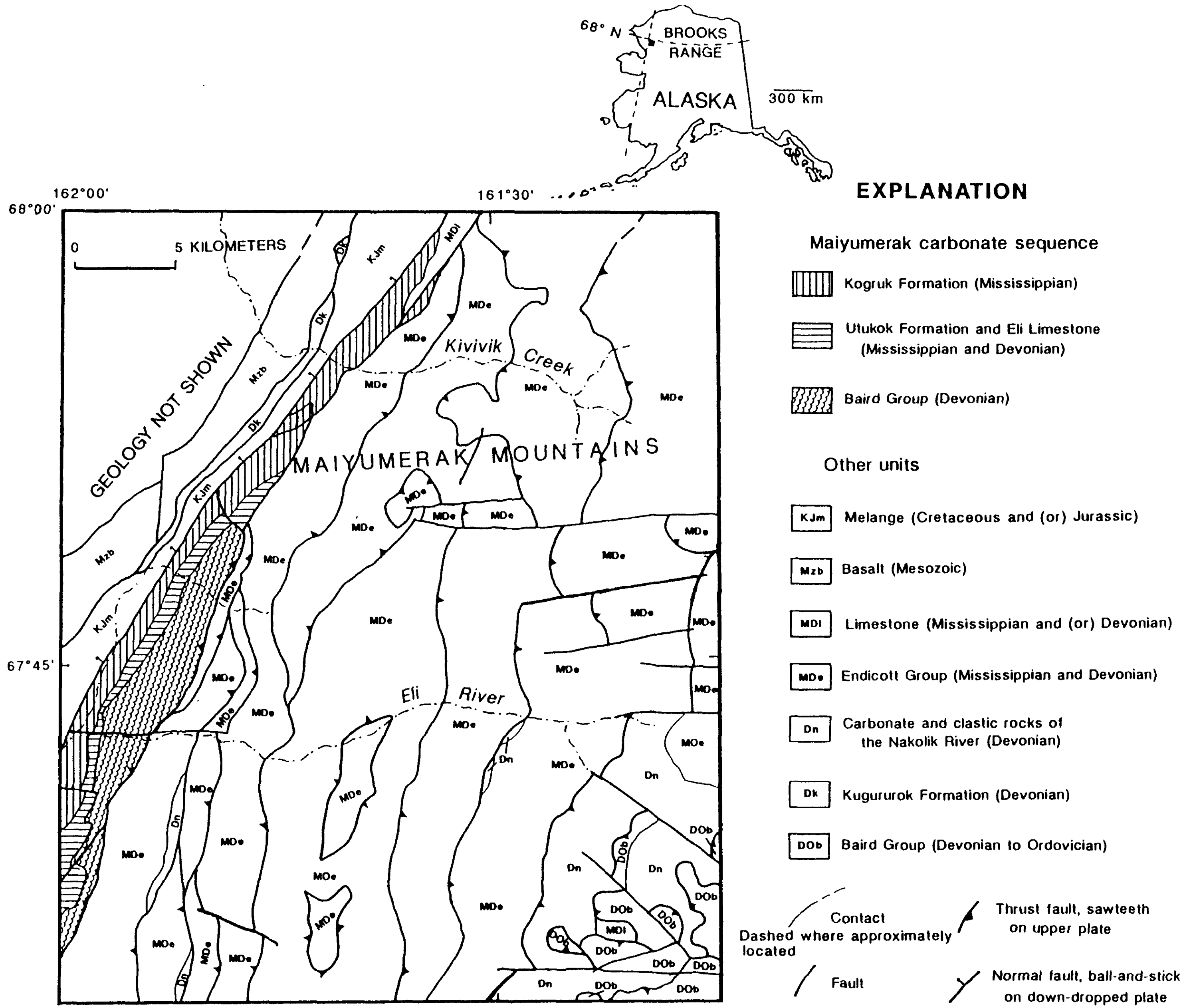


Figure 1. Bedrock geology of the Maiyumerak Mountains area, Baird Mountains quadrangle, northwestern Alaska, generalized and slightly modified from Karl and others (1989).

metasedimentary, and (or) igneous rocks;" a sedimentary sequence is "a distinctive column of sedimentary rocks that (has) slightly different lithologic facies compared to coeval rocks of other sequences." The term sequence has a much more restricted meaning in seismic stratigraphic studies (e.g., Mitchum, 1977; Sarg, 1988); Mitchum (1977, p. 210) defined a sequence as "bounded at its top and base by unconformities or their correlative conformities." The sequences in this paper, based on the usage of Mayfield and others (1988), are generally bounded by faults, not unconformities, and may include internal unconformities.

The Maiyumerak Mountains carbonate sequence records virtually continuous, dominantly shallow-water carbonate sedimentation from at least Middle Devonian through early Late Mississippian time and differs notably from Paleozoic sequences in the subsurface across northern Alaska and exposed throughout the eastern Brooks Range and in adjacent fault slices in the western Brooks Range. These other sequences contain Carboniferous carbonate and clastic rocks unconformably overlying Proterozoic or lower Paleozoic metasedimentary or sedimentary rocks, thick intervals of uppermost Devonian-Mississippian siliciclastic rocks, or condensed, basinal Carboniferous facies. The Maiyumerak Mountains carbonate sequence provides important constraints in reconstructing the late Paleozoic paleogeography of northern Alaska; this paper details the lithofacies and biostratigraphy of these previously little-studied carbonate rocks, and explores their paleogeographic implications.

GENERAL GEOLOGY

The early tectonic and plate-kinematic history of Alaska remains relatively poorly understood. Northern Alaska and parts of the eastern Soviet Union appear to have formed a single continental block, the North Slope-Chukotka block (e.g., Rowley and Lottes, 1988), through much of Paleozoic and Mesozoic time. Parts of this block, presently in the western Brooks Range, underwent rifting during the middle Paleozoic (Schmidt, 1987) and a south-facing passive margin developed (Moore and others, in press). Devonian-Mississippian carbonate rocks of the Maiyumerak Mountains accumulated on a carbonate platform attached to this margin.

During the Middle Jurassic to Cretaceous Brooks Range orogeny, rocks of the western Brooks Range were complexly folded, thrust-faulted, and underwent syntectonic regional metamorphism (Mayfield and others, 1988). The carbonate rocks of the Maiyumerak Mountains are exposed as a fault-bounded, moderately northwest-dipping homocline that extends from the southeast part of the Noatak 1 X 3 degree quadrangle into the northwest part of the Baird Mountains quadrangle. The carbonate rocks are in contact to the southeast with Devonian-Mississippian clastic rocks of the Endicott Group, and to the northwest with poorly exposed, dominantly Mesozoic rocks (Fig. 1). The southeast contact is a thrust fault that places carbonate rocks above at least partly coeval clastic rocks; the northwest contact has been variously interpreted as a normal fault, down-dropped to the west (Karl and others, 1989), or a thrust fault (Ellersieck, 1985).

The carbonate sequence is cut by several steep west- or northwest-trending faults but otherwise shows little internal deformation. The sequence contains conodonts that have color alteration indices (CAIs) of 3.5 or higher, indicating that the host rocks reached at least 180° C (Epstein and others, 1977). Although regional metamorphism has resulted in some recrystallization of the Maiyumerak Mountains carbonate sequence, many rocks retain considerable primary texture. These textures, along with environmentally diagnostic conodont assemblages, allow characterization of middle to late Paleozoic depositional environments.

STRATIGRAPHIC NOMENCLATURE

The rocks of the Maiyumerak Mountains carbonate sequence are here assigned to the Baird Group, the Eli Limestone, and the Utukok and Kogruk Formations of the Lisburne Group. The definition of the Baird Group is a matter of some disagreement. As originally defined by Tailleur and others (1967), the Baird Group encompasses all Devonian and older carbonate rocks exposed throughout the Brooks Range and includes three formations: the Skajit Limestone, the Eli Limestone, and the Kugururok Formation. The Skajit Limestone consists of relatively pure but strongly metamorphosed carbonate rocks, was defined in the central Brooks Range, and has yielded megafossil and microfossil ages of Middle Devonian to at least Middle Ordovician (Moore and others, in press). The Eli Limestone and Kugururok Formation contain a considerable siliciclastic component, are less strongly metamorphosed than rocks assigned to the Skajit Limestone, are exposed only in the western Brooks Range, and are of Middle and Late Devonian age.

Some recent workers (i.e., Mull and others, 1987; Karl and others, 1989) have excluded younger, less metamorphosed, and more impure carbonate rocks from the Baird Group. The usage of Karl and others (1989) is followed here; dolostones and lesser dolomitic limestones that constitute the lowest part of the Maiyumerak Mountains carbonate succession are considered part of the Baird Group, but overlying shaley carbonates are assigned to the Eli Limestone and are excluded from the Baird Group.

Stratigraphic nomenclature of the Mississippian rocks in the Maiyumerak Mountains is much less controversial; division of the Lisburne Group in northwestern Alaska into the Utukok, Kogruk, and Tupik Formations was proposed by Sable and Dutro (1961) and has been widely adopted. In the Maiyumerak Mountains, sandy carbonate rocks overlying the Eli Limestone are referred to the Utukok Formation, and cleaner, fossiliferous limestones and dolostones that constitute the upper part of the carbonate succession are assigned to the Kogruk Formation. The Tupik Formation has not been recognized as a distinct map unit in the Maiyumerak Mountains, but beds coeval with this unit may occur in the upper part of the Kogruk Formation (Karl and others, 1989).

PREVIOUS WORK

The sedimentology of Paleozoic carbonate rocks of the western Brooks Range has been little studied. Tailleur and others (1967) presented general descriptions of Devonian carbonate and siliciclastic rocks of the western Brooks Range, and defined the Baird Group and the Eli Limestone. The Utukok, Kogruk, and Tupik Formations of the Lisburne Group were established by Sable and Dutro (1961) for rocks in the Misheguk Mountain quadrangle, north of the area of the present study. Analyses of the carbonate lithofacies and lithostrotionid corals in several measured sections of the Kogruk Formation were carried out by Armstrong (1970a, 1972) and Armstrong and others (1971); these sections are in the Misheguk Mountain, De Long Mountains, and Point Hope quadrangles, north and west of the Maiyumerak Mountains. A series of mile:inch geologic maps of parts of the Misheguk Mountain, De Long Mountains, and Noatak quadrangles (Curtis and others, 1983, 1984; Ellersieck and others, 1983, 1984; Mayfield and others, 1983, 1984, 1987) include biostratigraphic data and brief lithologic descriptions of Devonian and Missisissippian carbonate rocks in these areas.

No previous studies of carbonate rocks in the Maiyumerak Mountains have been published, and the geology of the Baird Mountains quadrangle is relatively poorly known. A generalized geologic map of the Baird Mountains quadrangle was first published as part of a U.S. Geological Survey Open-File Report (Brosgé and others, 1967); a more detailed but still reconnaissance geologic map of the quadrangle has since appeared (Karl and others, 1989). Ellersieck (1985) produced a larger scale map of the northwestern quarter of the quadrangle which includes the Maiyumerak Mountains. A preliminary description of lithofacies and conodont assemblages of the Baird Mountains carbonate section (Dumoulin and Harris, 1987) did not include rocks of the Maiyumerak Mountains.

METHODS

The carbonate rocks described in this report were observed and sampled in a series of partial measured sections along the cutbanks of Ahaliknak Creek and in the mountains to the north and south; this area of detailed study extends about 11 km and lies within a single fault block (Figs. 1, 2, and 3). Less detailed lithologic studies and sampling were also carried out further north and south along the trend of the Maiyumerak Mountains carbonate sequence within the Baird Mountains quadrangle.

Petrographic descriptions are based on field studies of lithology and sedimentary structures as well as examination of polished slabs and more than 200 thin sections. Sections were measured using Jacob's staff, Brunton compass, and tape; identification of calcite and dolomite was made using the Alizarin Red-S and potassium ferricyanide staining technique of Dickson (1966). Carbonate rocks are classified following Dunham (1962); when descriptive modifiers are used, they are listed in order of increasing abundance. Biostratigraphy relies largely on conodont faunas from our measured sections and spot samples, but data from previous U.S. Geological Survey collections of foraminifers, brachiopods, corals, and stromatoporoids that were made within the study area have been included where appropriate. Interpretations of depositional environments are based on depositional models for carbonate rocks outlined in Wilson (1975), and on a version of these models designed specifically for the Lisburne Group by Armstrong and Mamet (1977, 1978). The environmental implications of conodont assemblages, as outlined by Sandberg (1976), Sandberg and Gutschick (1984), and Sandberg and Ziegler (1979), were also used to constrain our interpretations.

SEDIMENTARY SUCCESSION IN THE MAIYUMERAK MOUNTAINS

The original configuration of the basin in which Paleozoic carbonate rocks in northwestern Alaska were deposited has been obscured by subsequent regional metamorphism and tectonic dismemberment, and is at present poorly understood. Most carbonate rocks throughout the Brooks Range occur in discrete, thrust-bounded sequences; thus, the initial relationships between these sequences, the nature of the basement on which they accumulated, and the type of shelf-to-basin transitions they once formed is uncertain. No encompassing depositional model has yet been presented for Devonian and older carbonate rocks of northwestern Alaska; the biostratigraphy and lithofacies of these rocks are only beginning to be unraveled (e.g., Dumoulin and Harris, 1987).

The Carboniferous Lisburne Group has been more studied, and general depositional patterns across the Brooks Range have been described in a series of publications by Armstrong and others (e.g., Armstrong, 1974; Armstrong and Bird, 1976; Armstrong and Mamet, 1978). These studies suggest that much of the Lisburne Group was deposited on a carbonate platform with a low-gradient, south-facing ramp margin that developed after initial northward transgression across an irregular surface. However, this model is based largely on sections in the northeastern Brooks Range; Carboniferous paleogeography to the west may have been more complex and involved a number of small (rift?) basins (Mayfield and others, 1988).

Devonian-Mississippian carbonate rocks in the Maiyumerak Mountains appear to have formed through relatively continuous deposition in a range of shallow-water environments. In the following sections, the general terms "carbonate platform" and "shelf" will be used to describe the depositional setting of these rocks; speculations concerning the shape of this platform and its relationships to other geographic elements of northwestern Alaska will be further discussed below.

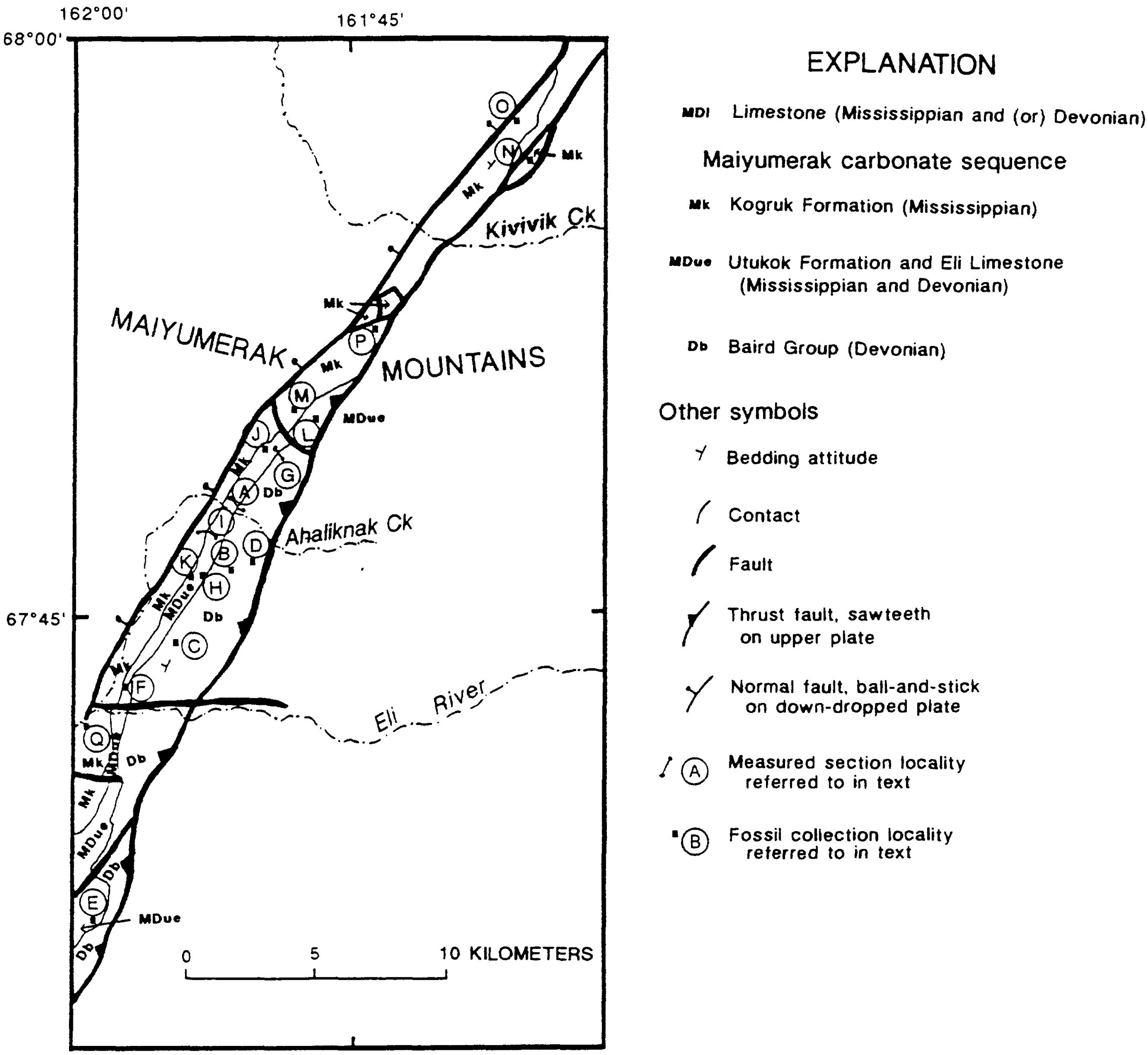


Figure 2. Locations of measured sections and lithologic and fossil collections, Maiyumerak Mountains area, Baird Mountains quadrangle.

Figure 3. Devonian-Mississippian carbonate succession in the Maiyumerak Mountains.

BAIRD GROUP

Medium- to dark-gray, medium- to light-gray-weathering dolostone and lesser dolomitic limestone and limestone forms the base of the carbonate sequence in the Maiyumerak Mountains and is here assigned to the Baird Group. Exposures include massive cliffs, but consist largely of blocky rubble. The unit may be as much as 1000 m thick in this area (Tailleur and others, 1967); the base is truncated by a thrust fault which places carbonate rocks above siliciclastic rocks of the Endicott Group. The upper part of the Baird Group includes a few thin beds of argillaceous dolosiltstone similar to the overlying Eli Limestone; the contact is placed above the highest light-gray-weathering dolomitic bed, and is marked by a sharp change in overall weathering color, from light-gray below to brown above.

The Baird Group was most closely studied in an incomplete measured section 440 m thick on the north side of Ahaliknak Creek (Fig. 2, locality A; Figs. 4 and 5); the measured section includes only the upper part of the unit and at least several hundred meters of additional section are exposed at this locality. Reconnaissance studies through the entire Baird Group were made along a series of traverses in the mountains to the north and south.

Lithologies

Most of the Baird Group in the Maiyumerak Mountains has been thoroughly dolomitized but retains considerable relict primary texture that is visible both megascopically and microscopically. Some beds, primarily towards the top of the section and in outcrops in the southern part of the study area, have been only slightly to partially dolomitized; these intervals provide additional information on the composition of the Baird Group prior to dolomitization. Lithologies discerned in the Baird Group and described below are: laminated mudstone, bioclastic wackestone, peloidal grainstone, and argillaceous dolosiltstone.

Laminated Mudstone

Light- to dark-gray, fine-grained dolostone and lesser limestone that is generally laminated and contains fenestral fabric, local sheet cracks, desiccation cracks, and evaporite laths occur throughout the Baird Group. Relict microtextures indicate that most of these rocks originated as carbonate mudstone; they are associated with thin beds of grainstone and flat-pebble conglomerate.

Fine lamination is the most notable megascopic feature of these mudstones. Laminae are 0.5-5 mm thick, crinkled and irregular, form small-scale hummocks with several mm of relief, and are interpreted as cryptalgal in origin (Fig. 6A). Fenestral fabric is well-developed in these rocks (Fig. 6B) and occurs in intervals a few cm to 20 m thick. Fenestrae range from horizontal, laminar forms that are 0.5-1 mm X 3-10 mm in size, to more irregular shapes as much as 5 mm across. Relatively coarse, sparry calcite or coarsely crystalline dolomite fills the fenestrae. Sheet cracks occur as horizontal zones a few cm thick and several cm long that contain finely laminated, red-weathering sediment. In some cases, a layer of coarse dolomite or calcite spar overlies (and rarely, underlies) the red sediment, coating the upper and lower surfaces of the crack (Fig. 6C). V-shaped, vertical cracks as much as 0.5 cm wide at the top and 1.5 cm deep are interpreted as desiccation cracks; they are filled with red sediment like that found in the sheet cracks (Figs. 6C and D).

Most of the rocks that contain the distinctive sedimentary features described above are dolostone, and consist largely of euhedral to subhedral dolomite crystals 8 to 80 µm in size. Such saccharoidal dolomite typically replaces carbonate mudstone (Armstrong, 1970b), and the fine-grained laminated dolostone in the Baird Group is thought to have originated in this way. This interpretation is

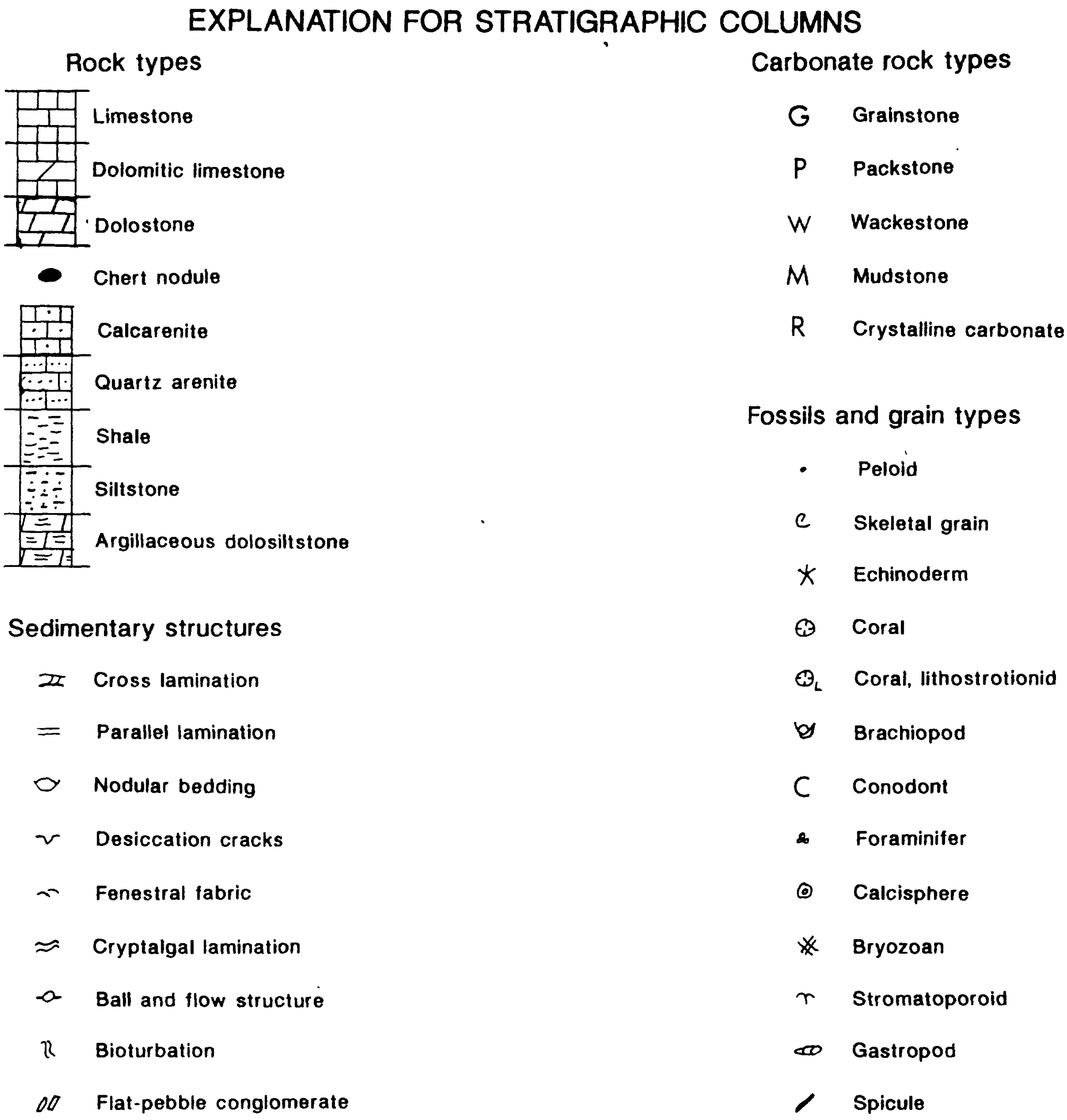


Figure 4. Lithologic and paleontologic symbols used in this report.

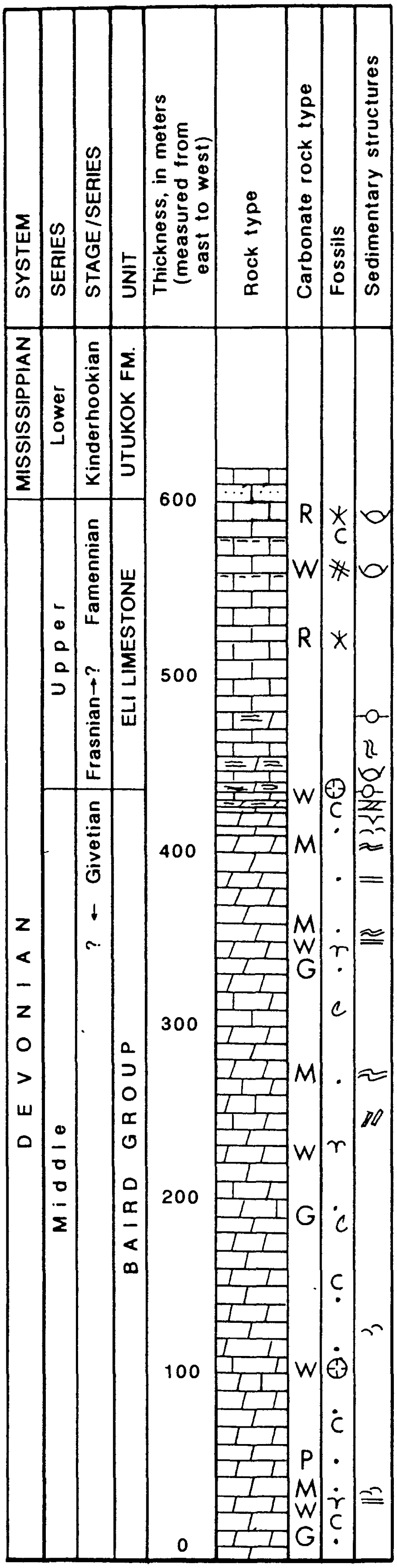


Figure 5. Generalized section, Baird Group and Eli Limestone, based on measured sections at localities A and G, Fig. 2.

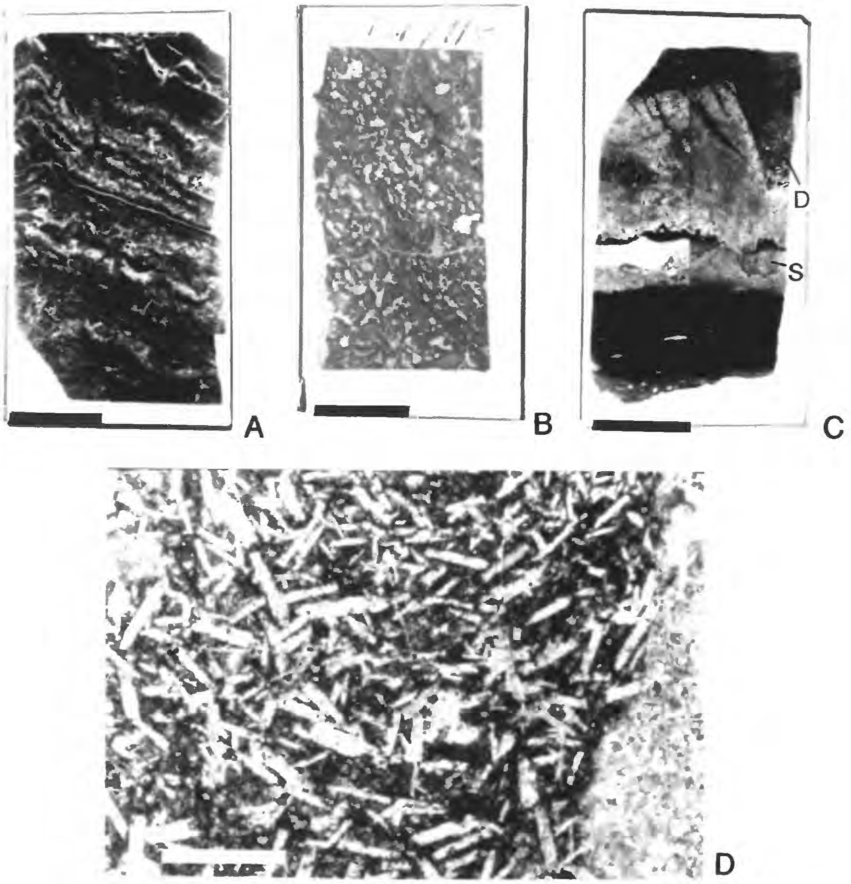


Figure 6. Sedimentary features of laminated mudstone lithology, Baird Group. Scale bar equals 1 cm in A-C,1 mm in D. **A.** Whole thin-section photograph of cryptalgal layering in dolomitic mudstone, locality G, Fig. 2. **B.** Whole thin-section photograph of well-developed fenestral fabric in peloidal lime mudstone, locality D, Fig. 2. **C.** Whole thin-section photograph of sheet crack (S) and desiccation crack (D) in laminated dolomitic mudstone, locality G. **D.** Photomicrograph of anhydrite laths in sediment filling the desiccation crack shown in Fig. 6C.

strengthened by the occurrence of locally undolomitized or partly dolomitized intervals of carbonate mudstone that are interbedded with the laminated dolostone and possess identical megascopic features. For example, lime mudstone interbedded with dolostone at locality B (Fig. 2) contains cryptalgal lamination, well-developed fenestral fabric, and excellently preserved original microtexture. Fenestrae in these rocks are surrounded by lime mud or fine-grained peloids; the peloids have locally coalesced into a flocculent, clotty mass (*structure grumeleuse*) in which individual grain outlines are difficult to discern (Fig. 7A). The peloids are made of micrite (crystals 2-4 μm), have maximum diameters of 75 to 150 μm, and are quite uniformly ellipsoidal in shape.

Laminae in these rocks generally reflect subtle variations in dolomite color or crystal size or in the amount of intercrystalline opaque material, but some are formed by alternations of lime micrite and finely crystalline dolomite.

Several percent bioclasts and bioclastic debris occur disseminated throughout these fine-grained rocks. Bioclasts are best preserved in the undolomitized rocks but also occur as remnant forms in dolostone. Whole bioclasts are dominantly calcispheres that range from 60-300 μm in diameter and include thick-walled radiosphaerid types.

The red sediment in the sheet and desiccation cracks consists mostly of silt-sized dolomite euhedra and lesser bioclastic and quartz silt in a clay-sized matrix that appears dark brownish black in thin section. Laths of anhydrite a few mm long occur within the red sediment in both horizontal and vertical cracks, but are especially large and abundant at the base of the vertical cracks. The laths are generally randomly oriented within the mud matrix (Fig. 6D).

Lighter colored layers of relatively coarse grained peloidal and (or) bioclastic grainstone and packstone are locally interbedded with laminated mudstone (Fig. 7B). These layers are generally undolomitized or partly dolomitized, 0.5 to 5 cm thick, and some are distinctly graded. Peloids are irregular to ovoid in form, 0.1-0.5 mm in diameter, and very similar to those in the peloidal grainstone lithology described below. Recognizable bioclasts include calcispheres, foraminifers, and algae.

Rare flat-pebble conglomerate occurs in beds a few cm to 12 cm thick. Clasts are elongate (typical dimensions are 0.5-1.0 cm thick and 5-10 cm long), imbricated, and consist mostly of dolomitic laminated mudstone and subordinate peloidal grainstone.

Bioclastic Wackestone

Another major Baird Group lithology is bioclastic wackestone and lesser packstone; these rocks are mostly dolostone or slightly calcitic dolostone. Bioclasts are dominantly stromatoporoids, primarily the small, tubular form *Amphipora*, and more rarely, massive laminar forms 1-2 cm thick and 3-6 cm long (Fig. 8). Locally, amphiporids make up 30-70 percent of these rocks and form biostromes 0.5 to 2.5 m thick and several tens of m in lateral extent. Elsewhere, amphiporid material is less concentrated (10-30 percent of the rock) and occurs in even to undulatory beds 2-10 cm thick. The amphiporid tubes are 1-3 mm in maximum diameter and 1-2 cm long; details of internal structure are poorly preserved, as most tubes have been replaced by dolomite euhedra or rarely, chert. The matrix of the amphiporid rocks is variably grain-rich, fine-grained bioclastic wackestone; small bioclasts in the matrix are generally broken and not specifically identifiable, but whole forms observed include ostracodes and calcispheres. Bioclasts are surrounded by fine-grained saccharoidal dolomite; this dolomite is interpreted as a replacement of carbonate mudstone as described above.

Megafossils other than stromatoporoids are rare in the Baird Group in the Maiyumerak

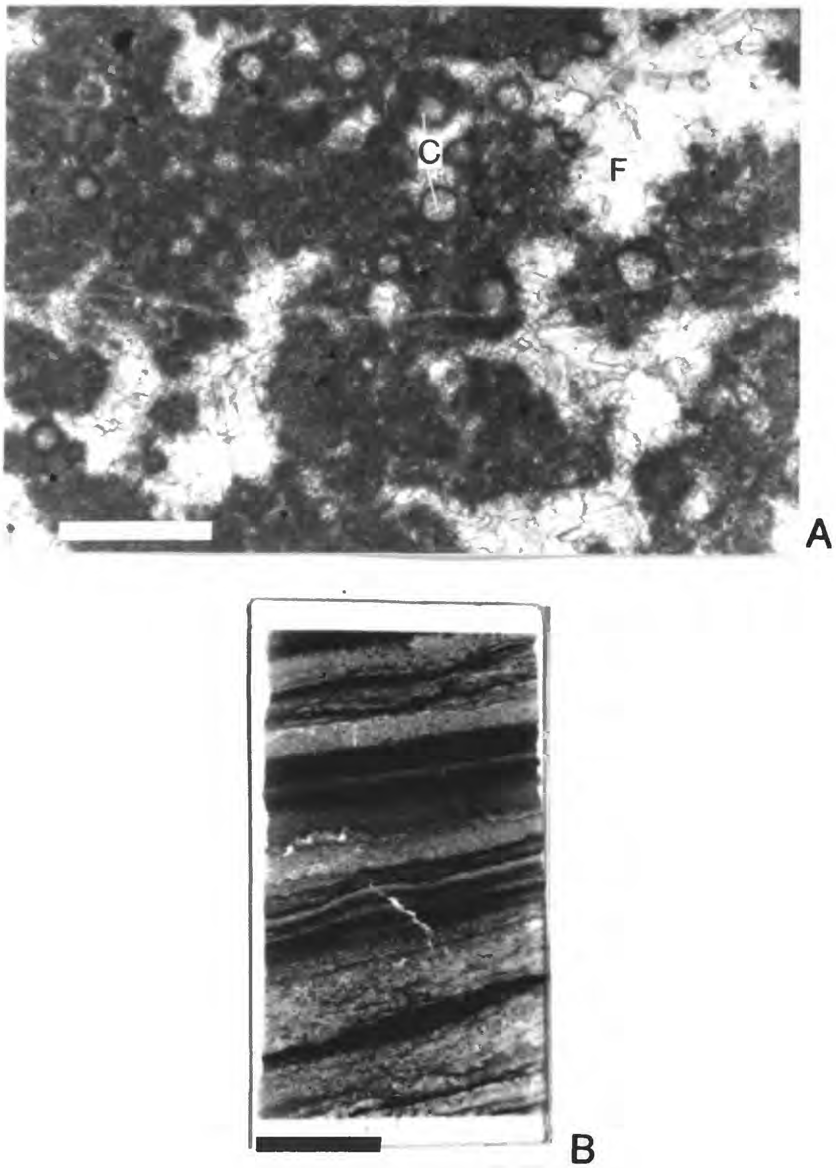


Figure 7. Sedimentary features of laminated mudstone lithology, Baird Group. **A**. Photomicrograph of *structure grumeleuse* in peloidal limestone, locality D, Fig. 2. Small spheres (C) are calcispheres; calcite spar-filled voids (F) are fenestrae. Scale bar is 0.5 mm. **B**. Whole thin-section photograph of thinly interlayered bioclastic peloidal grainstone (light) and laminated mudstone (dark), locality G, Fig. 2. Scale bar is 1 cm.

Figure 8. Stromatoporoid wackestone, Baird Group, Maiyumerak Mountains. Laminar form on far left; stick-shaped forms mostly *Amphipora* sp. Field locality no. 86 AD 33.

Mountains. Corals, including *Thamnopora* sp., *Alveolites*? sp., *Cladopora* ?sp., *Dendrostella*? sp., and indeterminate dissepimented rugose corals, are reported, generally associated with *Amphipora* sp. (written commun., W. A. Oliver, Jr., 1974). Like the amphiporids, the corals are typically poorly preserved and occur in dolomitized wackestone or packstone.

Two other types of bioclastic wackestone are observed in the Baird Group. Relatively grain-rich fine-grained wackestone forms blocky rubble and contains brachiopod, echinoderm, and bryozoan debris 0.1 mm to 1.0 cm in size. More grain-poor wackestone occurs in irregular bioturbated beds as much as 30 cm thick; bioclasts are generally less than 30 percent of the rock, smaller than 0.5 cm, and include ostracodes, gastropods such as *Macrocheilus* sp. (written commun., E. L. Yochelson, 1972), calcispheres, and rare sponge? spicules.

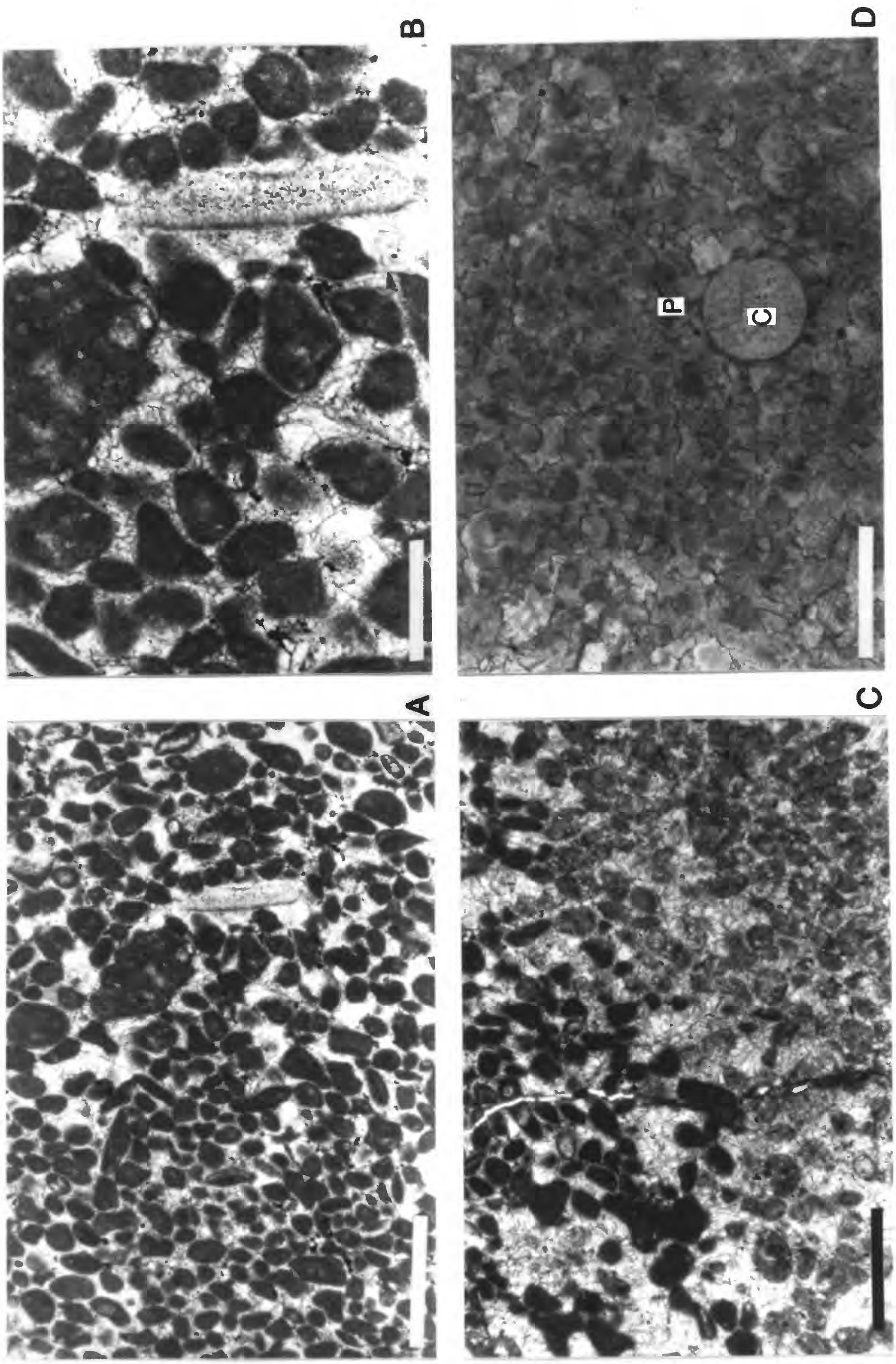
Peloidal Grainstone

The most widely distributed Baird Group lithology is grainstone and (or) packstone made up of peloids and lesser skeletal grains. Excellent exposures of this lithology that are undolomitized to only slightly dolomitized occur north of the Eli River (Fig. 2, locality C). Here, beds are even to slightly irregular, 2 to 80 cm thick, and consist of moderately well-sorted, fine- to medium-grained peloidal grainstone. The peloids are ellipsoidal to spherical to irregular in form, 0.1 to 0.5 mm in maximum dimension (average 0.2-0.3 mm), and are notably larger and more irregular in shape than those in the pelleted mudstones described above. Most consist entirely of micrite (crystals 2-3 μm), but rare peloids are composed of skeletal fragments and micrite (Figs. 9A and B). Peloids constitute more than 95 percent of the grains in the samples examined; other grains are bioclasts, mainly echinoderm, bryozoan, and brachipod fragments. The grainstone is closely packed (locally, overly closely packed with interpenetrative grain contacts) and has a matrix of fine crystalline sparry calcite.

Rocks similar to these peloidal grainstones but moderately to completely dolomitized make up much of the Baird Group in the Maiyumerak Mountains. Partially dolomitized rocks retain a sparry calcite matrix, but peloids have been replaced by dolomite euhedra that are 50 μm or less in diameter and choked with opaque (probably organic) material (Fig. 9C). Completely dolomitized rocks consist of anhedral to subhedral dolomite crystals that range from 50 μm to 1.5 mm in size (average 0.2-0.4 mm). Within the dolomite crystal mosaic, a second texture is clearly visible: a closely packed mass of brown ellipsoidal to irregular forms, 0.1-0.5 mm in maximum dimension (Fig. 9D). Individual ellipsoids clearly cross-cut dolomite crystal boundaries, and their size and shape are identical to those of the peloids in the limestones described above; however, they consist not of micrite but of a dark-brownish residue (organic matter?) enclosed within one or more dolomite crystals. These rocks also contain some spherical to irregular, relatively coarse single grains of dolomite that resemble echinoderm fragments (Figs. 10A and B).

It seems probable that the dolostone with brown ellipsoids was once lime grainstone and(or) packstone that has been completely dolomitized but has retained a palimpsest of original texture. The brown ellipsoids are ghosts of the original peloids, and the coarse, spherical to irregular dolomite crystals are echinoderm debris that has been pseudomorphically replaced. In some cases, both echinoderm fragments and associated calcite rim-cement overgrowths have been replaced; the relict contact between the more turbid echinoderm grain and the clearer rim cement is clearly discernable within the dolomite crystal (Fig. 10A). The tendency of dolomite to pseudomorphically replace crinoid fragments and rim cements was noted by Lucia (1962); similar textures were described by Armstrong (1970b) in the Lisburne Group north of the study area.

Figure 9. Photomicrographs of peloidal grainstone, Baird Group. A-C, locality C, Fig. 2; D, locality A, Fig. 2. Scale bars equals 1 mm in A, C, and D, 0.5 mm in B. **A.** and **B.** Undolomitized sample; grains are lime micrite peloids and rare skeletal fragments in a matrix of sparry calcite cement. Some peloids contain small skeletal fragments in addition to micrite. **C.** Partially dolomitized sample; peloids in lower right have been replaced by dolomite. **D.** Completely dolomitized sample; peloids (P), skeletal grains such as crinoid fragments (C), and sparry cement have been replaced by dolomite.


A
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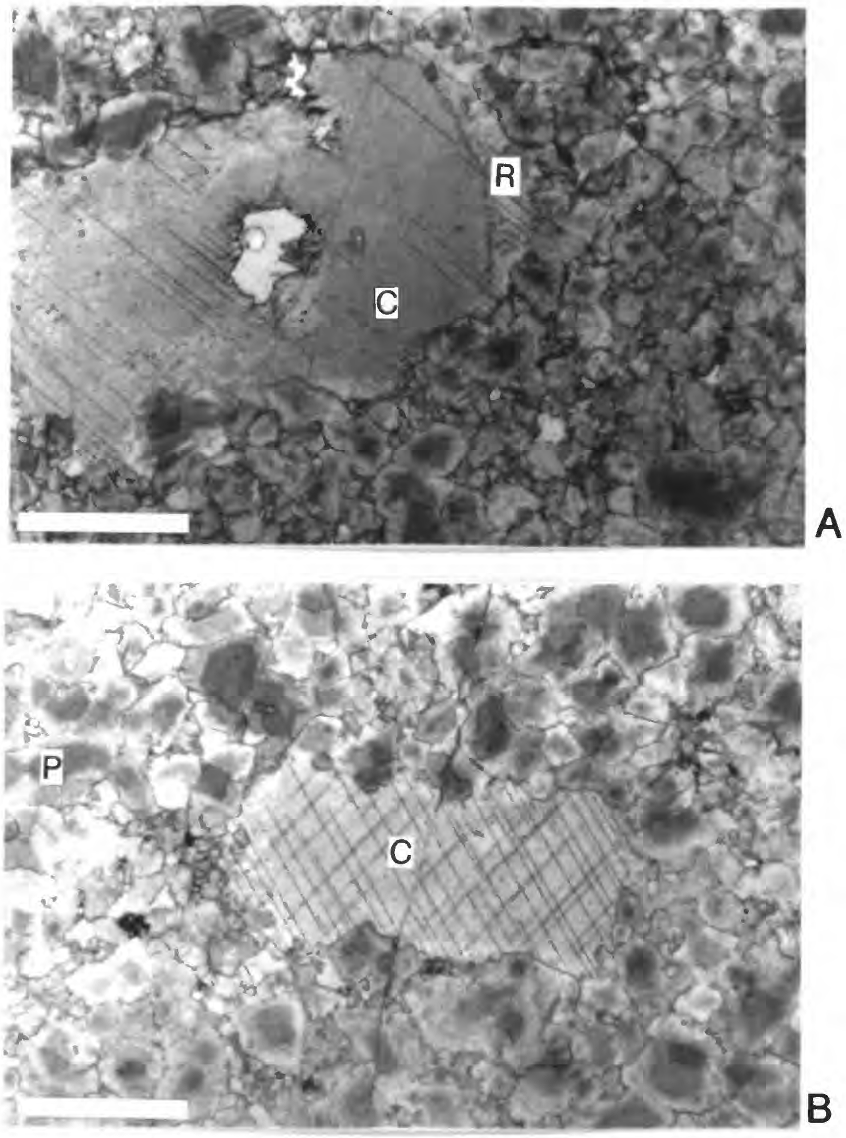


Figure 10. Photomicrographs of dolomitized peloidal grainstone, Baird Group, locality A, Fig. 2. **A.** and **B.** Peloids (P), crinoid fragments (C) and associated rim cement overgrowths (R), and sparry matrix have all been replaced by dolomite. Scale bars equal 1 mm.

Argillaceous Dolosiltstone

The final lithology distinguished in the Baird Group of the Maiyumerak Mountains is brown- to red-weathering argillaceous dolosiltstone; it occurs only in the uppermost part of the unit in beds a few cm thick. These rocks are parallel- to cross-laminated and consist of dominantly silt-sized dolomite euhedra intermixed with argillaceous material and as much as 10 percent quartz and calcite silt. Calcareous grains include peloids and spicules. Laminae are straight and laterally continuous, not irregular and locally domed like the cryptalgal laminae in the laminated mudstone lithology, and are formed mostly by alternations of clay and silt. Similar rocks occur in the overlying Eli Limestone, and are more fully described below.

Distribution

Most of the Baird Group in the Maiyumerak Mountains consists of dolostone with relict peloidal grainstone or amphiporid wackestone texture. Wackestone containing corals, brachiopods, echinoderms, and (or) bryozoans is rare and was observed mainly in the lower half of the unit and in the uppermost beds. The upper half of the unit is characterized by alternations of the first three lithologies described above; some intervals are distinctly cyclic. A typical cycle is 2-5 m thick and consists of 1-2 m of peloidal grainstone or packstone overlain by a similar thickness of amphiporid wackestone. The wackestone grades up into a thinner interval of laminated mudstone with fenestral fabric, which is in turn overlain by another bed of peloidal grainstone (Fig. 11). The cycles appear to have formed under shallowing-upward (regressive) conditions, because transitions from peloidal grainstone up into amphiporoid wackestone and from amphiporoid wackestone up into laminated mudstone are generally gradational, whereas those from laminated mudstone up into peloidal grainstone are abrupt (cf. otherwise similar cycles described by Fischer, 1975, interpreted as deepening-upward deposits). Bioclastic wackestone containing ostracodes, gastropods, calcispheres, and (or) spicules is locally associated with (and grades into) amphiporid wackestone and laminated mudstone. Sheet cracks, desiccation cracks, and evaporite laths were noted in laminated mudstone in the uppermost third of the unit (Fig. 5). At the very top of the section, argillaceous dolosiltstone that is lithologically similar to beds in the overlying Eli Limestone occurs interbedded with gray calcitic dolostone that contains corals and brachiopods. The base of the Eli Limestone is placed at the top of the highest gray dolostone bed.

Age and Sedimentation Rate

The Baird Group is the oldest unit known in the Maiyumerak Mountains; the base is not exposed and is consistently fault-bounded. Conodont faunas provide the most precise information currently available on the age of the Baird Group in the study area. The oldest biostratigraphically restricted conodont fauna obtained contains *Polygnathus* aff. *P. robusticostatus*, indicating an early Middle Devonian (earliest Eifelian through earliest Givetian) age (USGS colln. 11385-SD); this fauna occurs in a sample of bioclastic peloidal grainstone collected near the base of the section (Fig. 2, locality D). The youngest biostratigraphically restricted samples contain *Polygnathus xylus* and *P.* cf. *P. pseudofoliatus*, (USGS collns. 11137-SD and 11138-SD) which denote a middle(?) Givetian (possibly Lower to Middle *varcus* Subzone) age; these faunas come from argillaceous dolosiltstone and interbedded coralline dolostone that directly underlies the Eli Limestone (Fig. 2, locality A). All other samples from the Baird Group contain conodonts that are longer ranging within the late Early through Middle Devonian (Emsian through Givetian). Poorly preserved coral and stromatoporoid faunas from the Baird Group in the Maiyumerak Mountains yield long-ranging ages of Middle Devonian or Devonian (written commun., W. A. Oliver, Jr., 1974).

Because the age and total thickness of the Baird Group in the Maiyumerak Mountains is not

Figure 11. Laminated mudstone overlying medium- to thick-bedded peloidal grainstone, Baird Group, Maiyumerak Mountains; field locality no. 86 AD 43.

precisely known, the sedimentation rate can only be estimated. Assuming a thickness of 700 to 1000 m, an age of Eifelian through Givetian, and an absolute time span of 14 m.y. (Haq and van Eysinga, 1987), a sedimentation rate of 0.05-0.07 m/1000 years is calculated. This is within the range (0.03-0.08 m/1000 years) reported by Wilson (1975) for pre-Holocene limestone sequences formed in shallow neritic environments.

Depositional Environment

The major lithologies of the Baird Group formed in a shallow- to very shallow-water depositional environment with at least locally restricted circulation, most likely an inner shelf lagoon and associated peritidal flats. Laminated mudstone was deposited in the most restricted and shallowest depositional settings; amphiporid wackestone formed in somewhat restricted but slightly deeper water environments. Peloidal grainstone accumulated in more agitated but still shallow and somewhat restricted water, and rare coral and (or) brachiopod wackestone was deposited in quiet-water, open-marine conditions. Beds of argillaceous dolosiltstone, found only in the uppermost part of the unit, are current-laid deposits that appear to mark the initial stages of a transgression.

Sedimentary structures and fauna of the laminated mudstone lithology indicate deposition in a supratidal to shallow subtidal setting (Wilson, 1975; Shinn, 1983b; James, 1984). The crinkly, irregular, and locally domal form of the laminae suggests an algal (stromatolitic) origin; in modern environments that are not hypersaline, algal mats are best developed in intertidal to supratidal environments (James, 1984). Fenestral fabric, sheet cracks, and desiccation cracks are most commonly preserved in supratidal settings; red or tan windblown sediment characteristically fills these cracks and adheres to exposed algal mats (Shinn, 1983b). Micrite-sized crystals of dolomite within these sediments may be detrital (Shinn, 1983b) and (or) authigenic (Fischer, 1975). Bladed anhydrite after gypsum is also typical of modern and ancient tidal flats.

Shallow subtidal sediments consist largely of gray (reduced) pelleted muds that have been throughly bioturbated and lack primary sedimentary structures (Shinn, 1983b). Storms introduce such sediments onto tidal flats, where they form layers a few mm to several cm thick that alternate with algal laminites. Thin, graded layers of peloidal grainstone typically accumulate on natural levees adjacent to tidal channels (Wilson, 1975). Flat-pebble conglomerate also forms during storms; intraclasts are eroded and redeposited in subtidal channels or on supratidal flats (Shinn, 1983b).

The sparse fauna of the laminated dolostone lithology is consistent with deposition in a restricted, stressful environment and contains no forms characteristic of normal marine conditions. Gastropods, ostracodes, and many foraminifers and algae are comparatively tolerant of restricted circulation (Wilson, 1975). Paleozoic calcispheres probably represent reproductive cysts of dasycladacean algae, and are most commonly found in very shallow water, high-salinity environments (Rupp, 1966).

The laminated mudstone lithology of the Baird Group is thus interpreted to have formed in a very shallow water setting that was at least locally and periodically emergent. Although individual structures described above can occur in deeper water settings (i.e., fenestral fabric; see Shinn, 1983a), the constellation of sedimentary and biotic features in these rocks are characteristic of tidal flat deposition.

Most bioclastic wackestone in the Baird Group also formed in somewhat restricted environments, although these rocks show no evidence of subaerial exposure. Amphiporid biostromes are common in Devonian sediments throughout the world and are characteristic of backreef lagoon or inner shelf settings; *Amphipora* appears to have been the stromatoporoid most tolerant of variable temperature and salinity (Fischbuch, 1968; Wilson, 1975). The abundant carbonate mud in these amphiporid-bearing rocks indicates that deposition took place in relatively quiet water lacking "currents of removal"

(Dunham, 1962). Fauna such as corals and bryozoans that are typical of environments with normal salinity and good circulation are rare in the Baird Group, and generally occur as isolated specimens associated with more abundant *Amphipora*. Such associations most likely formed through storm or current transport of open-marine fauna onto the inner shelf.

Thicker beds of peloidal grainstone are interpreted to have formed in somewhat agitated shallow water above fair-weather wave-base, the "restricted marine shoals" of Wilson (1975). These peloids are larger and less uniform than the clotted peloids in the laminated mudstone lithology, and are not texturally gradational into mudstone (i.e., there are no coalesced peloid masses). Most peloids in these grainstones are similar in size and shape to modern fecal pellets, but some grains are quite irregular in form and may be skeletal particles that have been replaced by micrite (Bathurst, 1976). Such micritization most commonly occurs in the photic zone as a result of boring by endolithic algae. Both amphiporid wackestone and pelloidal grainstone contain conodont faunas consisting chiefly of Dvorakias, an association which suggests a shallow-water, somewhat restricted depositional environment.

Rare beds of wackestone that contain corals, bryozoans, and (or) brachiopods, but lack amphiporid stromatoporoids, occur in the lower half and uppermost beds of the Baird Group. The association of abundant carbonate mud and normal marine faunal elements in these rocks suggests that they were deposited below wave-base and in less restricted conditions than those prevalent during deposition of other Baird Group lithologies.

In the uppermost part of the Baird Group, coral wackestone is interbedded with current-laminated argillaceous dolosiltstone. The basal part of the Lisburne Group in some areas is similarly argillaceous, spiculitic, and peloidal, and is interpreted as the initial deposits of a regional transgression (Armstrong and Bird, 1976). A similar origin is proposed for the argillaceous dolosiltstone in the Baird Group, and will be discussed further below.

Thus, the bulk of the Baird Group in the Maiyumerak Mountains was deposited in shallow to very shallow water with restricted circulation, and this depositional setting probably accounts for the pervasive dolomitization of these rocks. Dolomite in the laminated mudstone lithology may be detrital and (or) authigenic; both types of dolomite are common in modern tidal flats (Shinn, 1983b). Subtidal Baird Group lithologies may have been dolomitized through reflux of Mg-rich surficial brines produced in nearby supratidal environments. This mechanism was originally proposed by Adams and Rhodes (1960), and has since been used to explain dolomitization of a variety of modem and ancient sediments. For example, parts of the Lisbume Group northeast of the study area are pervasively dolomitized and contain sedimentary features similar to those of the Baird Group; dolomitization of these rocks has been ascribed to reflux of hypersaline brines formed in a supratidal environment (Armstrong, 1970b).

The cause of the restricted conditions evident during deposition of much of the Baird Group in the Maiyumerak Mountains is uncertain. No reefs or bank margin shoals have been recognized that might have formed a physical barrier to open circulation. However, as will be discussed below, the Baird Group has been tectonically dismembered into a series of imbricate thrust sheets; it is possible such bank margin facies exist but are located in other thrust sheets outside of the Maiyumerak Mountains. Restricted circulation may also occur in the absence of shelf-edge barriers if shelf width is very great (Shaw, 1964); deposition of the Baird Group may have occurred in such a setting.

The timing of restricted circulation during deposition of the Baird Group is somewhat better understood than its cause. Normal marine fauna occurs mostly in the lower half of the unit and again in the uppermost beds. The base of the Baird Group in the Maiyumerak Mountains is Eifelian to earliest Givetian in age; uppermost beds contain conodont faunas indicative of a middle? Givetian age. Thus, the shallowest and most restricted depositional environments apparently prevailed during early to middle

Givetian time.

ELI LIMESTONE

The Eli Limestone is 165 m thick in its type section along a short eastern tributary of the north fork of the Eli River (Tailleur and others, 1967); the north fork is now called Ahaliknak Creek (locality A, Fig. 2). The lower part of the unit is best exposed along the stream bed at the type section, but the upper beds of the formation are better exposed and less recrystallized on ridgetops to the north and south. The following description of the lithologies and biostratigraphy of the Eli Limestone is based on studies of both stream-bed and ridgetop exposures. The unit is distinguished from the underlying Baird Group by a distinct change in weathering color from gray to brown; it differs from the overlying Utukok Formation by containing clastic material which is chiefly clay-sized rather than sand-sized. In this study, the upper contact of the Eli Limestone is drawn at the base of the lowest bed of sandy limestone; where rocks have been pervasively recrystallized, this contact can be difficult to recognize (Karl and others, 1989).

Lithologies

In the Maiyumerak Mountains, the Eli Limestone consists mostly of laminated to nodular argillaceous dolostone, dolomitic limestone, and limestone intercalated with cleaner bioclastic limestone (Figs. 5, 12); the argillaceous component of the unit decreases upsection. Four lithologies are recognized. Laminated to cross-bedded dolosiltstone and nodular-bedded dolomitic limestone dominate the lower third of the unit; both lithologies contain abundant argillaceous material and weather a distinctive yellowish brown to orangish gray. Nodular limestone also occurs in the upper part of the unit, where it is interlayered with light-gray-weathering, echinoderm-bearing crystalline limestone. Skeletal wackestone/packstone is a subordinate lithology recognized throughout the Eli Limestone.

Dolosiltstone

Fine-grained dolomitic rocks are abundant in the lower 50 m of the Eli Limestone and form intervals a few cm to several m thick (Fig. 5). In outcrop, these rocks are distinguished from fine-grained gray dolostones of the underlying Baird Group by their orangish weathering color. In addition, dolomitic rocks of the Eli Limestone have distinctive sedimentary structures and compositional features that indicate a protolith and depositional environment different from that of the Baird Group dolostones. Fine-grained dolostones of the Eli Limestone are parallel-laminated or cross-laminated siltstones (Fig. 13A) that lack the cryptalgal lamination and fenestral fabric which is common in fine-grained dolostones of the Baird Group. In thin section, both lithologies consist primarily of dolomite euhedra, but in the Eli Limestone, these euhedra are intermixed with quartz silt and argillaceous material.

Parallel laminae in the Eli Limestone dolomitic rocks are a few tenths of a mm to 2 mm thick; cross laminae form sets about 0.5 cm thick and have asymmetric profiles. Laminae are made of concentrations of dolomite euhedra alternating with argillaceous material or lime peloids (Fig. 13B). Dolomite crystals range from 15-120 µm in diameter, but most are 40-60 µm. As much as 10-20 percent argillaceous material, 10 percent noncarbonate silt (mostly quartz with minor amounts of opaque grains, feldspar, and mica), and a few percent calcispheres and crinoidal debris are disseminated among the dolomite crystals.

Nodular Limestone

The most widely distributed and distinctive lithology of the Eli Limestone is nodular limestone in platy beds 1-3 cm thick (Fig. 14). This lithology comprises light-gray, locally dolomitic limestone

Figure 12. Even-bedded, clean, bioclastic limestone overlying nodular-bedded argillaceous dolostone, Eli Limestone, locality A, Fig. 2. Contact between the two lithologies is just above hammer head.

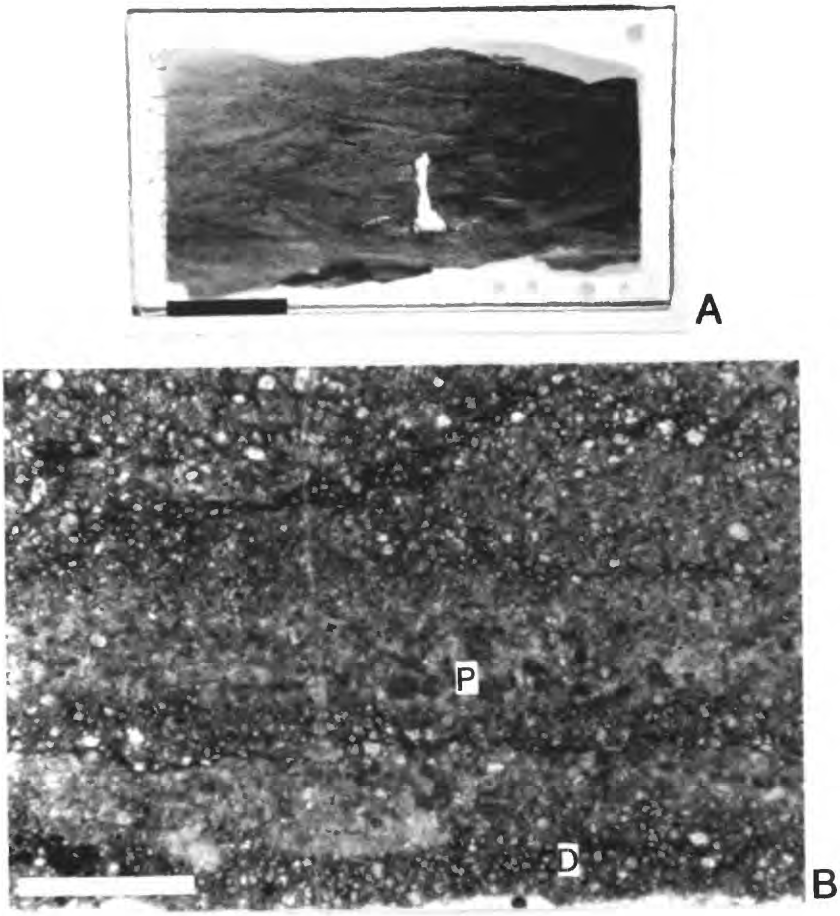


Figure 13. Microtextures of dolosiltstone, Eli Limestone, locality A, Fig. 2. Whole thin-section photograph (**A**) and microphotograph (**B**) of cross-laminated dolosiltstone; laminae consist of alternations of lime peloids (P) and dolomite rhombs (D). Scale bar equals 1 cm in A, 1 mm in B.

Figure 14. Nodular limestone, Eli Limestone, locality A, Fig. 2.

nodules separated by seams of orange-weathering argillaceous dolostone. The nodules are a few mm to several cm long, cylindrical to ovoidal to irregular in shape, and locally form sedimentary boudinage or ball-and-flow structures (Fig. 15A); they consist of skeletal wackestone to packstone, locally peloidal (Fig. 15B). The dolostone seams consist of brownish euhedral dolomite crystals, 15-100 µm (average 40-50 µm) in diameter, with considerable (10-30 percent) dark-brown intercrystalline argillaceous material and as much as 5 percent disseminated quartz silt. Skeletal fragments also float within the dolostone seams, but are generally more abundant in the limestone nodules (Fig. 15C). Identifiable fossils found in both nodules and seams include coral and stromatoporoid fragments, brachiopods, gastropods, and calcispheres. Shelter porosity, now filled with calcite spar or geopetal layers of carbonate sediment and sparry cement, is locally well developed beneath and within larger shell fragments in the packstones; such umbrella effects indicate that the skeletal fragments were deposited in grain support (Dunham, 1962).

The nodular limestone lithology is interpreted as a combination of two discrete sediment types, skeletal wackestone to packstone and argillaceous carbonate mud, that were originally interbedded but have been partially mixed by bioturbation; the argillaceous carbonate mud has been thoroughly dolomitized. Locally, the light-gray limestone fills vertical and horizontal burrows a few mm to several cm in diameter, but discrete burrow forms are relatively rare. Both dissolution seams and fitted fabric, as defined by Bathurst (1987, p. 763), occur locally within this lithology; the former are "smooth, undulose seam(s) of insoluble (noncarbonate) residue which lack the sutures of stylolites" and the latter is "a framework of interpenetrant grains."

Skeletal Wackestone/Packstone

Subordinate intervals, generally less than 2 m thick, of thin-bedded skeletal wackestone and lesser packstone that contain little argillaceous material occur throughout the Eli Limestone. Beds are 2-10 cm thick and generally nodular, but locally more even, planar beds predominate. Most intervals are nodular bedded, relatively grain-rich wackestone to packstone that is thoroughly bioturbated; bioclasts include fenestrate bryozoans, brachiopods, echinoderms, ostracodes, and foraminifers, as well as unidentified calcite spheres and spicules (Fig. 15D). Shelter porosity, now filled with calcite spar, is locally well-developed under larger shelly fragments such as brachiopods in packstone (Fig. 15D). More evenly bedded intervals of this lithology contain a similar range of relatively well-preserved bioclasts, but also include up to 30 percent peloids and 10 percent quartz and subordinate feldspar silt and fine sand (Fig. 15E). Some samples contain a few percent disseminated dolomite rhombs.

Echinoderm-bearing Crystalline Limestone

Intervals of echinoderm-bearing crystalline limestone less than a meter to several tens of meters thick occur throughout the Eli Limestone but are especially abundant in the upper part of the unit. Some intervals contain virtually no argillaceous material, weather light gray, and are crudely bedded on a scale of 10-40 cm. Other intervals weather orange and consist of nodular beds 2-10 cm thick separated by irregular, undulatory partings of argillaceous dolostone. Locally, beds are so nodular and argillaceous material is so abundant that this lithology grades into the nodular limestone lithology; most of the crystalline limestone, however, contains little (0-5 percent) argillaceous material. Lenses and nodules of black to gray chert a few cm thick occur rarely. The limestone consists mostly of relatively coarse and inequigranular calcite crystals, dominantly 0.5-5.0 mm in diameter. Much of the calcite is anhedral but relict echinoderm fragments (0.2-2.5 mm) are abundant and readily identifiable (Fig. 16A). In some intervals, saccharoidal dolomite and (or) opaque material forms irregular wisps and patches between the calcite crystals (Fig. 16A). Some samples contain a few percent disseminated quartz (and rarely feldspar) silt.

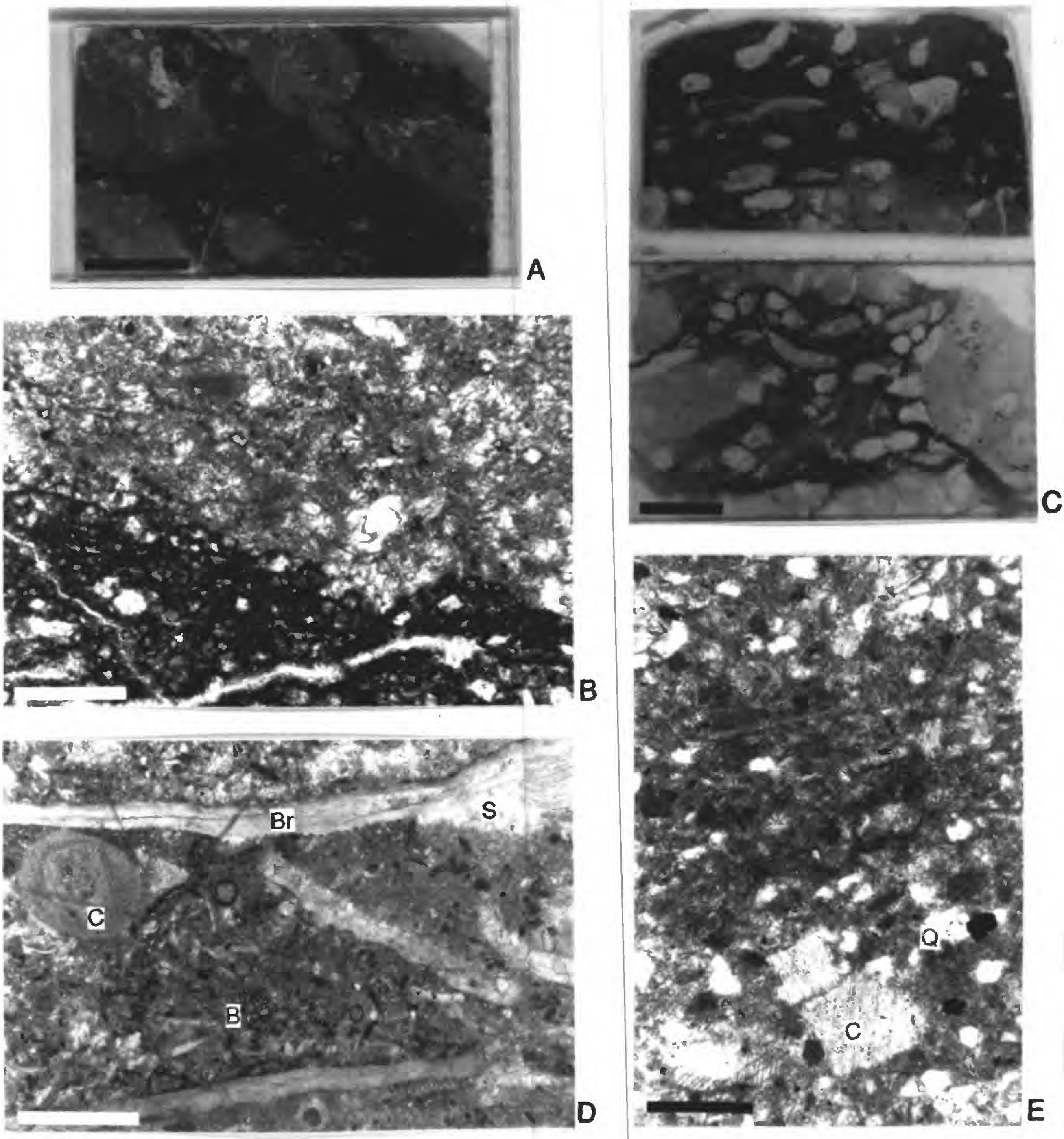


Figure 15. Microtextures of Eli Limestone. A-C, locality A, Fig. 2; D-E, locality G, Fig. 2. A and C are whole thin-section photographs; B, D, and E are photomicrographs. Scale bar equals 1 cm in A and C, 1 mm in D, and 0.5 mm in B and E. **A.** Ball-and-flow structure in nodular limestone; nodules of light-colored limestone in darker dolomitic, argillaceous matrix. **B.** Close-up of A, showing peloids in limey nodule (above) and dolomite rhombs in argillaceous matrix (below). **C.** Stick-like tabulate corals, stomatoporoids, and nodules of peloidal limestone in dolomitic, argillaceous matrix. **D.** Skeletal packstone containing bryozoa (B), echinoderm fragments (C), and brachiopod shells (Br); shelter porosity under brachiopod shells is filled with calcite spar (S). **E.** Peloidal bioclastic packstone with minor quartz silt (Q); recognizable skeletal grains include echinoderm fragments (C).

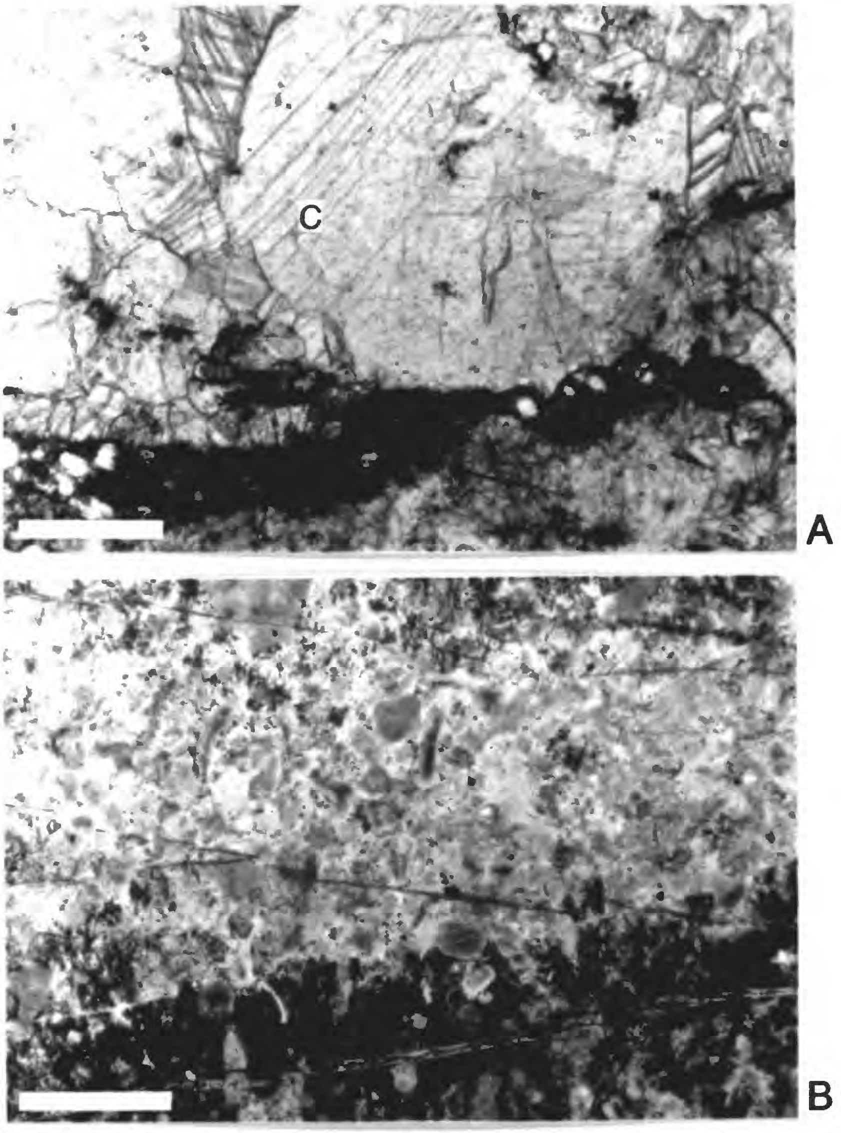


Figure 16. Photomicrographs of echinoderm-bearing recrystallized limestone, Eli Limestone; scale bar equals 0.5 mm. **A.** Relict echinoderm fragment (C) in recrystallized sparry matrix above seam of argillaceous material containing saccharoidal dolomite crystals. **B.** Relict bioclastic grainstone texture preserved in chert layer.

These rocks are interpreted as grainstones and lesser packstones that have undergone recrystallization. The framework grains were chiefly (exclusively?) bioclasts, especially echinoderm (crinoid) fragments; skeletal grains other than echinoderm debris and all material interstitial to the grains has been recrystallized to anhedral to bladed calcite spar. Relict textures in chert nodules (see below) and less recrystallized intervals indicate that these sediments were originally deposited in grain-support. Local wispy seams and irregular pockets of saccharoidal dolomite in these rocks are interpreted as replacement of carbonate mud (e.g., Armstrong, 1970b); thus, intervals containing notable patchy dolomite were probably packstones, whereas those lacking dolomite were more likely grainstones.

Local chert lenses and nodules a few cm thick and less than 0.5 m long occur in recrystallized dolomitic limestone near the top of the Eli Limestone. These lenses preserve a palimpsest of the original limestone texture and indicate that it consisted of relatively well sorted, medium-grained bioclasts in grain support (Fig. 16B). Similar textures probably characterized other unsilicified parts of this lithology in which original textures have been obscured by recrystallization.

Distribution

Parallel- to cross-laminated dolosiltstone occurs only in the lower 40 m of the Eli Limestone and is most abundant in the basal 10 m of the type section. Nodular dolomitic limestone is found throughout the unit but contains less argillaceous material in the upper part of the formation. Skeletal wackestone/packstone forms subordinate intervals 1-2 m thick throughout the unit. Echinoderm-bearing recrystallized limestone occurs largely in the upper two-thirds of the unit; the degree of recrystallization of this lithology varies sharply both laterally and vertically within the formation in the Maiyumerak Mountains. Argillaceous material is most abundant in the lower fourth of the Eli Limestone; noncarbonate silt (predominantly quartz but including rare feldspar) is most common in the upper half of the unit.

Age and Sedimentation Rate

The Eli Limestone is of late Givetian or Frasnian through at least middle Famennian age. Biostratigraphically definitive faunas of Frasnian and Famennian age have been collected from the sections studied. The basal beds of the Eli Limestone are well exposed only in the type section (locality A, Fig. 2); however, the upper part of the formation here is strongly recrystallized and barren of conodonts. In the mountains to the north and south of the type section, the lower part of the formation is covered or poorly exposed but the upper beds are better exposed, less recrystallized, and produce conodonts.

Conodont faunas from the basal 10 m of the type section indicate that the lower part of the Eli Limestone is at least as old as Frasnian. A collection obtained from a skeletal wackestone 1 m above the base of the section is dominated by *Polygnathus* aff. *P. pacificus* (USGS colln. 11056-SD); *P. pacificus* is known only from Frasnian rocks of Arctic Canada and Alaska. A collection from laminated dolosiltstone about 10 m above the base of the type section yielded *Dvorakia*? sp. and very poorly preserved polygnathids of Middle or Late Devonian morphotype (USGS colln. 11090-SD). *Dvorakia* indicates an age of Middle Devonian or older, but this collection appears to have undergone hydraulic sorting and abrasion. Sedimentologic analysis of the lithology which produced the two conodont collections supports the interpretation that the Middle Devonian coniform elements may be reworked into younger (Frasnian) sediment. The *Dvorakia*?-bearing dolosiltstone is well-sorted and contains sedimentary structures, such as parallel and cross lamination, that are indicative of current action, whereas the skeletal wackestone which produced the Frasnian conodonts contains articulated bryozoan fronds, abundant carbonate mud, and no evidence of reworking by currents. Two other collections from the basal 10 m of the type section also contained conodonts, but the faunas consist mostly of poorly preserved polygnathids and are not diagnostic. All samples from the upper part of the Eli Limestone at the type section were barren.

In the mountains north and south of the type section, however, beds on strike with the barren upper interval of the Eli Limestone yield Famennian conodonts. In the study area, beds assigned to the upper part of the Eli Limestone have produced five collections of Famennian age (localities E, F, and G, Fig. 2) and several less diagnostic assemblages (one of Late Devonian age, and two that indicate a late Famennian through early Kinderhookian age; field nos. 85 BT 78A and 78B). The Famennian collections are dominated by several species of polygnathids, including *P. semicostatus*, *P. communis*, and *P.* cf. *P. glaber*, together with *Apatognathus varians* and poorly preserved icriodids (USGS collns. 11302-SD, 11372-SD, 11375-SD, 11386-SD, and 12129-SD).

The lower part of the type section of the Eli Limestone contains a fauna of stromatoporoids and corals, including *Amphipora* sp., *Cladopora* ? sp., and *Thamnopora* sp., of Middle to early Late Devonian age (Oliver and others, 1975). Beds on strike with this locality, but about 8 km to the southwest (locality H, Fig. 2), also contain a stromatoporoid-coral fauna suggestive of Middle to early Late Devonian age; this fauna includes *Amphipora* sp., *Syringopora* sp., *Siphonophrentis*? sp., and *Tabulophyllum*? sp. (written commun., W. A. Oliver, Jr., 1967). About 27 km southwest of the type section, the Eli Limestone contains brachiopods of probable Frasnian age (Tailleur and others, 1967); the stratigraphic position of this collection is not given.

Thus, conodont and megafossil collections indicate that the lower part of the Eli Limestone in its type area is at least as old as Frasnian, but the upper part of the unit is of Famennian age.

Assuming a thickness of 165 m and an absolute time span of 16 m.y. (duration of Frasnian and Famennian stages given in Haq and van Eysinga, 1987), the sedimentation rate of the Eli Limestone is approximately 0.01 m/1000 years. This is somewhat lower than the lowest rates (0.03 m/1000 years) reported for ancient neritic carbonate sequences by Wilson (1975).

Depositional Environment

The Eli Limestone accumulated in shallow to moderate water depths in an inner to middle shelf setting that received periodic input of fine-grained siliciclastic material. Dolosiltstone in the lower part of the section that contains sedimentary structures indicative of current action may represent initial deposits of a transgression across the inner shelf. Middle and upper parts of the Eli Limestone consist largely of nodular limestone and skeletal wackestone-packstone. These lithologies formed below wave-base and have features such as variable bed thickness, nodular beds, abundant carbonate mud, shale partings, and normal marine faunas that are characteristic (Wilson and Jordan, 1983) of middle shelf deposits. Local intervals of echinoderm-bearing crystalline limestone contain little or no carbonate mud and accumulated in areas of greater current agitation such as sand shoals.

Parallel- and cross-laminated dolosiltstone in the lower part of the Eli Limestone is interpreted as a current deposit formed in relatively shallow water. In most shelf environments, laminae are destroyed by bioturbation. Well-laminated intervals in the Eli Limestone contain abundant argillaceous material; thus, these beds appear to have formed during pulses of terrigenous input. Turbidity due to suspended terrigenous material strongly inhibits benthonic invertebrates (e.g., Wilson, 1975) and probably allowed preservation of laminae in these sediments. Current laminae, particularly asymmetric cross-laminae, are common in shallow-water environments but can form in deeper water settings (Wilson, 1975). However, the conditions in which the dolosiltstone accumulated are further constrained by features of the nodular limestone and skeletal wackestone lithologies with which it is interbedded.

Sedimentary and paleontologic evidence suggest that the lower third of the Eli Limestone was deposited in a somewhat restricted inner shelf setting, in water depths greater than those in which much of the underlying Baird Group accumulated but still relatively shallow. Features characteristic of tidal flats, such as cryptalgal lamination, desiccation cracks, or evaporites, that are found in the underlying Baird Group do not occur in the Eli Limestone. However, nodular limestone and skeletal wackestone in the lower Eli Limestone contain faunal elements characteristic of restricted conditions, such as calcispheres and amphiporid stromatoporoids, mixed with normal marine forms, such as echinoderms, brachiopods, and corals. Such mixed faunas typically occur in the inner shelf (Wilson, 1975). The lime mud matrix of the nodular limestone and skeletal wackestone lithologies indicates accumulation below fair-weather wave base; dolosiltstone intervals may have been deposited during storms and (or) periods of slightly lower sea-level.

Biota and structures of the upper Eli Limestone suggest a slightly deeper and (or) more open depositional environment for this part of the unit and have many features characteristic of middle shelf deposits (such features are summarized in Wilson, 1975, and Wilson and Jordan, 1983). For example, this part of the section contains a largely stenohaline fauna, indicating that open circulation and normal marine salinity prevailed during deposition. Variable bed thickness, thin shale layers, nodular beds, and sedimentary boudinage are other characteristics of middle shelf sediments that are especially well-developed in the upper Eli Limestone. Bedding planes on the middle shelf are typically marked by thin clay partings, and vertical sequences of irregular bed thickness in this setting result from episodic introduction of fine-grained argillaceous material (Wilson and Jordan, 1983). Original inhomogeneities in composition and fabric thus typify middle shelf sediments and are exacerbated during diagenesis. Argillaceous material compacts whereas calcareous material is cemented early and resists compaction, resulting in nodular bedding and sedimentary boudinage (Wilson, 1975; Bond and others, 1989).

Bathurst (1987) has suggested that at least some middle shelf limestone sequences contain vertical variations in clay content that do not reflect original compositional differences but were produced during diagenesis. He examined couplets of hard and fissile limestone in a variety of open-marine platform successions and noted that effects of pressure-dissolution, such as dissolution seams and fitted fabric, were concentrated in fissile limestone layers but largely absent from intercalated hard limestone layers. He inferred that the hard limestones had undergone early cementation whereas the fissile limestones had not, and hypothesized that this differential early cementation was controlled by a repetitive signal of wide areal extent implanted synchronously and syndepositionally, perhaps during early subsurface diagenesis. Such a diagenetic signal may have affected the Eli Limestone; the nodular limestone layers display features produced during pressure-dissolution such as fitted fabric and dissolution seams. However, the rocks in Bathurst's study have been completely bioturbated and virtually all primary depositional bedding has been destroyed. The Eli Limestone has been less pervasively burrowed as it retains local current structures (parallel- and cross-lamination) and at least some original vertical inhomogeneity in clay content seems likely.

Shallow shoals are common in shelf settings, and are the probable environment in which much of the echinoderm-bearing crystalline limestone was deposited. As noted above, this lithology occurs mainly in the upper part of the Eli Limestone and consists largely of recrystallized crinoidal grainstone. Skeletal grainstones lack mud and indicate relatively high energy depositional settings; encrinites, however, require less strong water movement for their formation than do other grainstones (Wilson, 1975). Crinoid grainstone in the Eli Limestone forms irregular intervals interbedded with nodular limestone and skeletal wackestone and thus is also thought to have formed in a middle shelf setting. Grainstone bodies of the middle shelf are less abundant, thinner, and more complexly distributed than shoals of the inner and outer shelf, which tend to parallel the shoreline and shelf margin respectively (Wilson and Jordan, 1983).

Conodonts are relatively sparse in the Eli Limestone; interpretations of the depositional environment suggested by conodont biofacies agree with those based on sedimentary structure outlined above. Conodont faunas from nodular limestone, skeletal wackestone, and echinoderm-bearing recrystallized limestone are similar and consist mostly of polygnathids with lesser apatognathids and minor icriodids and "ozarkodinids". This species association represents the polygnathid biofacies and suggests a shallow to moderate depth, normal marine depositional environment (Sandberg and Ziegler, 1976; Sandberg, 1976). The laminated dolosiltstone lithology has produced only Dvorakias(?) and poorly preserved polygnathids that appear to have undergone hydraulic sorting and abrasion; as previously discussed, these assemblages may have been reworked.

Clay-rich bedding surfaces in the middle shelf environment typically represent diastems; hiatuses occur mostly during periods of terrigenous sedimentation that separate spurts of more rapid and continuous carbonate deposition (Wilson and Jordan, 1983). Numerous, brief episodes of non-deposition could account for the overall low sedimentation rate of the Eli Limestone; no discrete erosional surfaces were found in the sections examined.

In summary, sedimentologic and paleontologic evidence suggest that the lower (Frasnian) part of the Eli Limestone was deposited in a somewhat restricted inner shelf setting, whereas the upper (Famennian) part of the section accumulated in a more open middle shelf environment. Argillaceous material occurs throughout the formation but is more abundant in the lower beds; grainstone shoals are developed primarily in the upper part of the unit. No major erosional surfaces were observed within the Eli Limestone, but numerous diastems may occur throughout the section.

UTUKOK FORMATION

The Utukok Formation in the Maiyumerak Mountains consists of gray to brown limestone, sandy limestone, quartzose to calcareous sandstone, and subordinate siltstone and shale; it is at least 180 m thick and exposed in a series of resistant limestone and sandstone ridges separated by recessive intervals of siltstone and shale. Dolomite and chert occur only locally in carbonate rocks of this unit, and constitute less than 15 percent of most samples studied. Like the Eli Limestone, the Utukok Formation is variably recrystallized within the study area; our analyses concentrated on sections with relatively well-preserved original textures. The unit was most closely studied in a measured section along the ridgetop due south of the type section of the Eli Limestone (Locality I, Fig. 2), and in several other ridgetop sections to the north and south (Localities J and K, Fig. 2). The contact with the underlying Eli Limestone is drawn at the base of the lowest calcarenite bed; the upper contact with the Kogruk Formation is placed at the top of the highest interval of siltstone and shale.

Lithologies

Siliciclastic rocks, mostly fine-grained sandstone, lesser siltstone, and minor shale, make up about two-fifths of the Utukok Formation in the Maiyumerak Mountains and increase in abundance upward within the section (Fig. 17). The clastic rocks are plane- to cross-laminated and range from relatively pure quartz arenite to quartzose calcarenite; they are interbedded with skeletal lime grainstone, packstone, and wackestone that contain little siliciclastic material. No completely satisfactory nomenclatural scheme has yet been proposed for mixed calcareous-quartz sediments (Zuffa, 1980; Mount, 1984). In the descriptions below, quartz arenite is used to describe sandstone that contains more than 80 percent quartz (not including chert) and grainstone is used for rocks that consist mostly of carbonate clasts and include less than 10 percent noncarbonate detrital grains. Sandstone of intermediate composition is called calcarenite.

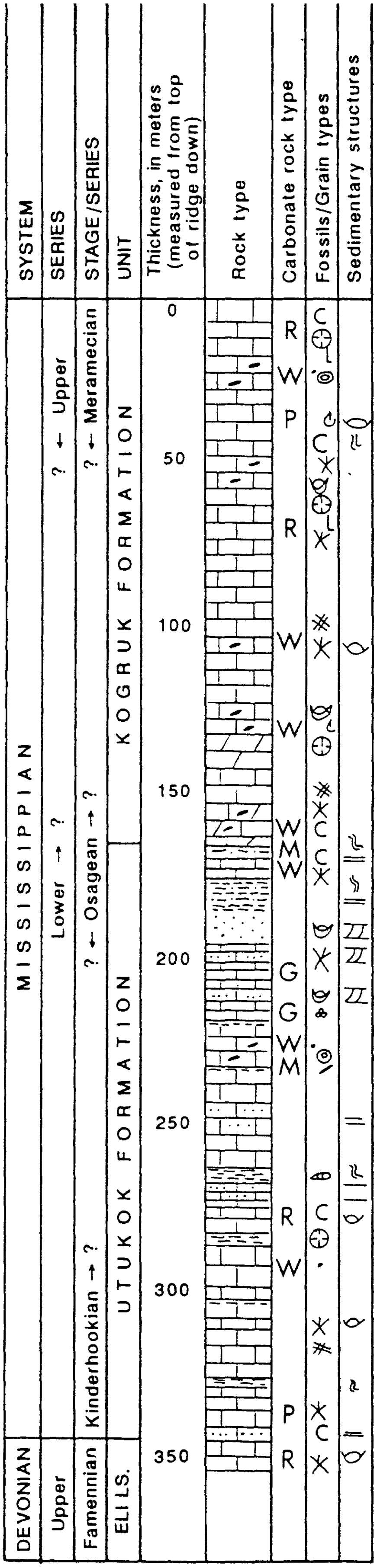


Figure 17. Generalized section, Utukok and Kogruk Formations, based on measured sections at localities I and J, Fig. 2.

Siliciclastic Rocks

Quartz Arenite Relatively pure quartz arenite occurs in the upper part of the Utukok Formation, most notably about 20 m below the top of the unit in a distinctive, white-weathering horizon that is 10 m thick and can be traced along strike for at least 12 km. Within this horizon, quartz arenite is interbedded with subordinate quartzose calcarenite and brachiopod coquina. The quartz arenite forms even beds 4-30 cm thick that are plane- and cross-laminated; cross laminae are 1-5 cm thick.

A combination of textural immaturity and compositional maturity characterizes this lithology. Samples are fine- to very fine-grained, sorting is good, but grains are primarily subangular to subrounded (Fig. 18A). Silica cement has overgrown most grains but original grain outlines can still be seen because inclusions have been trapped at the boundary between detrital and authigenic quartz. Later pressure solution has produced local seriate grain contacts and wispy stylolites. A few samples (those richest in calcareous grains) contain patchy, locally poikilotopic calcite cement.

Quartz grains constitute 80-95 percent of the samples studied and are dominantly monocrystalline with straight to slightly undulose extinction. Other grains are mostly sedimentary lithic clasts and include chert, shale and mudstone, limestone, calcareous bioclasts such as crinoid fragments, dolomite rhombs, white mica, opaque grains, tourmaline, and zircon (Fig. 18A). The dolomite rhombs appear to be detrital and not authigenic, as shown by presence of rounded rhomb corners, equivalence of dolomite crystal size and sediment grain size, and a lack of replacement textural relations.

Quartzose Calcarenite Quartzose calcarenite occurs in intervals 10-25 m thick throughout the Utukok Formation. Beds are thin to medium (1-20 cm) and mostly even to slightly irregular; local beds are lenticular and have distinctly channeled bases. The sediment is plane- or cross-laminated fine- to very fine-grained sandstone and lesser siltstone; cross beds are low angle and form sets up to 5 cm thick. Local vertical burrows a few mm to a cm in diameter cut some sedimentary laminae. Differences in the amount of quartz and carbonate in these sediments are very evident in outcrop weathering profile and color: slightly calcareous quartz arenite is resistant and white to orange or pink, quartzose calcarenite is more recessive and tan to light brown, and calcarenite with subordinate quartz is distinctly recessive and light gray (Fig. 18B). Relatively quartz-rich sandstone and more calcareous sandstone are intercalated throughout the Utukok Formation on a scale ranging from several cm to tens of meters.

Carbonate grains make up 30-85 percent of most samples and are mostly bioclasts, peloids, calcareous lithic clasts, and dolomite rhombs. Bioclasts are chiefly echinoderm and lesser brachiopod fragments, but include ostracodes, foraminifers, and calcispheres; some bioclasts have well-developed micritic rims. Peloids are chiefly ovoid (less commonly spherical to irregular) in form, and 0.2 mm or less in maximum dimension. Micritic intraclasts as much as 3 mm in diameter have very irregular shapes and appear to have been deposited while still soft. Dolomite rhombs typically have iron-rich reddish-brown rims and clear centers, are the same size as associated quartz grains, and appear to be detrital as described above. Some patchy dolomite may be cement, but sparry calcite is the predominant cement in the calcarenite samples studied.

Monocrystalline quartz grains identical in size and shape to those in the quartz arenite comprise 30 to 70 percent of most quartzose calcarenite. Other noncarbonate grains consist chiefly of chert and lesser mudstone, tourmaline, and opaques.

Size sorting in these mixed carbonate-quartz sandstones is notably poorer than in the quartz arenites; for example, crinoid columnals to 2 mm occur within very fine grained quartz sand (Fig. 19A). This disparity probably does not indicate reduced current action but instead reflects the hydraulic

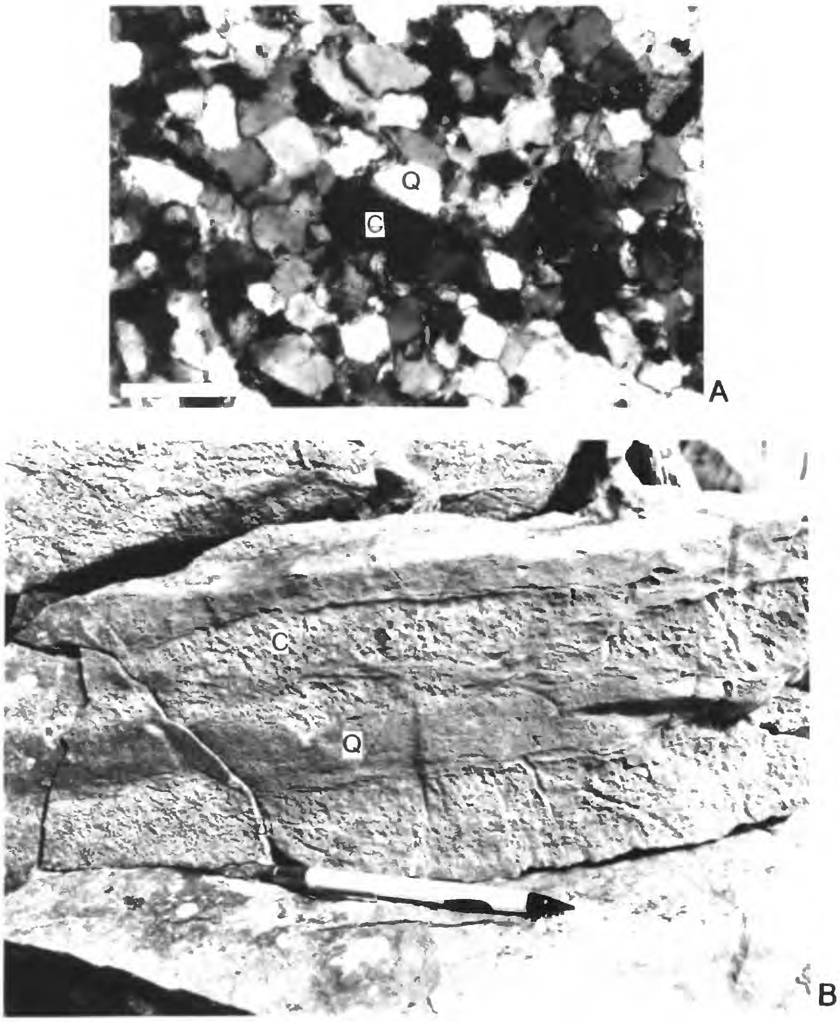
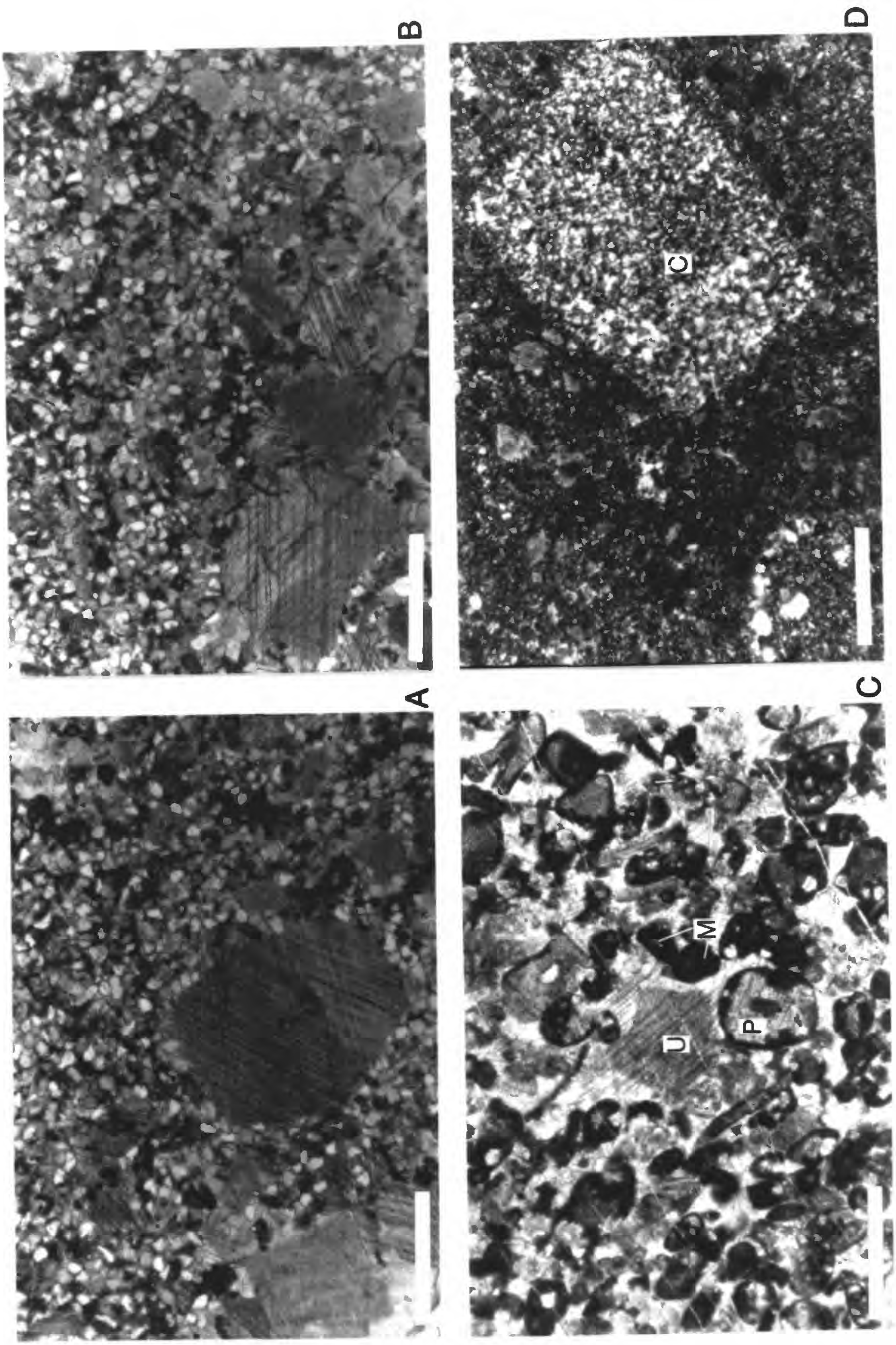


Figure 18. Sedimentary features of Utukok Formation. **A.** Photomicrograph (crossed nicols) of fine-grained quartz arenite, locality K, Fig. 2. Grains are subangular to subrounded and consist mostly of quartz (Q) and lesser chert (C). Scale bar is 0.5 mm. **B.** Interbedded quartzose calcarenite (Q) and less resistant calcarenite (C).

Figure 19. Photomicrographs of Utukok Formation. A and B are quartzose calcarenite, locality J, Fig. 2. Scale bar equals 1 mm in A, B, and C, 0.5 mm in D. **A.** Large echinoderm fragments float in finer grained matrix of quartz-peloid silt. **B.** Graded couplet of quartz-peloid silt and calcareous sand. **C.** Skeletal grainstone rich in foraminifers and echinoderm fragments; grains range from essentially unmicritized (U) to partially micritized (P) to completely micritized (M). **D.** Relict echinoderm fragments (C) in silicified bioclastic packstone.


A
B
C
D
C
M
U
P

equivalence of large porous bioclasts and smaller, denser siliciclastic grains. Locally, graded couplets 0.5-15 cm thick occur of dolomitic quartz-peloid silt and calcareous fine-grained sand (Fig. 19B).

Quartzose brachiopod coquina forms beds 10-20 cm thick intercalated with quartz arenite and quartzose calcarenite. Disarticulated brachiopod valves make up about 30 percent of this lithology and are uniformly oriented, concave side down, in a matrix of smaller bioclasts (principally echinoderm fragments, bryozoans, and ostracodes), quartz sand, and calcite cement. The development of shelter porosity (now filled with sparry calcite) and sediment-floored interstices within the coquina indicates (Dunham, 1962) that the shells, although relatively loosely packed, were deposited in grain support.

Siltstone and Shale Subordinate thin layers of siltstone and shale form intervals of platey rubble throughout the Utukok Formation. Siltstone weathers orange, yellow, or brown, is generally plane laminated, and consists mostly of quartz, carbonate grains, bioclasts (crinoids, ostracodes), and peloids. Intraclasts of shale and silty shale as much as 2 cm long and several mm thick occur locally and may be rimmed by calcite cement. Thin shale beds are generally calcareous and weather tan or, less commonly, red, gray, or green; they contain rare gastropods and abundant horizontal trace fossils.

Skeletal Grainstone

Grainstone containing skeletal grains and lesser peloids occurs interbedded with calcarenite and with skeletal wackestone and packstone (described below). Beds are generally 3 to 15 cm thick and may be plane- or cross-laminated; bioclasts are mainly echinoderm debris and endothyrid foraminifers but also include fragments of algae, brachiopods, bryozoans, and corals (Fig. 19C). Many of the bioclasts are micritized, and in some samples a complete spectrum of micritization can be observed, ranging from well-preserved skeletal fragments, such as crinoid columnals with thin micritic rims, to completely micritized grains in which all internal fabric has been obliterated (Fig. 19C). These skeletal grainstones also contain 5-20 percent ovoid peloids (0.1-0.2 mm in diameter), rare calcareous intraclasts, as much as 5 percent quartz silt and fine sand, and sparry calcite cement.

Skeletal Wackestone/Packstone

Clean carbonate rocks that contain lime mud but little or no siliciclastic material comprise intervals a few to tens of m thick in the Utukok Formation, and are especially abundant in the lower half of the unit (Fig. 17). Bioclastic wackestone and packstone occur in thin to medium, even to slightly irregular beds (Fig. 20); locally, beds are nodular with argillaceous partings, similar to parts of the underlying Eli Limestone. Bed thickness is variable both vertically and horizontally, and most intervals appear strongly bioturbated. Bioclasts are mostly echinoderm and lesser brachiopod and coral fragments. A few samples in the middle part of the section consist mostly of lime mudstone, locally pelleted, with disseminated calcareous sponge spicules and calcispheres. Clean carbonate rocks in the Utukok Formation contain as much as 20 percent black chert in nodules and layers 3-5 cm thick; in addition, skeletal material, particularly solitary corals, may be partly to completely silicified.

Depositional textures of some carbonate rocks in the Utukok Formation have been obscured by recrystallization and (or) silicification, but enough original fabric remains in most of these rocks to suggest a bioclastic wackestone or packstone protolith. Recrystallized limestone generally consists of skeletal fragments (mostly crinoid columnals) in a sparry calcite "matrix"; the original presence of carbonate mud in most of these samples is indicated by seams and patches of relict lime micrite or of saccharoidal dolomite (interpreted as a replacement of carbonate mud). Most partly or completely silicified intervals in the Utukok Formation also locally preserve a bioclastic wackestone/packstone texture (Fig. 19D).

Figure 20. Thin-bedded skeletal wackestone/packstone, Utukok Formation, Maiyumerak Mountains, locality J, Fig. 2.

Distribution

Nodular-bedded skeletal wackestone and packstone with normal marine faunas dominate the lower half of the Utukok Formation, and are locally interbedded with quartzose calcarenite. Calcarenite increases upsection, and becomes more quartzose; pure quartz arenite occurs largely in a 10-m-thick marker bed near the top of the unit. Clean carbonate rocks in the upper half of the formation are chiefly skeletal grainstone and subordinate, locally spiculitic, skeletal wackestone.

Age and Sedimentation Rate

The age of the Utukok Formation in the Maiyumerak Mountains is Kinderhookian through middle Osagean, based on conodont faunas collected from a measured section at locality I (Fig. 2). A fauna of robust polygnathids diagnostic of Kinderhookian age occurs in calcarenite at the base of the section (USGS colln. 29412-PC). Sixty meters higher, echinoderm-bearing crystalline limestone (probably recrystallized skeletal wackestone or packstone) contains robust polygnathids, *P. communis,* and a poorly preserved bispathodid that indicate an Early Mississippian, probably Kinderhookian, age. Skeletal wackestone 3 m below the top of the section yields abundant and diverse conodonts, including *Polygnathus communis communis*, *Gnathodus typicus*, *Pseudopolygnathus multistriatus*, and *Ps. nudis*; this fauna indicates a middle Osagean age (USGS colln. 29383-PC).

A single sample from the middle part of the Utukok Formation at locality L (Fig. 2), 6 km NE of the measured section, also contained conodonts. Fine-grained, locally dolomitic, spicule- and calcisphere-bearing wackestone produced abundant elements of *Hindeodus* cf. *H. crassidentatus* and *Bispathodus stabilis* that denote a late Kinderhookian through Osagean age.

Foraminifers and a variety of megafossils, as noted above, also occur in the Utukok sections studied. These faunas have not been examined in sufficient detail to provide additional information on the age of the Utukok Formation in the Maiyumerak Mountains.

A sedimentation rate of about 0.01 m/1000 years is calculated for the Utukok Formation in the study area, assuming a thickness of 180 m and an absolute time span of 14 m.y. for the Kinderhookian through middle Osagean (Haq and van Eysinga, 1987). This rate is equivalent to that determined for the Eli Limestone, and somewhat lower than those reported by Wilson (1975) as typical of ancient platform carbonate sequences.

Depositional Environment

The Utukok Formation accumulated in a moderate- to high-energy middle to inner shelf setting; terrigenous input, largely fine-grained quartz sand, was episodic but persistent. Open circulation and normal marine salinity predominated during deposition of the lower and upper thirds of the unit, but a somewhat more restricted, and perhaps shallower, depositional environment is indicated for the middle part of the formation.

The lower third of the Utukok Formation, like the upper Eli Limestone, consists largely of skeletal wackestone and packstone in sequences characterized by variable bed thickness, nodular bed form, bioturbation, argillaceous partings, and a predominantly normal marine fauna, and probably formed in a middle shelf setting. Most of the section contains abundant carbonate mud and was deposited below wave base, but intervals of skeletal grainstone accumulated near or above wave base in local shoals. Terrigenous material in the lower Utukok Formation occurs largely as discrete argillaceous layers separating beds of skeletal wackestone, and as subordinate quartz sand disseminated in local intervals of skeletal grainstone and calcarenite.

The upper two-thirds of the Utukok Formation contains less skeletal wackestone and packstone and more skeletal grainstone and quartzose calcarenite than the lower part of the unit. Local peloidal wackestone in the middle part of the formation contains a fauna limited to calcispheres and sponge spicules, which suggests somewhat restricted circulation. Skeletal wackestone in the uppermost part of the formation, however, contains a normal marine fauna dominated by echinoderms.

Skeletal grainstone, quartzose calcarenite, and quartz arenite in the Utukok Formation appear to have formed in two major settings. Individual beds or thin sequences of well-washed calcareous and (or) quartz sand within thick intervals of bioclastic wackestone and packstone may have been deposited by storm-generated currents; graded couplets of calcareous sandstone and quartz siltstone in the Utukok Formation are similar in many respects to limestone-quartzite couplets in Morocco that have been interpreted as storm deposits (Kelling and Mullin, 1975). Thicker intervals of sandstone probably formed in local shoals, but the shape and orientation of these shoals is uncertain. The dimensions of the conspicuous quartz arenite horizon near the top of the formation are comparable to those of modern and ancient tidal-bar and marine sand belts (Halley and others, 1983), but the orientation of the Utukok sand body relative to the paleoshoreline is unknown. No indication has been found that any of the Utukok sand shoals were emergent; features characteristic of intertidal or supratidal facies are absent throughout the formation.

The various quartzose calcarenites in the Utukok Formation are hybrid arenites in the terminology of Zuffa (1980); they contain both carbonate and noncarbonate framework grains. Carbonate grains appear to be largely of "intrabasinal" origin, and consist chiefly of bioclasts and peloids. Other calcareous clasts are rare; most appear to be intraclasts, as they have a rounded, irregular shape suggesting they were deposited while only partly lithified. No features definitive of "extrabasinal" origin, such as reworked older fossils or recrystallized veins, were observed in any of the carbonate clasts. Bioclasts are predominantly normal marine forms, such as echinoderms and brachiopods, but locally (particularly in the middle part of the section) they include fauna more tolerant of restricted circulation, such as foraminifers, gastropods, and ostracodes. Many of the skeletal grains have been extensively micritized, a process that is most common in the photic zone where it is mediated by algae. The major extrabasinal constituents of Utukok sandstones are quartz and lesser chert and mudstone; as noted above, at least some dolomite grains appear to be detrital and could also have had an extrabasinal source.

Hybrid arenites are not as uncommon in shallow shelf settings as was once thought, and a number of mechanisms have been proposed to account for their formation (Mount, 1984; Doyle and Roberts, 1988). Two of the processes described by Mount (1984) appear to have operated during deposition of the Utukok Formation. On a small scale, punctuated mixing (transfer of sediments by sporadic storms) may account for introduction of quartz sand into the predominantly calcareous Utukok environment. But in a broader sense, the Utukok Formation appears to represent facies mixing between adjacent nearshore siliciclastic and carbonate environments. Such facies mixing occurs, for example, where longshore transport contributes quartzose detritus from continental or island sources (Halley and others, 1983; Flood and Orme, 1988) or where siliciclastic deltaic systems cross broad carbonate shelves (Wilson, 1975; Pilkey and others, 1988). The Utukok Formation may have formed where deltaic sediments (Endicott Group) met platform carbonate rocks (Lisburne Group); this idea, as well as sources and significance of siliciclastic material in the Utukok Formation, are discussed below.

The timing of siliciclastic input into the Utukok Formation may reflect, at least in part, eustatic changes. Many authors (e.g., Davies and others, 1989; Read, 1989; Sarg, 1988) have documented deposition of quartz sands across shallow-water carbonate platforms and shelves during times of sea level fall. Recently published eustatic curves for the late Paleozoic (Ross and Ross, 1988) indicate generally rising long-term sea level throughout the Early Mississippian, punctuated by several short-term falls in the Osagean. Quartz sand is most abundant in the upper (Osagean) part of the Utukok Formation, but paleontologic control in these strata is not precise enough to postulate correlation of individual sand layers with specific global sea level events.

Conodont faunas from the Utukok Formation support the conclusion that most of the section accumulated in normal marine, moderate energy conditions in water of shallow to moderate depth. Faunas from the lower third of the unit are typical of relatively shallow-water, moderate-energy environments. A fauna representative of the hindeodid biofacies of Sandberg and Gutschick (1984), which indicates a shallow-water, possibly restricted depositional environment, was collected from peloidal wackestone in the middle of the section. The uppermost beds of the formation yield conodonts characteristic of a normal-marine, outer platform or shelf setting (Sandberg and Gutschick, 1984).

The Utukok Formation thus appears to have been deposited in a middle to inner shelf environment characterized by generally normal marine salinity and moderate energy and water depths; some faunal evidence for restricted circulation is noted about the middle of the section. Calcareous and (or) quartz sandstone formed in local shoals and was introduced into muddier environments by storms; sandy lithologies and quartz are most abundant in the upper (Osagean) part of the formation. No paleontological evidence of hiatuses and no physical evidence of exposure and (or) erosional surfaces have been found within the Utukok Formation, but the low sedimentation rate, like that in the underlying Eli Formation, suggests diastems occur within the section.

KOGRUK FORMATION

The Kogruk Formation in the Maiyumerak Mountains consists of light- to medium-gray-weathering, medium- to dark-gray, fine- to coarse-grained limestone and dolostone. Chert, black or less commonly gray or white, forms layers or nodules a few cm thick that constitute 10-50 percent of most sections; the amount of chert varies markedly both laterally and vertically. The unit typically crops out in terraced hillsides made up of resistant low cliffs of skeletal grainstone or packstone and less resistant rubbly intervals of wackestone or mudstone. The top of the Kogruk Formation in the Maiyumerak Mountains is an erosional surface; the lower contact is gradational into the underlying Utukok Formation and is placed above the highest bed of sandstone or shale more than 1 m thick. At locality I (Fig. 2) in the central part of the study area, the Kogruk Formation is 163 m thick; further north, more than 300 m of section may be exposed (Karl and others, 1989). Our studies concentrated on the measured section at locality I, another section 6 km north (locality M), and the spiculitic limestone belt north of Kivivik Creek (localities N and O).

Lithologies

Recrystallization, dolomitization, and silicification have locally obscured original texture and composition of the Kogruk Formation, but three major lithologies can be recognized. Skeletal wackestone, typically dolomitic and (or) cherty and rich in echinoderms and bryozoans, makes up most of the unit, and is intercalated with subordinate intervals of echinoderm-bearing crystalline limestone (Fig. 17). A third lithology, spiculitic limestone, has been found only in the uppermost part of the Kogruk Formation in the structurally complex area north of Kivivik Creek (Figs. 1, 2). These spiculitic rocks are similar to rocks assigned to the Tupik Formation (Sable and Dutro, 1961) in the Misheguk Mountain quadrangle.

Skeletal Wackestone

Bioclastic limestone relatively rich in lime mud and partly dolomitized and (or) silicified makes up most of the Kogruk Formation (Fig. 21). These rocks are dark gray, weather light to medium gray, and may have shaley partings. Most beds are wavy, irregular, or nodular; thickness varies but is generally 5-30 cm. Many beds are mottled and appear thoroughly bioturbated. Wackestone texture predominates, but packstone and mudstone occur locally. Peloids, generally ovoid and less than 200 μm in diameter, are locally abundant (20-30 percent) but everywhere subordinate to skeletal grains.

Bioclasts in most intervals consist primarily of echinoderm debris (crinoid columnals) but include notable bryozoan fragments as well as brachiopods and ostracodes (Fig. 22A). Large bryozoan fronds and articulated crinoid stems occur on some bedding planes. Foraminifers, calcareous algae, and calcispheres are locally common, particularly in peloid-rich intervals (Fig. 22B). Corals, chiefly lithostrotionids, occur sporadically in this lithology and may be as much several tens of cm across, but biostromal accumulations have not been recognized. Corals are most abundant in skeletal packstone interbedded with echinoderm-bearing crystalline limestone described below.

Much of the muddy matrix of this lithology has been altered to fine-grained, saccharoidal dolomite, but only rare, disseminated dolomite rhombs occur within bioclasts. Scattered quartz silt (a few percent) occurs locally. Black to gray chert, in lenses, nodules, and irregular masses a few to several tens of cm thick and 0.3 to more than 5 m long, constitutes 10-20 percent (rarely, 40 percent) of this lithology. Some discontinuous and irregular chert blebs appear to follow burrows (Fig. 23A).

Echinoderm-bearing Crystalline Limestone

Crystalline limestone forms intervals a few to tens of meters thick in the Kogruk Formation. In contrast to the rocks just described, this lithology is slightly lighter colored and contains little or no dolomite or chert. Beds are variable in thickness and somewhat irregular in form; most are 3-40 cm thick and slightly nodular. Most samples consist of coarse-grained sparry limestone in which abundant echinoderm fragments can be recognized; some samples also contain foraminifers and fragments of corals and bryozoans. Bioclasts are typically partly or completely micritized. These rocks are similar to crystalline limestone in the Eli Limestone, and are interpreted as recrystallized skeletal grainstone.

Spiculitic Limestone

Spiculitic limestone makes up most of the upper part of the Kogruk Formation north of Kivivik Creek. A pink or reddish weathering tint, a dark gray to black fresh surface, and rhythmic bedding are characteristic of these rocks and distinguish them from other Kogruk lithologies. Beds are generally thin (0.5-6 cm), regular, internally laminated, and separated by shaley partings (Fig. 23B). Chert content is variable but reaches 50 percent in some outcrops; it generally occurs as even layers a few cm thick that are more regular in shape, consistent in thickness, and persistent laterally than chert elsewhere in the Kogruk Formation.

Most rocks are fine-grained packstone or lesser wackestone and are made up chiefly of calcareous and siliceous sponge spicules and subordinate peloids and other bioclasts (Fig. 24). The original composition of spicules in these samples is uncertain, as siliceous and calcareous spicules are readily replaced by calcite and silica, respectively (Horowitz and Potter, 1971). Some spicules exhibit an internal canal in cross section; most appear to consist of a single ray. Peloids are small (40-100 μm); other bioclasts include poorly preserved radiolarians?, echinoderm debris, and calcispheres.

Figure 21. Black chert nodules in bioclastic limestone, Kogruk Formation, Maiyumerak Mountains, locality I, Fig. 2.

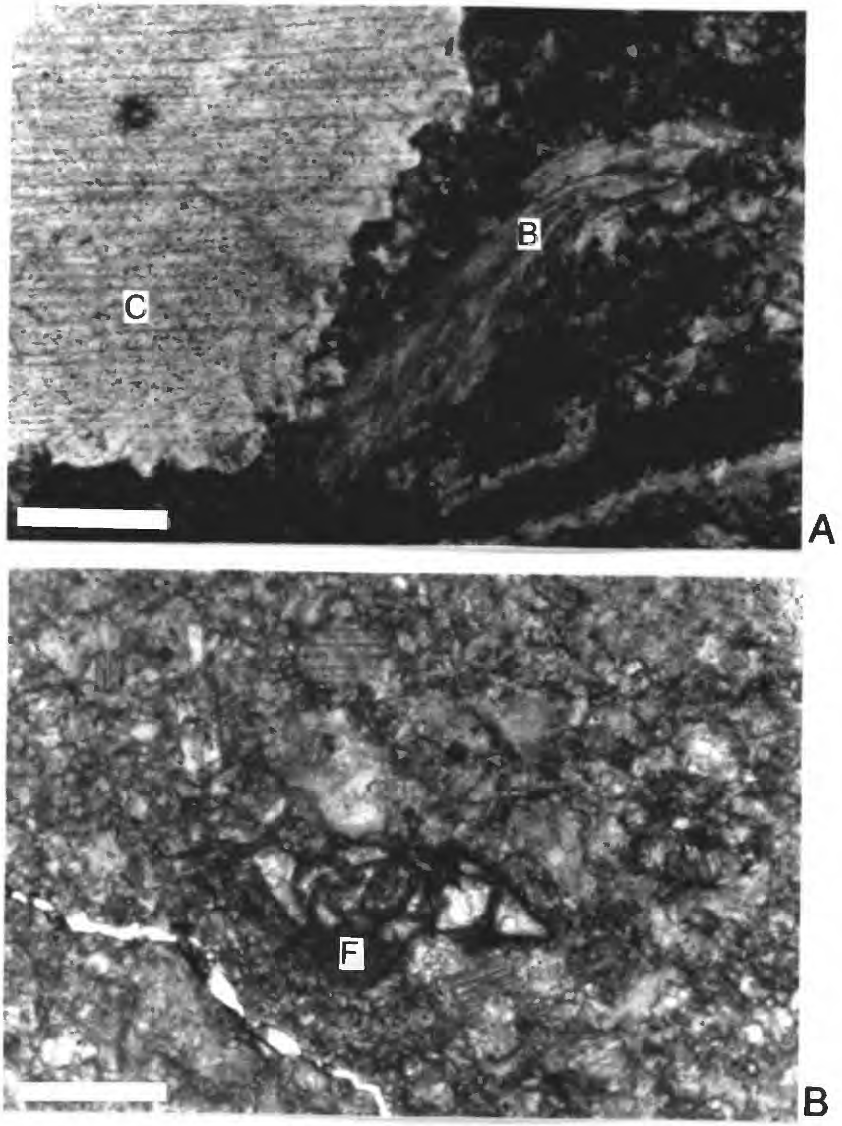
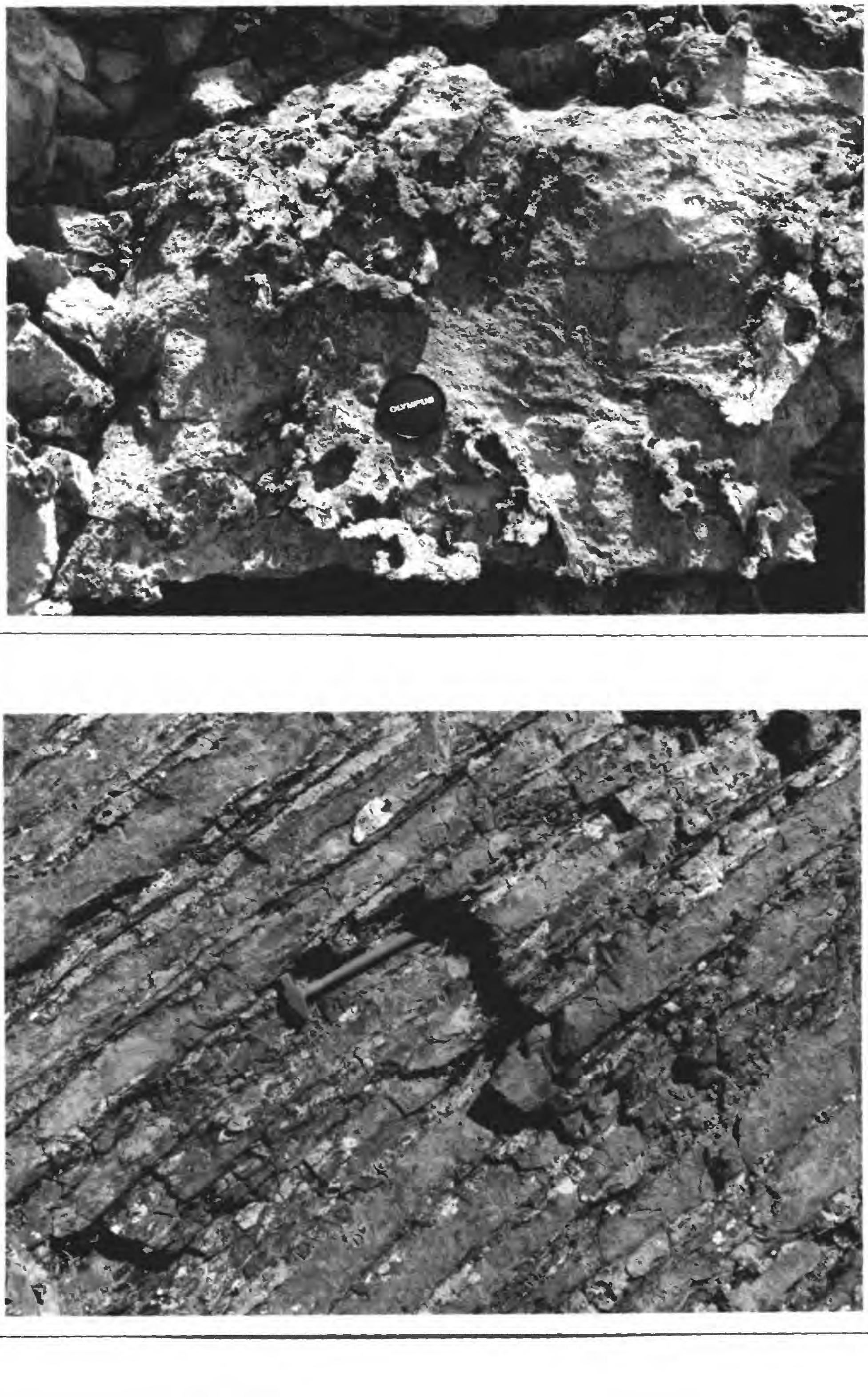


Figure 22. Photomicrographs of skeletal wackestone, Kogruk Formation; scale bars equal 0.5 mm. **A.** Echinoderm fragment (C) and bryozoa (B), locality I, Fig. 2. **B.** Foraminifer (F), locality M, Fig. 2.



A

B

Figure 23. Sedimentary features, Kogruk Formation, Maiyumerak Mountains. **A**. Irregular chert blebs that may be silicified burrows. **B**. Rhythmically interbedded shale and spiculitic limestone, locality O, Fig. 2.

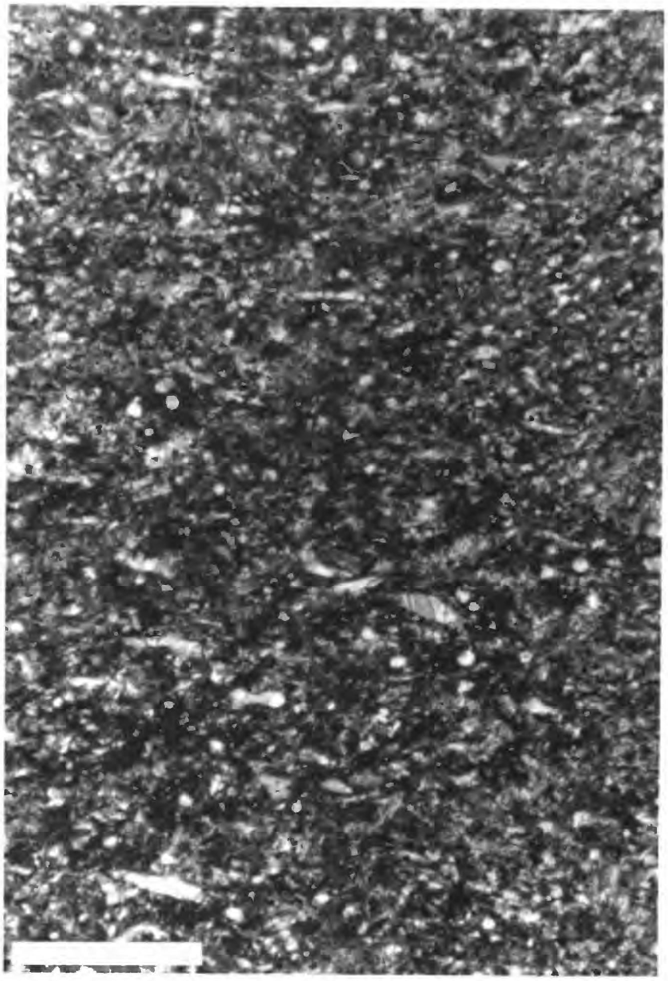


Figure 24. Photomicrograph of spiculitic limestone, Kogruk Formation, locality N, Fig. 2. Scale bar is 0.5 mm.

Laminae range from less than a mm to one cm thick and are produced by changes in composition and (or) size of included grains; individual laminae may consist of limestone, dolomitic limestone, partly silicified limestone, or chert. Many laminae contain alternations of siliceous spicules and calcareous spicules or peloids; some laminae are clearly graded. Dolomite occurs mostly as disseminated rhombs less than 100 µm in diameter and makes up no more than 10-15 percent of most samples.

Distribution

Bryozoan-echinoderm wackestone makes up most of the Kogruk Formation in the Maiyumerak Mountains. Peloidal wackestone containing foraminifers and calcispheres occurs locally, most notably in the middle third of the section. Intervals of crystalline limestone occur throughout the unit but appear to be most common in the middle part. Spiculitic limestone was found only in the upper 50 m of the formation in the northern part of the study area, and contains local beds of bryozoan-echinoderm wackestone.

Age and Sedimentation Rate

The Kogruk Formation in the Maiyumerak Mountains is no older than middle Osagean and is at least as young as Meramecian. Conodont faunas were obtained from a measured section at locality I (Fig. 2) and from spot samples further north. A sample of echinoderm-bryozoan wackestone from the base of the measured section contains abundant *Eotaphrus burlingtonensis* (USGS colln. 29411-PC) and is of middle Osagean to earliest Meramecian age; a sample of crystalline limestone 160 m higher in the section contains *Mestognathus* aff. *M. beckmanni* and *Hindeodus scitulus* (USGS colln. 29381-PC) indicating a latest Osagean-Meramecian age. Additional samples were collected 6 km north at locality M (Fig. 2). Here, crinoidal wackestone about 150 m above the base of the section contained cavusganthids (USGS colln. 29972-PC) of latest Osagean or younger Mississippian age, and foraminiferal wackestone taken about 100 m higher yielded only *Hindeodus scitulus* (USGS colln. 29973-PC) of late Osagean-earliest Chesterian age. Samples taken from uppermost beds of the Kogruk Formation still futher north yielded only sparse faunas. Skeletal wackestone from locality P (Fig. 2) and spiculitic packstone from locality N yielded "*Ozarkodina*" sp. of late Famennian-Meramecian morphotype.

The age of the Kogruk Formation in the Maiyumerak Mountains is further constrained by megafossils. Lithostrotionid corals of Meramecian age (Tailleur and others, 1967; Armstrong, 1970a) occur throughout the upper two-thirds of the Kogruk Formation in the southern part of the study area; corals were not observed in the spiculitic limestone lithology north of Kivivik Creek. Orthotetid and productid brachiopods of probable Late Mississippian age occur in the uppermost beds of the Kogruk Formation south of the Eli River (locality Q, Fig. 2) (written commun., J. T. Dutro, Jr., 1981).

Thus, conodonts and megafossils indicate that the Kogruk Formation in the Maiyumerak Mountains is largely of Meramecian age, is no older than middle Osagean, and could be as young as Chesterian.

A sedimentation rate of 0.03 m/1000 years is estimated for the Kogruk Formation in the study area, assuming a thickness of 300 m and a duration of 12 m.y. for middle Osagean-Meramecian time (Haq and van Eysinga, 1987). This rate is at the low end of the range reported by Wilson (1975) as typical of neritic carbonate sequences.

Depositional Environment

Sedimentary structures, lithofacies, and biofacies of the Kogruk Formation in the Maiyumerak Mountains indicate that deposition took place primarily in an open-marine setting below wave base.

Grainstone shoals formed locally, and faunal evidence suggests sporadically restricted circulation. Spiculitic limestone in the uppermost part of the section appears to have formed in a somewhat deeper, sediment-starved environment and marks the drowning of the Maiyumerak carbonate platform.

Skeletal wackestone was deposited in relatively quiet environments of the inner to middle shelf (facies belts 5 and (or) 7 of Armstrong and Mamet, 1978). The presence of lime mud (now largely altered to saccharoidal dolomite), large bryozoan fronds, and articulated crinoids indicate that these deposits were little affected by currents and probably deposited below wave-base. This lithology contains a predominantly normal marine fauna, although some intervals rich in peloids include forms such as foraminifers and calcispheres that are more tolerant of restricted conditions.

Echinoderm-bearing crystalline limestone is interpreted as recrystallized skeletal grainstone deposited in local shoals. Bioclasts consist mainly of fragments of open-marine fauna that have been abraded and (or) micritized, consistent with a high-energy, shallow-water setting. Lithostrotionid corals are most abundant in packstone formed adjacent to these shoal deposits; this same relationship was documented by Armstrong (1970a) in his studies of the Kogruk Formation northwest of the Maiyumerak Mountains.

No evidence for the shallowest water environments of the inner shelf has been found in the Kogruk sections studied. Sedimentary structures characteristic of intertidal and supratidal settings, such as fenestral fabric, cryptalgal lamination, and mud cracks, have not been observed. Some elements of the conodont fauna (e.g., mestognthids and some cavusgnathids) are indicative of shallowest water, inner shelf environments and probably represent post-mortem transport into the Kogruk environment.

Spiculitic limestone in the upper part of the Kogruk Formation is interpreted as a deeper water deposit. Generalized carbonate facies models (e.g., Wilson, 1975) and previous studies of the Lisburne Group (Armstrong, 1970a; Armstrong and Mamet, 1978; Murchey and others, 1988) suggest that rocks rich in sponge spicules form in at least two distinct settings: shallow-water, restricted platforms and deeper water, outer shelf or basin environments. Spiculitic rocks deposited in shallow, restricted settings are typically muddy, pervasively dolomitized, and contain fenestral fabric; spiculitic rocks formed in deeper water tend to be grainier, contain radiolarians, and are associated with thin shale layers and bryozoan-echinoderm wackestone.

Spiculitic limestone in the Maiyumerak Mountains fits the deeper water profile; it does not contain tidal to shallow subtidal sedimentary structures, like those so well developed in the underlying Baird Group, or biota suggestive of restricted circulation, such as some hindeodid or mestognathid conodonts. The reddish-purple tint and thin, rhythmic bedding characteristic of this lithology are common features of slowly deposited sediments formed in deeper water settings (Wilson, 1975).

Conodont biofacies of the Kogruk Formation support the interpretation of depositional conditions outlined above. Bryozoan-echinoderm wackestone contains representatives of the eotaphrid and cavusgnathid biofacies, which indicate normal marine salinity and shallow to moderate water depths. However, peloidal wackestone containing foraminifers and calcispheres and some crystalline limestone yield conodonts of the hindeodid and mestognathid biofacies; these assemblages denote very shallow and possibly restricted depositional regimes (Sandburg and Gutschick, 1984). Environmentally diagnostic conodonts have not been obtained from spiculitic limestone.

Thus, most of the Kogruk Formation in the Maiyumerak Mountains was deposited in a middle to inner shelf setting with normal marine salinity. Conditions resulting in development of grainstone shoals and somewhat restricted circulation occurred locally, particularly during accumulation of the middle part of the section in the early or middle Meramecian. Spiculitic limestone in the uppermost part of the Kogruk Formation indicates that a deeper water environment prevailed by late Meramecian or early Chesterian time; this facies change coincides with a regional drowning of carbonate platforms that will be further discussed below.

SUMMARY OF THE MAIYUMERAK MOUNTAINS CARBONATE SEQUENCE

The sedimentary sequence that is exposed along the west side of the Maiyumerak Mountains consists of dominantly shallow-water carbonate rocks of Middle and Late Devonian and Early and Late Mississippian age. Diagnostic faunas from these rocks are mostly conodonts but include corals, stromatoporoids, and brachiopods, and are of Givetian, Frasnian, Famennian, Kinderhookian, Osagean, and Meramecian age; Eifelian (and older?) and Chesterian rocks may also be present. Any hiatus in this succession is less than a stage in duration.

The Maiyumerak sequence accumulated in a range of open middle shelf to more restricted inner shelf environments. Shallow-water conditions existed throughout deposition of the Baird Group in the Middle Devonian; sedimentary structures characteristic of intertidal and supratidal settings and faunas suggestive of restricted circulation are particularly well-developed in the uppermost (Givetian) beds. A transgression occurred in latest Givetian-early Frasnian time and resulted in deposition of the lower, more argillaceous part of the Eli Limestone; open circulation, moderate to shallow water, and periodic input of dominantly clay-sized clastic material persisted during formation of the upper (Famennian) part of this unit.

Relatively open, moderate- to shallow-water conditions also prevailed throughout deposition of the Utukok and Kogruk Formations in Kinderhookian, Osagean, and Meramecian time; well-washed skeletal grainstone (and arenite in the Utukok Formation) formed in local high-energy shoals. Siliciclastic detritus, largely fine-grained quartz and subordinate chert sand grains, occurs sporadically throughout the Utukok Formation and is most abundant in the upper (Osagean) part of the unit, but is exceedingly rare in the overlying Kogruk Formation. Possible sources of this siliciclastic input are discussed below. Spiculitic limestone in the uppermost (Meramecian-Chesterian?) part of the Kogruk Formation suggests an outer shelf to basinal setting; this is a deeper water depositional environment than that indicated for any other part of the Maiyumerak Mountains carbonate sequence, and marks the demise of the Maiyumerak carbonate platform.

Several recent models relate the development of specific constellations of carbonate facies to global sea-level changes, generally within the context of seismic stratigraphy (e.g., Sarg, 1988; Bond and others, 1989). The complex present-day tectonic setting of northwestern Alaska (foreland fold-and-thrust belt) and the virtual absence of seismic data from this region preclude direct application of these models to the Maiyumerak carbonate succession. However, possible eustatic influences on carbonate facies within the Maiyumerak succession can be noted and are summarized here.

The most recently published eustatic curves for the Paleozoic (Ross and Ross, 1988) indicate long-term sea level generally rose from the Middle Devonian through the Early Mississippian, then declined gradually through most of the rest of the Mississippian. Thus, the Baird Group was deposited during a period of relatively low sea level, the Eli Limestone and Utukok Formation during a time of generally rising sea level, and the Kogruk Formation during a period of overall sea level decline. Short-term pulses of eustatic change are superimposed on these long-term trends, however, and include several pronounced cycles of sea-level fall and rise in the Osagean and Meramecian.

In general, carbonate facies in the Maiyumerak sequence are consistent with this suggested eustatic curve. A short-term sea-level fall inferred for the early and middle Givetian correlates with the upper part of the Baird Group, which includes the shallowest depositional environments (supratidal and intertidal) that have been documented within the Maiyumerak sequence. Facies in the Eli Limestone and Utukok Formation, deposited during a period of generally rising sea level, indicate deeper water conditions. These units include abundant intervals of nodular to thin-bedded argillaceous limestone; such lithologies, rich in carbonate and (or) siliciclastic mud and relatively slowly deposited, are common on incipiently drowned platforms (Read, 1985) and have been described as "catch-up" carbonate systems by Sarg (1988). Particularly fast pulses of eustatic rise appear to have occurred during the Late Devonian (Kendall and Schlager, 1981) and would be expected to inhibit carbonate platform growth; carbonate production on the Maiyumerak platform may have been further suppressed by turbidity due to clastic input from the Endicott delta (discussed below).

Deposition of the upper part of the Utukok Formation and most of the Kogruk Formation coincide with a period of overall eustatic decline. Mixed carbonate and siliciclastic strata, notable in the upper part of the Utukok Formation, typically form during the early part of a global sea level fall (Sarg, 1988). The final inundation of the Maiyumerak platform appears to correlate with a short-term eustatic rise, but also reflects tectonic factors, such as the northward drift of Alaska (see below).

REGIONAL RELATIONSHIPS

The Maiyumerak Mountains lie within a fold and thrust belt that extends across northern Alaska, and are part of the De Long Mountains allochthon belt of Mayfield and others (1988) (Figs. 25, 26). These authors have proposed the most detailed paleogeographic and tectonic reconstruction presently available for northwestern Alaska. In their model, thrust sheets that contain similar lithologic sequences and occur at approximately the same structural level are grouped into structural units called allochthons. These allochthons, although structurally complex internally, are thought to overlie one another in a regionally consistent pattern of broad synclines parallel to the mountain front. Seven allochthons are formally named, sequentially numbered (allochthon 1 is structurally lowest), and considered to consist of fifteen sedimentary and two igneous sequences, which have also been formally named. As noted above, these sequences are not equivalent to seismic stratigraphic sequences, as defined by Mitchum (1977). Rather, the sedimentary sequences of Mayfield and others (1988, p. 146) are "distinctive column(s) of sedimentary rocks that have slightly different lithologic facies compared to coeval rocks of other sequences" that are found in other thrust sheets.

The Schwatka Mountains structural province to the south of the De Long Mountains allochthon belt (Fig. 26) consists of metasedimentary and metaigneous rocks thought by Mayfield and others (1988) to be autochthonous or parautochthonous relative to the allochthons of the De Long Mountains belt. Other workers (e.g., Mull and others, 1987; Till and others, 1988) have shown that these metamorphic rocks, like rocks of the allochthon belt, were folded and thrust during the Brooks Range orogeny and are thus not autochthonous, but the degree of displacement of the metamorphic rocks has not been established. In the following discussion, rocks of the Schwatka province are considered allochthonous, but recognition of two separate structural provinces (De Long Mountains and Schwatka Mountains) is maintained.

Carbonate rocks of the Maiyumerak Mountains are included by Mayfield and others (1988) in the Eli sequence of the Kelly River allochthon. Figure 26 shows the generalized regional extent of allochthons and sequences in northwestern Alaska as proposed by Mayfield and others (1988), and Figure 27 presents simplified stratigraphic columns for sedimentary sequences within the allochthons. Although the sequences include rocks of Devonian through Cretaceous age, only the Devonian-Pennsylvanian parts of the sequences are shown and will be considered in this report. In the discussion below, the sequences and allochthons of Mayfield and others (1988) are briefly defined, units of the Maiyumerak Mountains carbonate sequence are compared to correlative units in the allochthon belt and the Schwatka province, the position of the Maiyumerak sequence within the tectonostratigraphic

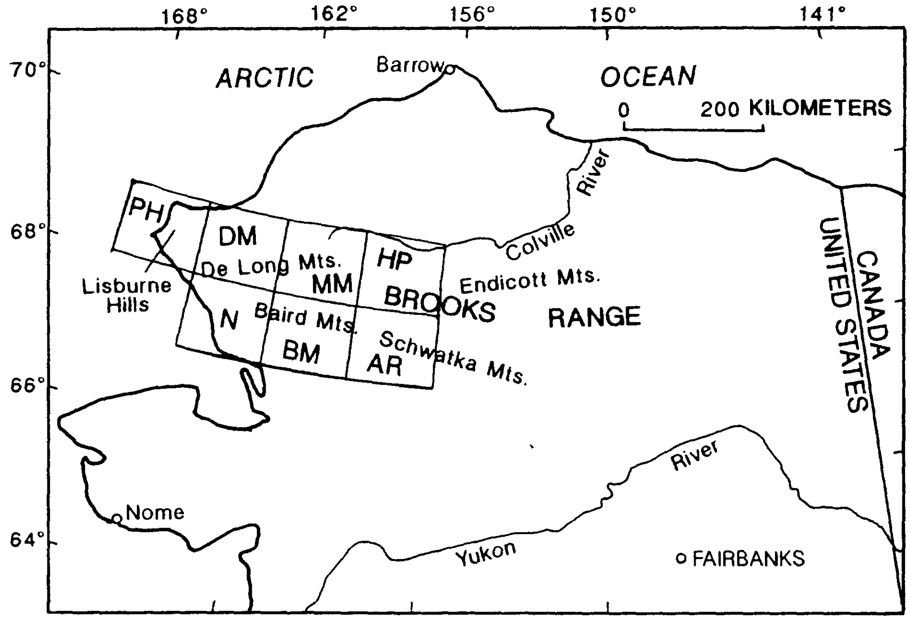


Figure 25. Central and northern Alaska, showing area of western Brooks Range discussed in this chapter. Letters identify 1:250,000 quadrangles outlined by dashed lines and referred to in text: PH, Point Hope; DM, De Long Mountains; MM, Misheguk Mountain; HP, Howard Pass; N, Noatak; BM, Baird Mountains; AR, Ambler River.

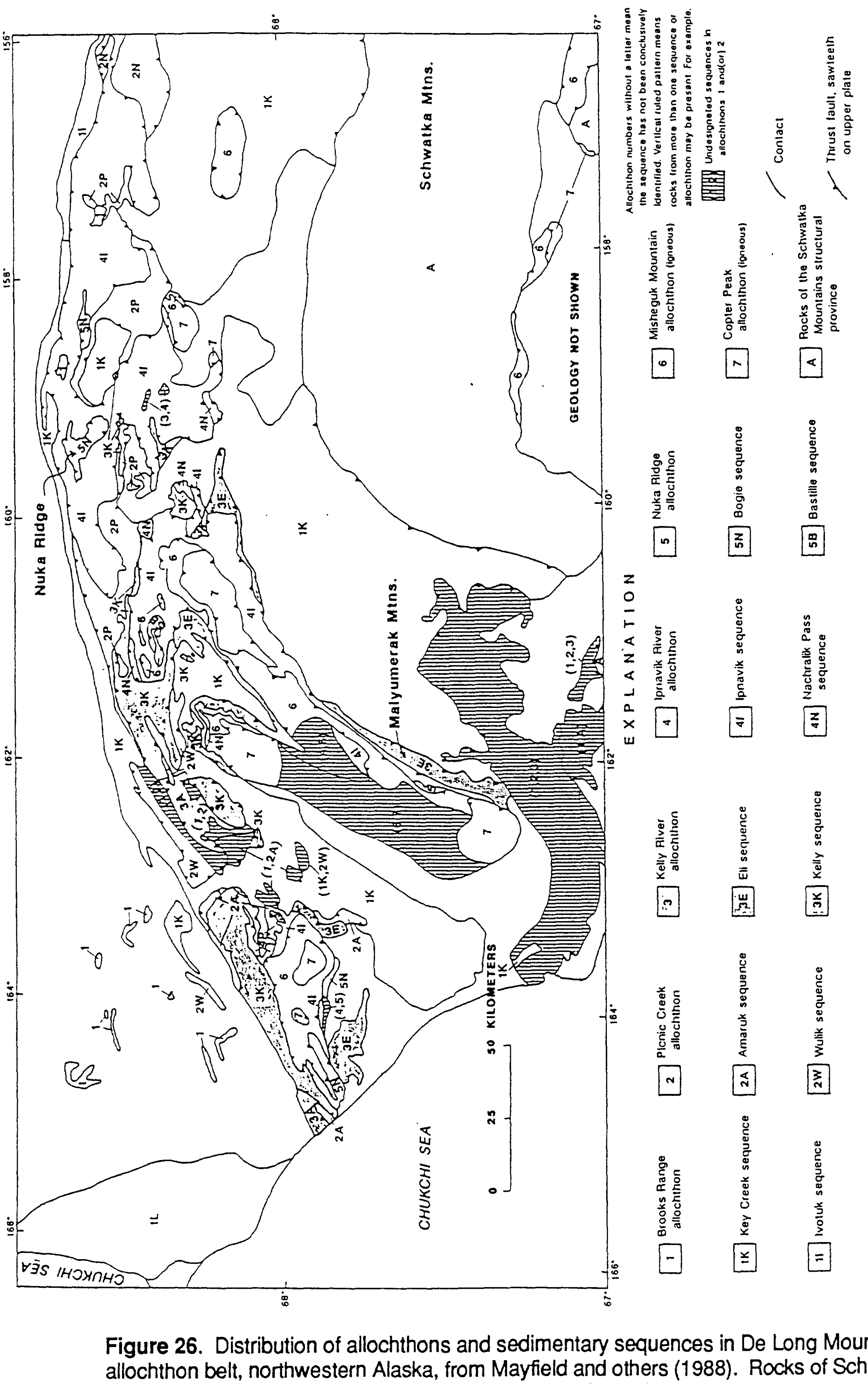
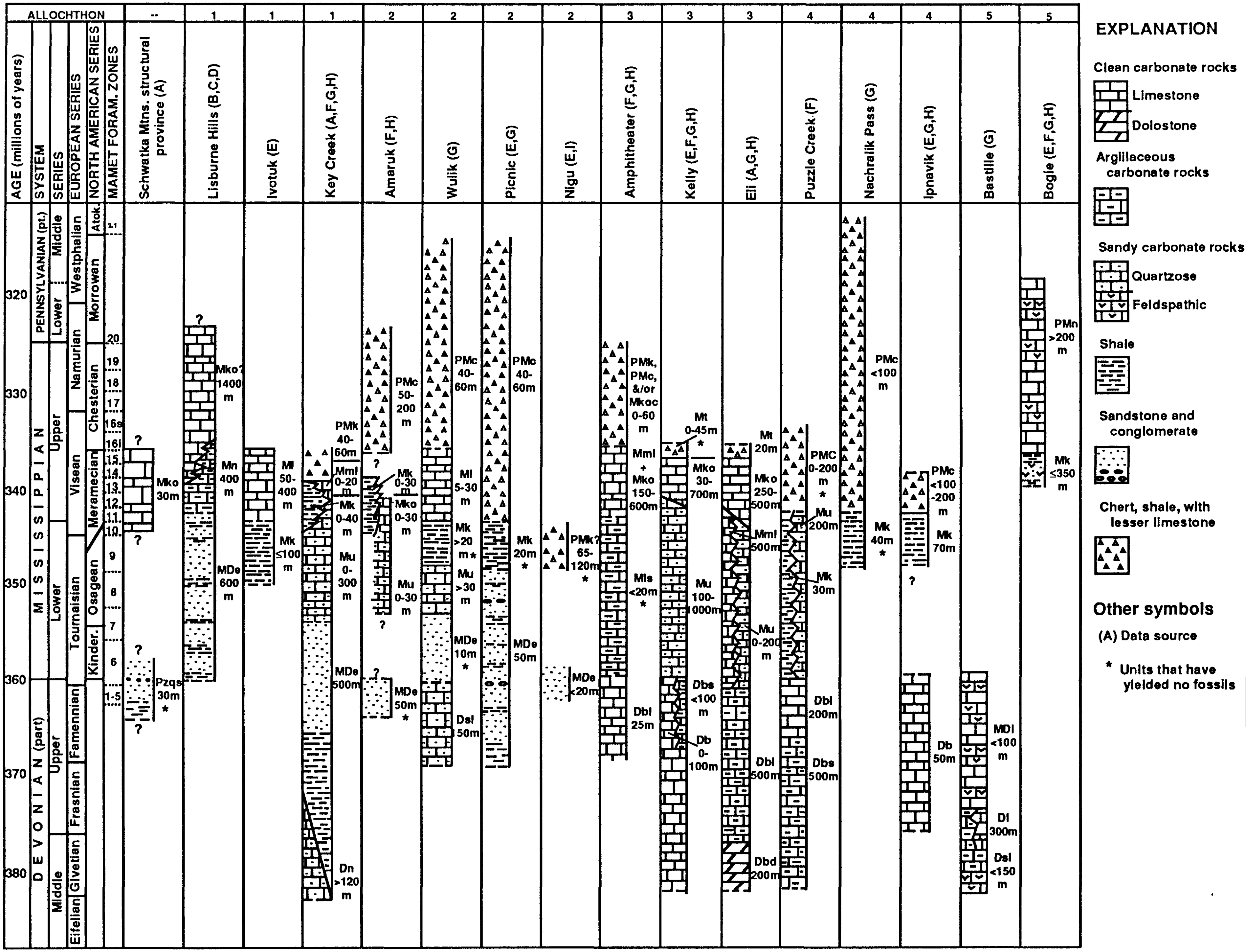


Figure 26. Distribution of allochthons and sedimentary sequences in De Long Mountains allochthon belt, northwestern Alaska, from Mayfield and others (1988). Rocks of Schwatka Mountains structural province occur in southeast quadrant of map.

Figure 27. Age, lithology, stratigraphy, and thickness of Devonian-Mississippian rocks in the western part of the Schwatka Mountains province (leftmost column) and in the sedimentary sequences of Mayfield and others (1988) in the De Long Mountains allochthon belt (all other columns). Numbers indicate allochthons of Mayfield and others (1988). Letters indicate data sources: A, Karl and others (1989); B, Armstrong (1970a, 1972) and Armstrong and others (1971); C, Campbell (1967); D, Dutro (1987); E, Mayfield and others (1988); F, Curtis and others (1983), Ellersieck and others (1983), and Mayfield and others (1983); G, Curtis and others (1984), Ellersieck and others (1984), and Mayfield and others (1984); H, Mayfield and others (1987); I, Holdsworth and Murchey (1988). Stratigraphic units: PMc, black chert, shale, limestone, and (or) dolostone; PMk, Kuna Formation; PMn, Nuka Formation; Mk, Kayak Shale; Mko, Kogruk Formation; Mkoc, cherty member of Kogruk Formation; Ml, Lisburne Group, undifferentiated; Mls, Lisburne Group, shale and micritic limestone; Mml, Lisburne Group, micritic limestone; Mn, Nasorak Formation; Mu, Utukok Formation; Mt, Tupik Formation; MDe, Endicott Group; MDl, limestone (in part equivalent to Kugururok Formation in Bastille sequence); Db, Baird Group, undifferentiated; Dbd, Baird Group, dolomite; Dbl, Baird Group, limestone (includes Eli Limestone in Eli sequence); Dbs, Baird Group, limestone and shale; Dl, limestone and dolomite (in part equivalent to Kugururok Formation in Bastille sequence); Dn, carbonate and clastic rocks of the Nakolik River; Dsl, sandstone, shale, and limestone (in part equivalent to Kugururok Formation in Bastille sequence); Pzqs, quartz metaconglomerate, metasandstone, and siliceous phyllite. Lithologic units that have yielded no fossils indicated by *; age estimates for these units based on age of similar units in adjacent sequences.



ALLOCHTHON
AGE (millions of years)
SYSTEM
SERIES
EUROPEAN SERIES
NORTH AMERICAN SERIES
MAMET FORAM. ZONES
PENNSYLVANIAN (pt.)
MISSISSIPPIAN
DEVONIAN (part)
Lower
Middle
Upper
Westphalian
Namurian
Visean
Tournaisian
Famennian
Frasnian
Givetian
Eifelian
Atok.
Morrowan
Chesterian
Meramecian
Osagean
Kinder.
Schwatka Mtns. structural province (A)
Lisburne Hills (B,C,D)
Ivotuk (E)
Key Creek (A,F,G,H)
Amaruk (F,H)
Wulik (G)
Picnic (E,G)
Nigu (E,I)
Amphitheater (F,G,H)
Kelly (E,F,G,H)
Eli (A,G,H)
Puzzle Creek (F)
Nachralik Pass (G)
Ipnavik (E,G,H)
Bastille (G)
Bogie (E,F,G,H)
Mko 30m
Pzqs 30m *
Mko? 1400 m
Mn 400 m
MDe 600 m
Ml 50-400 m
Mk ≤100 m
PMk 40-60m
Mml 0-20 m
Mk 0-40 m
Mu 0-300 m
MDe 500m
Dn >120 m
PMc 50-200 m
Mk 0-30 m
Mko 0-30 m
Mu 0-30 m
MDe 50m *
PMc 40-60m
Ml 5-30 m
Mk >20 m *
Mu >30 m
MDe 10m *
Dsl 50m
Mk 20m *
MDe 50m
PMk? 65-120m *
MDe <20m
PMk, PMc, &/or Mkoc 0-60 m
Mml + Mko 150-600m
Mls <20m *
Dbl 25m
Mt 0-45m *
Mko 30-700m
Mu 100-1000m
Dbs <100 m
Db 0-100m
Mt 20m
Mko 250-500m
Mml 500m
Mu 0-200 m
Dbl 500m
Dbd 200m
PMC 0-200 m *
Mu 200m
Mk 30m
Dbl 200m
Dbs 500m
PMc <100 m
Mk 40m *
PMc <100 -200 m
Mk 70m
Db 50m
MDl <100 m
Dl 300m
Dsl <150 m
PMn >200 m
Mk ≤350 m
EXPLANATION
Clean carbonate rocks
Limestone
Dolostone
Argillaceous carbonate rocks
Sandy carbonate rocks
Quartzose
Feldspathic
Shale
Sandstone and conglomerate
Chert, shale, with lesser limestone
Other symbols
(A) Data source
* Units that have yielded no fossils

framework of Mayfield and others (1988) is described, and the implications of the Maiyumerak sequence for paleogeographic reconstruction of the western Brooks Range are considered.

DEFINITIONS OF SEQUENCES AND ALLOCHTHONS

Each sedimentary sequence of Mayfield and others (1988) is characterized by a distinctive succession of Devonian-Cretaceous sedimentary rocks; the sequences are believed to have been deposited contiguously within a broad epicontinental basin. A few sequences are distinguished by a single unique lithostratigraphic unit, but most are differentiated on the basis of more subtle variations in coeval lithofacies or stratigraphic successions. Facies differences between sequences within the same allochthon are less pronounced than facies differences between sequences in different allochthons; overall, facies contrasts are greatest in rocks of Mississippian age.

The Brooks Range allochthon (1) is the most extensively exposed and structurally lowest of the allochthons. Sequences of this allochthon generally include a thick interval of Upper Devonian-Lower Mississippian clastic rocks (Endicott Group); three sequences (Ivotuk, Key Creek, and Lisburne Hills) are recognized (Figs. 26 and 27). The Picnic Creek allochthon (2) includes four sedimentary sequences (Amaruk, Nigu, Picnic, and Wulik); all contain notable bedded black chert of Late Mississippian age. The Kelly River allochthon (3) is exposed only in the western part of the De Long Mountains allochthon belt. Three sequences have been recognized (Amphitheater, Eli, and Kelly); all include thick intervals of Devonian-Mississippian carbonate rocks (Baird Group, Kogruk Formation) and lack Mississippian black shale (Kayak Shale). The Ipnavik River allochthon (4) contains three sequences (Ipnavik, Nachralik Pass, and Puzzle Creek) which are similar to those of allochthon 2 but distinguished by the presence of rare to common diabase sills. The Nuka Ridge allochthon (5) is structurally highest of the allochthons composed primarily of sedimentary rocks. Two sequences (Bastille and Bogie) are recognized and contain Devonian-Carboniferous arkosic limestone (Kugururok and Nuka Formations). The Copter Peak and Misheguk Mountain allochthons (6 and 7) consist of mafic igneous rocks.

Information on rocks of the allochthon belt is available primarily in a series of mile:inch geologic maps of parts of the Misheguk Mountain, De Long Mountains, and Noatak quadrangles (Curtis and others, 1983, 1984; Ellersieck and others, 1983, 1984; Mayfield and others, 1983, 1984, 1987); these maps include summaries of fossil collections and lithologic data. Unless otherwise stated, all data below on rocks of the allochthon belt north and west of the Baird Mountains quadrangle are taken from these maps. Endothyrid foraminifer zones referred to are those of Mamet and have been described in a number of publications (e.g., Mamet and Skipp, 1970; Armstrong and Mamet, 1977).

Metasedimentary rocks of the Schwatka structural province are treated as a single stratigraphic succession, the Schwatka sequence, by Mayfield and others (1988), but it is likely that several distinct sedimentary sequences exist within this poorly understood province (Dumoulin and Harris, 1987; Dillon and others, 1987). In the discussion below, remarks on stratigraphy of the Schwatka province refer chiefly to rocks in the westernmost part of this province (the northeastern Baird Mountains quadrangle), as relatively detailed stratigraphic and structural information (Dumoulin and Harris, 1987; Karl and others, 1989; Till and others, 1988) is available from this area.

CORRELATION

Baird Group

Rocks lithologically and biostratigraphically correlative with the Baird Group in the Maiyumerak Mountains occur both northwest and southeast of the study area within the De Long Mountains allochthon belt, but have not been found in the western Schwatka Mountains province. As discussed above, stratigraphic nomenclature of Devonian carbonate rocks in northwestern Alaska remains somewhat unsettled. The name Baird Group has been applied to a variety of carbonate rocks of Devonian and older age that occur in both the De Long Mountains and Schwatka Mountains structural provinces, but few formations or members have yet been delineated within this group. Baird Group rocks, however, show differences in internal stratigraphy and detailed sedimentology from one area and (or) structural package to another, and these differences may help constrain regional paleogeographic and tectonic reconstructions. In order to highlight this diversity, and to facilitate detailed comparisons with rocks of the Maiyumerak Mountains, specific Baird Group sequences will be treated separately below; mile:inch map unit designations and geographic references will be used as necessary to distinguish various sequences.

De Long Mountains Allochthon Belt

Rocks correlative with the Baird Group in the Maiyumerak Mountains occur in the Eli and Kelly sequences, exposed northwest of the Maiyumerak Mountains, and in a sequence of uncertain tectonic affinity that crops out through the central Baird Mountains quadrangle southeast of the Maiyumerak Mountains (Agashashok sequence of Ellersieck, 1985).

Northwestern Area Middle and (or) Upper Devonian carbonate rocks occur in all sequences of allochthon 3 and two sequences of allochthon 4 and have been assigned to the Baird Group by Mayfield and others (1988), but only the Eli and Kelly sequences of allochthon 3 contain clean carbonate rocks of probable Middle Devonian or older age. In these sequences, the base of the Baird Group is a thrust fault, and dominantly dolomitic Middle Devonian carbonate rocks are conformably overlain by locally argillaceous Upper Devonian carbonate rocks. In other sequences, rocks assigned to the Baird Group cannot, on the basis of presently available paleontologic evidence, be shown to be older than Late Devonian.

The Eli sequence in the Misheguk Mountain quadrangle contains carbonate rocks that, on the basis of published descriptions and fossil collections, are most like the Middle Devonian Baird Group in the Maiyumerak Mountains. These rocks are mapped as Db3e (Baird Group undivided) in most areas, but in the southeastern part of the quadrangle are subdivided into a lower unit, Dbd3e (dolomite), and an upper unit, Dbl3e (unnamed limestone and Eli (?) Formation) (Curtis and others, 1984). Dbd3e consists of 200 m or less of massive to thick-bedded, amphiporid-bearing dolostone, and contains corals and tentaculitids of Middle to Late Devonian age. This unit is exposed due north of the Maiyumerak Mountains along the east side of the Avan Hills, and is overlain by argillaceous carbonate rocks similar to the Eli Formation (see below). At least parts of Db3e undivided are also coeval with the Baird Group in the Maiyumerak Mountains; Middle Devonian corals occur in outcrops of Db3e along the west side of Misheguk Mountain.

The Kelly sequence in the Misheguk Mountain and De Long Mountains quadrangles also contains rocks assigned to the Baird Group that may correlate with the Middle Devonian carbonate rocks in the Maiyumerak Mountains. In the Misheguk Mountain quadrangle, map unit Db3 of Mayfield and others (1984) consists of about 100 m of medium- to thick-bedded limestone and dolostone. The lower part of this unit contains corals and stromatoporoids of probable Middle Devonian age as well as corals, stromatoporoids, and brachiopods of latest Silurian-Middle Devonian age. In the De Long Mountains quadrangle, map unit Dbl3 consists of medium- to coarse-grained limestone and is a maximum of 70 m thick; the lower part of this unit contains late Middle Devonian brachiopods as well as imprecisely dated Silurian-Devonian corals, stromatoporoids, and brachiopods (Curtis and others, 1983; Mayfield and others, 1983).

Southeastern Area Ordovician through Devonian carbonate rocks assigned to the Baird Group by Dumoulin and Harris (1987) and Karl and others (1989) are exposed through the central part of the Baird Mountains quadrangle (Fig. 26); no rocks of Mississippian or younger age are known in this area. Thus, referral of these rocks to one of the sequences of Mayfield and others (1988), which are distinguished primarily on the basis of Mississippian facies, is difficult. Affinities with sequences of allochthons 1, 2 or 3 have been suggested (Mayfield and others, 1988; Ellersieck, 1985) and the rocks have been designated by Ellersieck (1985) as the Agashashok sequence.

Devonian rocks occur mainly in the northern part of this outcrop belt and consist of dolostone, metalimestone, marble, and rare metasandstone. Where original textures are preserved, rocks are chiefly bioclastic grainstone to wackestone; stromatoporoids (primarily amphiporids) and corals form biostromes and bioherms a few to tens of meters thick (Dumoulin and Harris, 1987; Karl and others, 1989). Exposures in this area are rubbly and structure is complex; thus, total thickness and internal stratigraphy of the Devonian sequence is somewhat uncertain. However, a number of diagnostic fossil assemblages, chiefly conodonts, provide reasonable age control. Devonian rocks are a minimum of 60 m thick (probably at least several hundred meters thick) and are chiefly of Early Devonian (Emsian) age, but the uppermost part of the section is Middle Devonian. Definitively Eifelian conodont assemblages have been obtained from several localities, and at least two conodont collections may be Givetian (Dumoulin and Harris, unpublished data).

Schwatka Mountains Structural Province

Rocks further east in the Baird Mountains quadrangle are considered part of the Schwatka Mountains structural province by Mayfield and others (1988) and include carbonate rocks referred to the Baird Group by Tailleur and others (1967). Recent workers have questioned this assignment; for example, Karl and others (1989) include these rocks in a separate map unit, Devonian?, Silurian, and Ordovician carbonate rocks (DOc). DOc consists of dolostone and lesser metalimestone, and includes lithologies similar to those found to the west, such as coral-stromatoporoid packstone. None of DOc, however, is known to be as young as the oldest part of the Baird Group in the central Baird Mountains; no definitively Devonian faunas have been obtained, and less precisely dated, longer ranging faunas are no younger than Emsian.

Summary

Clean dolomitic carbonate rocks of Middle Devonian age in the Maiyumerak Mountains correlate best with rocks of allochthon 3 to the north and west, and perhaps with the uppermost part of the allochthonous carbonate rock sequence in the central Baird Mountains quadrangle. Our present state of knowledge suggests that carbonate rocks of the Schwatka province in the eastern Baird Mountains quadrangle are entirely older than the carbonate sequence of the Maiyumerak Mountains.

Eli Limestone

Carbonate rocks coeval with the Eli Limestone of the Maiyumerak Mountains are widely exposed through the De Long Mountains allochthon belt but have not been recognized in the western part of the Schwatka province (Baird Mountains quadrangle). Upper Devonian carbonate rocks occur in all of the allochthons and most of the sequences defined by Mayfield and others (1988) and are quite varied in composition. Only the Eli sequence of allochthon 3 contains argillaceous carbonate rocks specifically referred to the Eli Limestone, but the Kelly and Puzzle Creek sequences of allochthons 3 and 4 contain argillaceous carbonate rocks of Late Devonian age that may be correlative. In contrast, Upper Devonian carbonate rocks in the other sequences of allochthons 3 and 4 lack a significant terrigenous component, and coeval carbonate rocks in sequences of allochthons 1, 2, and 5 contain abundant sand-sized siliciclastic material.

De Long Mountains Allochthon Belt

Argillaceous Carbonate Rocks Exposures of Eli Limestone occur along a trend from the Maiyumerak Mountains in the Baird Mountains quadrangle southwest to the east side of the Noatak River lowlands in the Noatak quadrangle. In the Misheguk Mountain quadrangle to the north of the Maiyumerak Mountains, map unit Dbl3e of Curtis and others (1984) is a maximum of 500 m thick and "may be lithologically similar" to the Eli Limestone; it consists of thin-bedded limestone and minor shale overlain by massive light-gray limestone. The lower thin-bedded part of this unit contains corals and brachiopods of probable Middle Devonian (Givetian) age, foraminifers of Late Devonian (zone 2) age, and conodonts of Late Devonian to Early Mississippian age. The upper massive part of the unit contains foraminifers of latest Devonian to earliest Mississippian (zones 5-6) age.

Carbonate rocks that have not been referred to the Eli Limestone but are coeval and may be lithologically similar occur in the Kelly and Puzzle Creek sequences in the De Long Mountains quadrangle. Units Dbs3 (gray shale interbedded with flaggy to platy limestone) and Dbl3 (medium- to coarse-grained limestone) of Curtis and others (1983) occur in an uncertain stratigraphic relationship in the Kelly sequence; Dbs3 has not yielded fossils, but Dbl3 contains Famennian brachiopods, corals, and conodonts as well as late Middle Devonian brachiopods. Unit Dbs4 of Mayfield and others (1983) in the Puzzle Creek sequence consists of as much as 500 m of shale, limestone, and minor sandstone and contains conodonts of latest Early to Middle Devonian and Frasnian age; it is overlain by (and interfingers with?) as much as 200 m of massive to thin-bedded limestone that contains Famennian conodonts (unit Dbl4).

Clean Carbonate Rocks Carbonate rocks with no terrigenous component that are biostratigraphically correlative with the Eli Limestone occur in the Eli sequence in the Noatak quadrangle and in the Ipnavik sequence in the Misheguk Mountain and Noatak quadrangles. In the Eli sequence, Db3 (Mayfield and others, 1987) contains Devonian stromatoporoids and foraminifers of probable Frasnian age. In the Ipnavik sequence, Db4 (Ellersieck and others, 1984; Mayfield and others, 1987) contains brachiopods of possible Late Devonian age and foraminifers of probable Famennian age. Clean carbonate rocks that may be biostratigraphically correlative with the Eli Limestone based on regional relationships but that have not yet yielded fossils of definitively Late Devonian age include the upper part of Db3 (Kelly sequence) in the Misheguk Mountain quadrangle (Mayfield and others, 1984) and Dbl3 (Amphitheater sequence) in the De Long Mountains quadrangle (Curtis and others, 1983).

Sandy Carbonate Rocks Carbonate units coeval with the Eli Formation that contain a sand-sized siliciclastic component occur in the Key Creek sequence (allochthon 1) in the central Baird Mountains quadrangle, in the Wulik sequence (allochthon 2) in the southwestern Misheguk Mountain quadrangle, and in the Bastille sequence (allochthon 5) in the Baird Mountains and Misheguk Mountain quadrangles. In the central Baird Mountains quadrangle, the Key Creek sequence includes limestone of the Nakolik River (map unit Dnl of Karl and others, 1989), which consists of more than 120 m of interbedded metalimestone and subordinate metaclastic rocks. The metalimestone contains a locally abundant megafauna including corals, stromatoporoids, brachiopods, and crinoids. Metasandstone consists of 20-80 percent quartz, 10-80 percent calcareous lithic clasts and bioclasts, subordinate chert, argillaceous lithic clasts, and dolomite, and minor tourmaline and feldspar. Conodonts indicate an age of late Middle through early Late Devonian (Givetian through Frasnian) for this unit. In the Wulik sequence, map unit Dsl2 of Curtis and others (1984) consists of about 150 m of interbedded sandstone, shale, and limestone, and contains Famennian brachiopods and conodonts. Detailed petrographic analyses of the sandstone in this sequence are not available, but compositional similarity to sandstone of the Endicott Group is suggested by Curtis and others (1984).

The Kugururok Formation of the Bastille sequence also correlates with the Eli Limestone, but contains a more diverse clastic component than that of the units just described. In the Baird Mountains, the Kugururok Formation consists of as much as several hundred m of interbedded limestone, dolostone, and calcareous sandstone, siltstone and shale; it is Middle (probably late Middle) to Late Devonian in age, based on conodonts, brachiopods, and foraminifers (Karl and others, 1989). Sandstone composition is variable from bed to bed, but generally consists mostly of quartz, calcareous bioclasts, and sedimentary lithic clasts; feldspar (including potassium feldspar and microcline) and volcanic lithic clasts make up 5-20 percent of some samples (Dumoulin, unpublished data).

In the Misheguk Mountain quadrangle, rocks originally designated the Kugururok Formation by Sable and Dutro (1961) are included in map units Dsl5, Dl5, and MDl5 of Curtis and others (1984) and Ellersieck and others (1984). Dsl5 is equivalent to the lower part of the Kugururok Formation; it consists of 150 m or less of interbedded shale, limestone, calcareous siltstone, sandstone, and minor conglomerate and contains conodonts of Middle Devonian age. Dl5 and MDl5 interfinger laterally and are equivalent to the upper part of the Kugururok Formation. Dl5 is at least 300 m thick, consists of massive to thin-bedded limestone and dolostone, and contains Givetian brachiopods, corals and stromatoporoids and early or middle Late Devonian brachiopods. MDl5 is interbedded limestone and sandstone which may contain up to 15 percent potassium feldspar; it contains brachiopods and corals of Frasnian or older age and foraminifers of Famennian (zone 5) age.

Summary

Upper Devonian carbonate rocks are widely distributed in the De Long Mountains allochthon belt and are generally relatively impure. The coarsest noncarbonate detritus occurs in Upper Devonian carbonate rocks in the structurally highest and lowest sequences. Sandy limestone in the highest sequence (allochthon 5) contains quartz, feldspar, and volcanic and sedimentary lithic clasts; noncarbonate material in limestone of the lowest sequences (allochthons 1 and 2) is primarily quartz. Argillaceous carbonate rocks like the Eli Limestone in the Maiyumerak Mountains, as well as clean carbonate rocks lacking a significant terrigenous component, occur in sequences of intermediate structural level; purer carbonate rocks crop out mainly in the southwestern part of the allochthon belt (western Noatak quadrangle).

Utukok Formation

Impure carbonate rocks correlative with the Lower Mississippian Utukok Formation in the Maiyumerak Mountains occur in six of the fifteen sedimentary sequences in the De Long Mountains allochthon belt (Mayfield and others, 1988). Lower Mississippian rocks in most of the other sequences consist of a thin interval of black shale and subordinate limestone and sandstone, the Kayak Shale. Impure carbonate rocks or black shale of Early Mississippian age have not been recognized in western exposures of the Schwatka province (Baird Mountains quadrangle).

De Long Mountains Allochthon Belt

Impure Carbonate Rocks The Utukok Formation is widely exposed throughout the Misheguk Mountain, De Long Mountains and Noatak quadrangles in the western part of the De Long Mountains allochthon belt, but has not been recognized east of the western Howard Pass quadrangle. The formation occurs in sequences of allochthons 1 (Key Creek sequence), 2 (Amaruk and Wulik sequences), 3 (Eli and

Kelly sequences), and 4 (Puzzle Creek sequence), but it is thickest and most widely distributed in the Kelly sequence of allochthon 3. It is discontinuously present and less than 50 m thick in most sequences of allochthons 1 and 2, and is at most 200 m thick in allochthon 4. In contrast, thicknesses of 1000 m are reported for the Utukok Formation in the Kelly sequence, both at the type area in the Misheguk Mountain quadrangle (Sable and Dutro, 1961), and to the west in the De Long Mountains quadrangle (Mayfield and others, 1983). However, the unit appears to be less than 100 m thick in most of the Eli sequence and may be locally absent (Mayfield and others, 1988).

In addition to striking intersequence differences in thickness, the Utukok Formation displays notable vertical and lateral variations in clastic content. The unit includes more shale and less sand in structurally higher sequences and in the more westerly exposures of all sequences. For example, in the De Long Mountains quadrangle, estimates of shale content in the Utukok Formation range from 25 percent in the Key Creek sequence to 30-40 percent in the Amaruk sequence to 50 percent in parts of the Kelly sequence (Mayfield and others, 1983), and the Utukok Formation in all sequences in the De Long Mountains and Noatak quadrangles is shalier than in the Misheguk Mountain and Baird Mountain quadrangles. In contrast, interbeds of clean quartz sandstone in the Utukok Formation are reported mostly from structurally lower sequences and more easterly exposures.

Most fossil collections from the Utukok Formation are of Early Mississippian age; some may be as old as latest Devonian (Famennian) or as young as early Late Mississippian (Meramecian). The unit contains a diverse megafauna of crinoids, brachiopods, corals, gastropods, bryozoans, and pelecypods, but the tightest age determinations are based on microfossil assemblages of foraminifers and conodonts. Foraminifers representative of zones 7, 8, 9, 10 or 11, 11, and 12 indicate ages equivalent to late Kinderhookian through early Meramecian; a more limited number of conodont assemblages are of Famennian-early Kinderhookian, late Kinderhookian, and early-middle Osagean ages. Data at present are insufficient to prove regional or intersequence variations in the age of the Utukok Formation, but the youngest tightly diagnostic faunas, foraminifers of early Meramecian (zones 11 and 12) age, have been obtained from the Kelly sequence in all areas, and from westernmost exposures of the Key Creek and Eli sequences in the De Long Mountains and Noatak quadrangles, respectively.

Black Shale The other widely distributed unit of Early Mississippian age in the western Brooks Range is the Kayak Shale, uppermost formation of the Endicott Group. The formation was defined in the central Brooks Range by Bowsher and Dutro (1957), but has been recognized throughout the Brooks Range and in the subsurface in northern Alaska (e.g., Armstrong and Bird, 1976). In the sequences of the De Long Mountains allochthon belt, the Kayak Shale is generally less than 100 m thick and consists mostly of black to dark-gray shale; it contains beds of sandstone and siltstone in its lower part and thin layers of bioclastic argillaceous limestone in its upper part (Mayfield and others, 1988).

The Kayak Shale is part of the transgressive suite of Armstrong and Bird (1976). Sections of Kayak Shale in the western Brooks Range appear to have been deposited in progressively deepening water; the basal sandstone beds have sedimentary features indicative of tidal-flat deposits, but thin graded sandstone beds higher in the unit are turbidites and (or) storm deposits, and rare limestone beds in the upper part of the formation are interpreted as debris flows (Nilsen, 1981; Moore and Nilsen, 1984). Shale in this unit is characteristically black and is generally described as carbonaceous, but little geochemical data is available so total organic carbon content is uncertain (Bird and Jordan, 1977; Magoon and Bird, 1988).

The age of the Kayak Shale in the western Brooks Range is relatively poorly constrained but appears to be chiefly Early Mississippian. Many sections have not been dated or yield only long-ranging Mississippian or Early Mississippian forms (e.g., Mayfield and others, 1983, 1984); a few widely-scattered collections of goniatites and conodonts are of definitive Kinderhookian and Osagean age (Dutro, 1987; Karl and others, 1989). The unit may not be coeval in all allochthons and geographic areas; Meramecian fossils have been reported from sections in the Noatak quadrangle (Mayfield and others, 1987).

In general, sequences in the allochthon belt that contain the Utukok Formation do not contain Kayak Shale. Where both formations are recognized in the same sequence, the Kayak Shale either overlies the Utukok Formation, as in the Key Creek and Wulik sequences, or interfingers with it, as in the Amaruk and Puzzle Creek sequences. The depositional relationship between these two units is further discussed below.

Summary

Light-colored sandy limestone assigned to the Utukok Formation is widely distributed in the De Long Mountains allochthon belt; it occurs in some sequences of allochthons 1, 2, 3, and 4. The unit is thicker and contains more terrigenous detritus in the Kelly sequence and in more westerly exposures of all sequences. Lower Mississippian rocks in sequences that do not contain the Utukok Formation generally consist of thin intervals of black shale and subordinate sandstone and limestone (Kayak Shale).

Kogruk Formation

The Kogruk Formation has been recognized in sequences of allochthons 1, 2, and 3 in the De Long Mountains allochthon belt (Mayfield and others, 1988), and in the Schwatka province in the northeastern Baird Mountains quadrangle (Karl and others, 1989). Most of these rocks correlate well both biostratigraphically and lithologically with rocks referred to the Kogruk Formation in the Maiyumerak Mountains.

De Long Mountains Allochthon Belt

Sequences of allochthons 1 (Key Creek and Lisburne Hills), 2 (Amaruk), and 3 (Amphitheater, Eli, and Kelly) all contain carbonate rocks assigned to the Kogruk Formation (Mayfield and others, 1988); occurrences of this unit in the Lisburne Hills, however, are considerably younger than sections of this formation elsewhere, and will be discussed separately below. Like the Utukok Formation, the Kogruk Formation occurs only in the western part of the allochthon belt and displays pronounced intersequence and intrasequence variations in thickness. It is less than 30 m thick and only discontinuously present in sequences of allochthons 1 and 2 (exclusive of the Lisburne Hills sequence), but as much as 700 m thick in some sections of allochthon 3. Within individual sequences, the unit is thicker to the west and perhaps northwest. For example, the Kogruk Formation in the Kelly sequence is more than 300 m thick in the southwest part of the Misheguk Mountain quadrangle, but less than 30 m thick 60 km to the east (Curtis and others, 1984; Mayfield and others 1984). Greatest thicknesses of the formation in all sequences are reported from the De Long Mountains quadrangle (Mayfield and others, 1983).

Intersequence and intrasequence lithologic trends are also apparent. Corals (particularly lithostrotionids) are abundant in the Kogruk Formation only in the sequences of allochthon 3. Layers and nodules of black chert are most abundant in the Kogruk Formation in the sequences of allochthons 1 and 2 and in western occurrences of all sequences.

Only a few sections of the Kogruk Formation, in the Kelly and Eli sequences, have been studied in detail (Sable and Dutro, 1961; Armstrong, 1970a). These sections consist mainly of bryozoan-echinoderm packstone and wackestone with subordinate intervals of lime mudstone (composed of clotted pellets) and ooid and bioclastic grainstone and packstone. Dolomite occurs mainly as small disseminated rhombs that make up 1-15 percent of the lime mudstone intervals. Nodular to lenticular chert is found in all sections but varies markedly in abundance both vertically and laterally; it is most abundant in mudstone and wackestone. Armstrong (1970a) concluded that the Kogruk Formation was deposited in an open-marine environment in which carbonate deposition and subsidence were near equilibrium; shoal conditions were locally achieved but sedimentary features indicative of intertidal and supratidal environments are absent.

Rocks similar to the thin-bedded spiculitic limestone in the upper part of the Kogruk Formation in the Maiyumerak Mountains have been described from all three sequences of allochthon 3. In the Misheguk Mountain quadrangle, these rocks occur in the Kelly and Eli sequences and have been referred to the Tupik Formation (Mayfield and others, 1984); in the De Long Mountains and Noatak quadrangles, they occur in the Kelly and Amphitheater sequences respectively, and are assigned to map unit Mkoc3 (Mayfield and others, 1983, 1987). All occurrences are less than 75 m thick, form the upper part of or overlie the Kogruk Formation, and consist of dark-gray to black limestone thinly interbedded with as much as 50 percent chert.

Fossils are relatively abundant in the Kogruk Formation, and the age of this unit in the allochthon belt is well constrained by conodonts, corals, and foraminifers. The base of the unit in most sections is early Meramecian and contains foraminifers representative of zones 11 or 12, but in some parts of the Eli sequence (for example, the Noatak quadrangle), late Osagean ages (zone 10) are reported (Mayfield and others, 1987). The youngest definitive ages, late Meramecian (zone 14 or 15), have been obtained from the Kelly sequence in all areas, and the Eli sequence in the Misheguk Mountain quadrangle. The Tupik Formation and equivalent cherty limestone units are less well-dated; sparse fossil collections include foraminifers of late Meramecian (zone 14 or 15) age, and nautiloids (Gordon, 1957) considered by Dutro (1987) to indicate an early Chester age.

Lisburne Hills In the Point Hope quadrangle on the Lisburne Peninsula, rocks referred to the Kogruk Formation were studied by Armstrong (1970a, 1972) and Armstrong and others (1971) and rocks designated Kogruk? Formation were described by Campbell (1967). The structural position of these rocks is uncertain; they have been included in the Lisburne Hills sequence of allochthon 1, but Carbonifierous stratigraphy in the area is most like that in the sequences of allochthon 3 (Mayfield and others, 1988).

Several partial sections of Kogruk Formation, 70 to 600 m thick, were examined by Armstrong (1970a, 1972) and Armstrong and others (1971) in both northern and southern parts of the peninsula. These sections consist mostly of bryozoan-echinoid packstone to wackestone, locally cherty and (or) dolomitized; some intervals include shallowing-upward cycles 6-40 m thick of bioclastic grainstone or packstone capped by cherty dolomitic mudstone. The rocks contain foraminifers representative of Meramecian to Chesterian age (zones 13 through 18). Campbell (1967) describes several thoroughly dolomitized sections as much as 1400 m thick from the southern seacliffs of the peninsula that consist mostly of variously fossil-rich biomicrites and are of Chesterian age. The uppermost part of the Kogruk Formation on the Lisburne Peninsula contains large brachiopods that may be of Early Pennsylvanian (Morrowan) age (Dutro, 1987). Thus, the Kogruk Formation on the Lisbume Peninsula appears to be similar in lithology but notably younger than the Kogruk Formation elsewhere within the allochthon belt.

Schwatka Mountains Structural Province

Rocks referred to the Kogruk Formation in the Schwatka province crop out in the northeastern

Baird Mountains quadrangle; these rocks have been described by Karl and others (1989) and were further analyzed for the present study. They are similar in age and general lithology to the Kogruk Formation in the Maiyumerak Mountains, but occur in a distinctly different stratigraphic context and include sedimentary features suggestive of very shallow water (supratidal or intertidal) depositional environments. The section is 30 m thick and overlies undated siliceous metaclastic rocks that may be metamorphosed equivalents of the Endicott Group; these rocks in turn disconformably(?) overlie massive metacarbonate rocks that contain conodonts that are no younger than late Early Devonian (Emsian) and may be as old as Middle Silurian. All lithologic contacts in this area have probably been somewhat structurally disrupted, but the general stratigraphic succession at this locality appears to be relatively intact.

The Kogruk Formation in the northeastern Baird Mountains quadrangle consists of dolostone and lesser limestone with locally abundant black chert nodules and lenses. Some original textures are well preserved and indicate that much of the section was deposited as bryozoan-echinoderm wackestone and packstone; lithostrotionid corals occur locally. Several intervals are rich in sponge spicules; these spiculitic rocks contain laminar to hummocky cryptalgal layering and appear to have formed in very shallow, restricted environments. The section contains the conodont *Hindeodus scitulus* (USGS colln. 28976-PC) indicative of late Osagean to early Chesterian age and a shallow-water setting, and the coral *Lithostrotionella* aff. *L. birdi*, of middle Meramecian to early Chesterian age (equivalent to foraminifer zones 13-16) (written commun., A. K. Armstrong, 1978).

<u>Summary</u>

Carbonate rocks lithologically and biostratigraphically correlative with the Kogruk Formation in the Maiyumerak Mountains occur in sequences of allochthons 1, 2, and 3 in the De Long Mountains allochthon belt, and in the western part of the Schwatka province. In most sequences of the allochthon belt, with the exception of the Lisburne Hills sequence, the Kogruk Formation consists chiefly of bryozoan-echinoderm wackestone and packstone, locally dolomitic and (or) cherty, deposited in open marine conditions. Sections are thicker to the west and northwest and are late Osagean or early Meramecian to late Meramecian in age. Most sections are capped by thin-bedded cherty limestone of late Meramecian or early Chesterian age deposited in a deeper water setting. The Kogruk Formation in the Lisburne Hills is locally completely dolomitized, includes distinct shallowing-upward cycles, and is Meramecian to Chesterian or Morrowan in age. In the western part of the Schwatka province, the Kogruk Formation was deposited in shallow to very shallow water and is imprecisely dated; the base may be as old as late Osagean and the top may be as young as early Chesterian.

Correlation Summary and Discussion

As is evident from the discussion above and the generalized sections in Fig. 27, a number of distinct sedimentary facies coexisted during middle to late Paleozoic time in what is now northwestern Alaska. This lithologic diversity is thought to reflect a complex Devonian-Carboniferous paleogeography of shallow platforms and intracratonic basins in which allochthonous quartzose and quartzofeldspathic material and autochthonous carbonate sediment accumulated (Mayfield and others, 1988). Lithologic and stratigraphic features of sedimentary sequences in the De Long Mountains allochthon belt and in the western Schwatka province are summarized below, and compared to those of carbonate rocks in the Maiyumerak Mountains.

The Schwatka province and 11 of the 15 sequences in the allochthon belt contain rocks of confirmed or probable Devonian age (Mayfield and others, 1988) (Fig. 27). No rocks definitively older than late Middle Devonian (Givetian) have been found in most of the allochthon belt; in contrast, the western part of the Schwatka province contains no Devonian rocks known to be younger than late Early Devonian (Karl and others, 1989). All Devonian rocks in the allochthon belt were deposited in relatively shallow water and can be grouped into three broad categories: carbonate rocks with little or no sand-sized siliciclastic component (Baird Group, Eli Limestone), siliciclastic rocks with little carbonate component (Endicott Group), and quartzofeldspathic calcareous rocks (Kugururok Formation); facies transitional between the first two categories have also been recognized. Devonian rocks in sequences of allochthon 1 and 2 are siliciclastic rocks (Amaruk, Picnic Creek sequences) or mixed carbonate and siliciclastic rocks (Key Creek, Wulik, Nigu sequences). Devonian rocks in all sequences of allochthon 3 and 4 are relatively pure limestone; argillaceous limestone occurs in some parts of the Eli, Kelly, and Puzzle Creek sequences. Clastic rocks that contain greater than 10 percent feldspar grains have been recognized only in allochthon 5 (Bastille sequence).

The Schwatka province and all sequences of the allochthon belt with the exception of the Bastille sequence contain rocks of confirmed Mississippian age. Both Lower and Upper Mississippian rocks comprise several distinct facies. The major Lower Mississippian units are dark shale and lesser sandstone and limestone (Kayak Shale, uppermost unit of the Endicott Group) and limestone, sandy limestone, sandstone, and (or) shale (Utukok Formation of the Lisburne Group). In some sequences, most notably the Key Creek sequence, coarse siliciclastic rocks of the Endicott Group (Noatak Sandstone and (or) Kanayut Conglomerate) are of Early Mississippian age (Mayfield and others, 1984). Most sequences of the allochthon belt contain the Kayak Shale; the Utukok Formation occurs primarily in the sequences of allochthon 3. Endicott Group undivided is recognized in the Lisburne Hills and Nigu sequences; the Amphitheater sequence contains an interval of interbedded shale and limestone assigned to the Lisburne Group but not to the Utukok Formation (Fig. 27).

Upper Mississippian rocks in sequences of the allochthon belt consist of thick accumulations of light-colored carbonate rocks formed in relatively shallow water environments (Kogruk Formation, Lisburne Group undivided in the Ivotuk sequence), and (or) generally thinner intervals of dark limestone, shale and (or) chert deposited in deeper water settings (Tupik and Kuna Formations, Akmalik Chert, and various units informally referred to as "black Lisburne") (Fig. 27). "Kogruk-type" neritic carbonate rocks comprise relatively thick accumulations in all sequences of allochthon 3 and most sequences of allochthon 1, and thinner deposits in the Key Creek and Amaruk sequences and in at least parts of the Schwatka province. These rocks are overlain in most sequences by a thin interval of "black Lisburne" facies, generally the Tupik Formation. Upper Mississippian rocks in most sequences of allochthons 2 and 4, on the other hand, consist only of one or more of the "black Lisburne" facies, and in the Bogie sequence of allochthon 5 consist of feldspathic carbonate rocks (Nuka Formation).

The complete succession of Devonian-Mississippian carbonate rocks in the Maiyumerak Mountains is most similar to Devonian-Mississippian sections in the sequences of allochthon 3 (Kelly River allochthon) that are found throughout the Noatak, De Long Mountains, and Misheguk Mountain quadrangles to the north and west (Fig. 26). Thus, on sedimentologic and biostratigraphic grounds, the inclusion of the Maiyumerak sequence with sedimentary sequences of allochthon 3 proposed by Mayfield and others (1988) seems warranted.

Other sequences in the De Long Mountains allochthon belt include deeper water basinal deposits and (or) siliciclastic rocks of Devonian-Mississippian age. Only the sequences of allochthon 3 preserve a record of relatively continuous shallow-water carbonate deposition from at least Middle Devonian into Late Mississippian time, and even these sequences contain evidence of some clastic input during Late Devonian and Early Mississippian time. The lithologic and biostratigraphic similarities between Paleozoic rocks in all the sequences of the Kelly allochthon suggest that these sequences were once contiguous, and formed originally as part of a single carbonate platform. This hypothetical paleogeographic feature, which includes carbonate rocks of the Maiyumerak sequence, is here called the

Kelly platform. In the following section, implications of the Maiyumerak Mountains sequence for paleogeographic models of the northwestern Brooks Range are explored.

PALEOGEOGRAPHY

Paleogeographic Model

The prevailing model for the Paleozoic paleogeography of the northwestern Brooks Range is that of Mayfield and others (1988). Other authors (e.g., Churkin and others, 1979) have outlined alternate paleogeographic and tectonic reconstructions of northwestern Alaska, but the model of Mayfield and others (1988) is the only one presented in sufficient detail to permit precise stratigraphic and sedimentologic inferences to be drawn and tested. These authors propose a palinspastic synthesis in which the relative movement of all thrust sheets is north under south. Rocks of the Schwatka province, considered autochthonous or parautochthonous, are restored farthest north, igneous rocks of allochthons 6 and 7 are restored farthest south, and the sedimentary sequences of allochthons 1 through 5 are restored sequentially between them.

The Devonian-Mississippian paleogeography that results from this restoration is a complex series of platforms and intracratonic basins interpreted by Mayfield and others (1988) as follows (Fig. 28). Rocks of the Schwatka province are thought to have been an emergent land mass during much of middle Paleozoic time, and another continental mass ("Nukaland") is postulated to have existed south of the sequences of allochthon 5. Sequences of allochthon 1, which include thick sections of siliciclastic rocks of the Endicott Group, were deposited on a shallow shelf flanking the Schwatka continental mass and were derived from a source to the northwest. Sequences of allochthon 5, also shallow-water deposits, contain feldspar and volcanic lithics derived from Nukaland. Sequences of allochthon 3 are envisioned to have formed a topographic high (Kelly platform of this report) that was flanked by basins to the north and south; deposits of these basins are represented by sequences of allochthons 2 and 4, respectively.

It is beyond the scope of this paper to present a detailed structural critique of the model of Mayfield and others (1988), but some questions may be raised concerning the original position of rocks in the Schwatka province. As noted above, rocks of this province have been folded and thrust during the Brooks Range orogeny, and thus are not autochthonous (Till and others, 1988). In addition, if metamorphic rocks of the Schwatka province are restored farthest north, and igneous rocks of allochthons 6 and 7 are restored farthest south, present-day juxtaposition of these rocks (Fig. 26) is difficult to explain. Finally, metamorphism of rocks in the Schwatka province is attributed to underthrusting beneath more than 10 km of thrust sheets and is postulated to have occurred during the later stages of the underthrusting event. However, the high-pressure metamorphism of rocks in the Schwatka province took place during late Jurassic-Early Cretaceous time and is coeval with the oldest well-dated flysch deposits produced during thrusting (Armstrong and others, 1986; Till and others, 1988).

Paleogeographic Implications of Maiyumerak Sequence

Comparison of the Devonian-Mississippian carbonate sequence in the Maiyumerak Mountains to correlative sequences in the allochthon belt and within the Schwatka province constrains the paleogeographic model of Mayfield and others (1988) described above. Specific problems which the Maiyumerak data illuminate include the relationship between Paleozoic carbonate platforms in the allochthon belt and the Schwatka province, the source of the clastic material in the Maiyumerak sequence, the relationship between Paleozoic carbonate platforms and the Endicott clastic wedge, and the timing and cause of the demise of the Kelly platform.

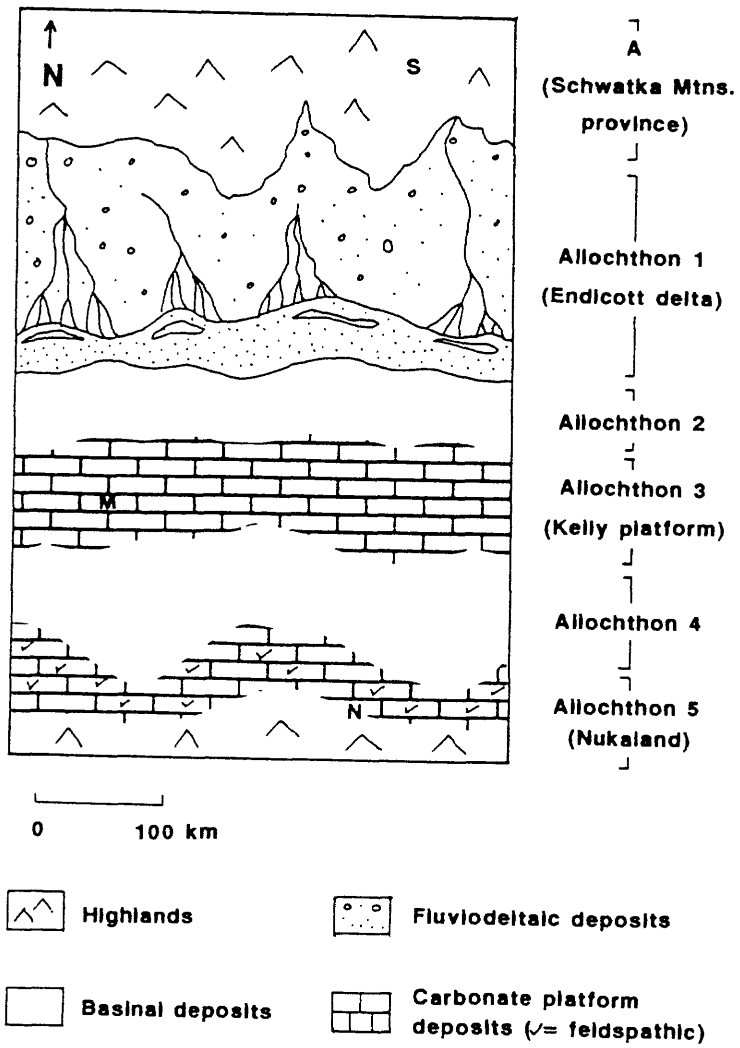


Figure 28. Schematic paleogeographic map of northwestern Alaska in Late Devonian-Early Mississippian time, based on palinspastic reconstruction of Mayfield and others (1988). Reconstruction restores each lower-numbered allochthon northward from under the adjacent allochthon to the south. Thrusting direction is assumed to have followed an arc with the pole of rotation centered in the Mackenzie River Delta area in northwestern Canada. Allochthons as in Fig. 26; geographic features from Fig. 26 are S, Schwatka Mountains, M, Maiyumerak Mountains, and N, Nuka Ridge.

Relationship Between Paleozoic Carbonate Platforms

Relatively extensive sequences of early and middle Paleozoic metacarbonate rocks occur throughout the Schwatka structural province and appear to represent the deformed remains of a Paleozoic carbonate platform or series of platforms that may extend more than 800 km through the Brooks Range (Dumoulin and Harris, 1987). The relationship of these older carbonate platform sequences to the oldest carbonate rocks of the allochthon belt is uncertain (Mayfield and others, 1988). Thus, a comparison of the Baird Group in the Maiyumerak Mountains with adjacent sequences of Devonian carbonate rocks in the Baird Mountains quadrangle provides some insight into middle Paleozoic paleogeography.

The oldest well-dated part of the Baird Group in the Maiyumerak Mountains is at least as old as early Givetian and could be as old as early Eifelian. The youngest part of the Baird Group in the central Baird Mountains quadrangle (Agashashok sequence of Ellersieck, 1985) is at least as young as Eifelian and could be, in part, Givetian. Middle Devonian rocks in both sequences consist of dolomitic bioclastic limestone containing local coral and stromatoporoid biostromes. Thus, these successions overlap in lithology and probably in age. This correspondence suggests that the Baird Group in the Maiyumerak Mountains was once depositionally contiguous with the Baird Group in the central Baird Mountains quadrangle but has since been structurally dismembered, and that on sedimentologic and stratigraphic grounds, the Agashashok sequence should be grouped with other sequences of allochthon 3. If this correlation is correct, the Kelly carbonate platform existed from at least Early Ordovician (Dumoulin and Harris, 1987) through early Late Mississippian time.

However, Middle-Upper Devonian carbonate and clastic rocks (limestone of the Nakolik River, unit Dnl of Karl and others, 1989) lie directly north of but structurally below Ordovician-Devonian carbonate rocks of the Agashashok sequence (Karl and others, 1989) (Fig. 1). Dnl is gradationally overlain by rocks of the Endicott Group and both units are included by Mayfield and others (1988) in the Key Creek sequence of allochthon 1. Karl and others (1989) suggest that a stratigraphic contact originally existed between Dnl and rocks of the Agashashok sequence. If this hypothesis is correct, the Agashashok sequence is actually part of allochthon 1, and Upper Devonian rocks deposited above the Baird Group in the central Baird Mountains quadrangle are much richer in siliciclastic detritus than are coeval rocks in the Maiyumerak Mountains. Such discordance in Upper Devonian facies suggests that the Agashashok and Maiyumerak sequences were not directly contiguous during middle Paleozoic time, and that the Agashashok sequence is not part of the Kelly carbonate platform.

The Baird Group in the Maiyumerak sequence cannot easily be compared with carbonate sequences in the western part of the Schwatka province (northeastern Baird Mountains quadrangle), because no rocks as young as Middle Devonian have been recognized in these sequences. Middle and Upper Devonian rocks may have been eroded or structurally removed from the Schwatka province, or may never have been deposited. It is possible that at least parts of the Schwatka province were emergent through Middle and (or) Late Devonian time. Much of northern Alaska (i.e., parautochthonous sequences in the northeastern Brooks Range and autochthonous sequences in the subsurface north of the Brooks Range) shows evidence of Devonian uplift and (or) regression; in these areas, Mississippian clastic rocks unconformably overlie Proterozoic or early Paleozoic sedimentary and metasedimentary rocks (e.g., Brosgé and Tailleur, 1970). This unconformity has been attributed to regional tectonism, the Ellesmerian orogeny (Lerand, 1973; Smith, 1987) but could at least in part reflect eustatic changes; evidence of Givetian regression has been noted in western Canada (Fischbuch, 1968), and Johnson and others (1985) and Ross and Ross (1988) proposed a worldwide fall in sea level during the early-middle Givetian.

Although there is no physical evidence of unconformity within the Maiyumerak carbonate sequence, and fossils indicate that any hiatus in deposition of this sequence was less than a stage in duration, very shallow water depositional environments are interpreted for the middle to late Givetian part of the sequence. Sedimentologic features of the upper part of the Baird Group in the Maiyumerak Mountains indicate that intertidal and supratidal environments prevailed across at least the Maiyumerak part of the Kelly platform near the end of Middle Devonian time; these are the shallowest water conditions that have been documented for any interval within the Maiyumerak section.

Source of Clastic Detritus in the Maiyumerak Sequence

The Endicott Group consists of as much as 4300 m of Upper Devonian-Lower Mississippian fluviodeltaic deposits that crop out for at least 950 km along the crest of the Brooks Range (Nilsen, 1981; Moore and Nilsen, 1984). Petrographic data and stratigraphic and spatial relationships suggest that most of the clay- to sand-sized noncarbonate material in the Maiyumerak sequence was derived from the same source that produced the Endicott Group; the present-day location of this source is uncertain.

In northwestern Alaska, the Endicott Group is exposed in a series of thrust plates and comprises four formations. The lowest unit, the Hunt Fork Shale, consists largely of fine detritus and is thought to have been deposited in a marine slope to outer shelf setting. The overlying Noatak Sandstone and Kanayut Conglomerate contain coarser siliciclastic material and formed as shallow-marine and fluvial deposits respectively. The uppermost part of the group, the Kayak Shale discussed above, is dominantly fine-grained and was deposited in a progressively deepening marine environment.

The Endicott Group in the western Brooks Range is roughly coeval with the most clastic-rich part of the Maiyumerak sequence. The Hunt Fork Shale contains brachiopods, cephalopods, and corals of Late Devonian age in the Misheguk Mountain quadrangle (Ellersieck and others, 1984), and brachiopods of late Frasnian or early Famennian age in the Baird Mountains quadrangle (Karl and others, 1989). Sandier parts of the Endicott Group are less well-dated; particularly poorly constrained is the age of the uppermost coarse clastic rocks in the Kanayut Conglomerate. In the Misheguk Mountain quadrangle, the Noatak Sandstone and Kanayut Conglomerate (undivided) contain brachiopods of Late Devonian to Early Mississippian age; in the Howard Pass quadrangle, Kanayut Conglomerate contains Mississippian plant fossils (Mayfield and others, 1984). Fossils from the overlying Kayak Shale chiefly indicate a broad Early Mississippian or Mississippian age and thus do not tightly limit the age of the top of the Kanayut.

Little detailed information is available on the composition of shale in the Endicott Group, but the coarser siliciclastic rocks have been broadly characterized. Conglomerate and sandstone in the Kanayut Conglomerate in the central and eastern Brooks Range are compositionally mature. Sandstone is well-sorted, subrounded, and consists of 30-75 percent quartz, 10-50 percent chert, less than 20 percent lithic grains, including argillite, quartzite, granite, and gneiss, and minor tourmaline and opaque grains; feldspar is generally absent (Moore and Nilsen, 1984; Brosgé and others, 1988). Karl and others (1989) report 90 percent quartz and chert and 10 percent argillite clasts in metasandstone of the Kanayut Conglomerate in the Baird Mountains quadrangle. Little variation in composition with respect to stratigraphic or geographic position has been noted in the Kanayut Conglomerate and the unit is thought to have been derived from a single major source terrane (Brosgé and others, 1988).

Paleocurrent and clast-size data indicate that the Endicott Group was derived primarily from the east and north (Nilsen, 1981); clast size maxima suggest that the depositional basin was fed by two major trunk streams in the east-central Brooks Range and a smaller stream in northwest Alaska. In the western Brooks Range, clast size in Kanayut Conglomerate declines southward from a maximum along the northwestern edge of the outcrop belt in the De Long Mountains quadrangle, and paleocurrent measurements west of 159° indicate transport to the southwest (Moore and Nilsen, 1984).

Determination of the source of the Endicott Group is complicated by the allochthonous nature of the unit in the central and western Brooks Range and by uncertainty concerning the proper palinspastic restoration of northern Alaska with respect to the rest of North America. Nilsen (1981) noted that the Endicott Group more closely resembles Devonian redbeds of the Franklinian orogen in northern Canada than Upper Devonian flysch of the adjacent Cordilleran orogen to the south. Anderson (1987) analyzed composition of sandstone in the Endicott Group in the central Brooks Range, and proposed a recycled orogenic provenance for the unit. Mayfield and others (1988) suggested that the Endicott Group was derived from rocks of the Schwatka province and (or) rocks presently under the Colville Basin in the subsurface of northwestern Alaska; these areas seem unlikely to have generated a huge wedge of dominantly quartzose sediment because known pre-Middle Devonian lithologies include abundant carbonate rocks (Schwatka province) and argillite (Colville basin). However, the compositional maturity of the Endicott Group could reflect intense chemical and physical abrasion during erosion and transport; if so, its present composition may not be fully indicative of its provenance (Brosgé and others, 1988). No completely satisfactory source for the Endicott Group has yet been proposed.

The composition and age of noncarbonate detritus in the Maiyumerak sequence matches the Endicott Group. Detritus in the Maiyumerak sequence coarsens upward, from clay in the Upper Devonian Eli Limestone to sand in the Lower Mississippian Utukok Formation. The Eli Limestone correlates with the fine-grained lower part of the Endicott Group, the Upper Devonian Hunt Fork Shale, and the Utukok Formation is at least partly coeval with the coarser grained upper parts of the Endicott Group, the Upper Devonian-Lower Mississippian Noatak Sandstone and Kanayut Conglomerate. Sand-sized noncarbonate material in the Utukok Formation, like sandstone in the Endicott Group, is subrounded, compositionally mature, and consists largely of quartz, chert, subordinate muddy lithic clasts, and minor tourmaline and opaque grains. Thus, we suggest that siliciclastic detritus in the Maiyumerak carbonate sequence and in the Endicott Group have a common provenance.

One possible complication in this scenario concerns the extent of overlap in age between the sand-rich part of the Endicott Group and the Utukok Formation. As discussed above, the age of the youngest thick sandstone beds in the Endicott Group (upper Kanayut Conglomerate and lowest Kayak Shale) is poorly constrained in the western Brooks Range; it may be as young as Osagean or even Meramecian or as old as Kinderhookian. The Utukok Formation is Kinderhookian and Osagean. If the uppermost sandstone beds in the Endicott Group were indeed deposited in the Kinderhookian, quartz could have been provided to uppermost (Osagean) parts of the Utukok Formation by erosion and reworking of previously deposited Endicott Group strata.

Relationship Between Paleozoic Carbonate Platforms and Endicott Clastic Wedge

Both the sandy middle part of the Endicott Group (Noatak Sandstone and Kanayut Conglomerate) and the upper black shale unit (Kayak Shale) are at least partly coeval with the Utukok Formation in the western Brooks Range. Paleogeographic and depositional implications of this correlation are explored below.

As noted previously, several intervals of interbedded quartz sandstone and bioclastic limestone in the De Long Mountains allochthon belt have been interpreted as deposits formed by intertonguing of the Endicott clastic wedge with one or more carbonate platforms (Curtis and others, 1984; Karl and others, 1989); these intervals occur in sequences of allochthons 1 and 2. If siliciclastic material in the Maiyumerak sequence of allochthon 3 was derived from the same source as the Endicott Group, some constraints on Devonian-Mississippian paleogeographic reconstructions are implied.

In the model of Mayfield and others (1988) (see also Fig. 27 of Moore and others, in press), a marginal sea or epicontinental basin 50 to 100 km wide is thought to have separated the Kelly carbonate platform (now preserved in the sequences of allochthon 3) and the Endicott fluviodeltaic system (preserved mostly in the sequences of allochthon 1) during Late Devonian-Mississipian time. Deposits of this intervening basin are represented by the sequences of allochthon 2 (Fig. 28).

A modern analog for this proposed paleogeography is the northeast continental margin of Australia. Here, carbonate platforms such as the Eastern and Queensland plateaus are separated from the Australian continental shelf by deep troughs which formed as rift basins (Davies and others, 1988, 1989). Terrigenous and carbonate sediments are juxtaposed and intercalated along the Australian margin; siliciclastic material derived from the continent is distributed along the inner continental shelf and carbonate reefs grow along the outer shelf and on the marginal plateaus. The outer shelf is a mixed carbonate/siliciclastic province; reefs are enclosed within terrigenous fluviodeltaic deposits and carbonate sediment occurs interbedded and intermixed with quartz sand and terrigenous mud. The plateaus, however, are relatively pure carbonate provinces; terrigenous detritus is not transported across the intervening troughs.

If the quartz sand in the Utukok Formation and in the Endicott Group was derived from the same source, a basin completely separating the Kelly platform from the Endicott delta seems unlikely; three solutions are possible. First, prevailing tectonic reconstructions may be in error, perhaps as a result of unrecognized out-of-sequence thrusting (Fig. 29A). Perhaps sequences containing carbonate platform deposits (allochthon 3) should be restored directly south of sequences containing fluviodeltaic deposits (allochthon 1); sections containing basinal deposits (allochthon 2) would then be restored south of the sequences of allochthon 3. Such a restoration has been proposed by previous workers (e.g., C. G. Mull, Alaska Department of Geological and Geophysical Surveys, written commun., 1990).

Alternatively, the basin between the Kelly platform and the Endicott delta may not have formed until the Late Mississippian, after the Utukok Formation was deposited. In this scheme, Late Devonian-Early Mississippian paleogeography of northwestern Alaska was like that shown in Figure 29A, but Late Mississippian paleogeography was like that in Figure 28. Presently available fossil data is permissive of this hypothesis but does not prove it. The oldest well-dated facies of basinal aspect in the sequences of allochthon 2 is bedded gray chert in the Nigu sequence which contains radiolarians of late Osagean to Meramecian age (Holdsworth and Murchey, 1988). However, this chert is underlain by at least 90 m of black to gray interbedded chert, shale, and limestone that also appears to have formed in a deep-water depositional environment; these rocks have yielded no diagnostic fossils, but contain poorly preserved tentaculitids? that suggest these strata are no younger than Devonian (Holdsworth and Murchey, 1988). Basinal facies in other sequences of allochthon 2 contain no definitive fossil assemblages older than Late Mississippian.

A third possibility is that the "basin" between the Kelly platform and Endicott delta was actually an embayment, open on only one end (Fig. 29B). Support for this third hypothesis is provided by geographic gradients in thickness and lithology of Devonian-Mississippian rocks in allochthons 2 and 3. These gradients suggest that, if present-day west-to-east disposition of facies is representative of their original configuration, the Kelly platform and Endicott delta were connected to the west and any embayment between them deepened to the east. Mississippian rocks in the eastern sequences of allochthon 2, the Nigu and Picnic Creek sequences, consist mostly of chert and black shale, whereas Mississippian sections in the Amaruk and Wulik sequences to the west contain some platform carbonate rocks and siliciclastic detritus. Within the sequences of allochthon 3, the Utukok Formation both thickens notably and contains more clastic detritus to the west.

Thus, if siliciclastic detritus in the Maiyumerak sequence was derived from the same source as the Endicott Group, the paleogeographic model of Mayfield and others (1988) must be modified. Present

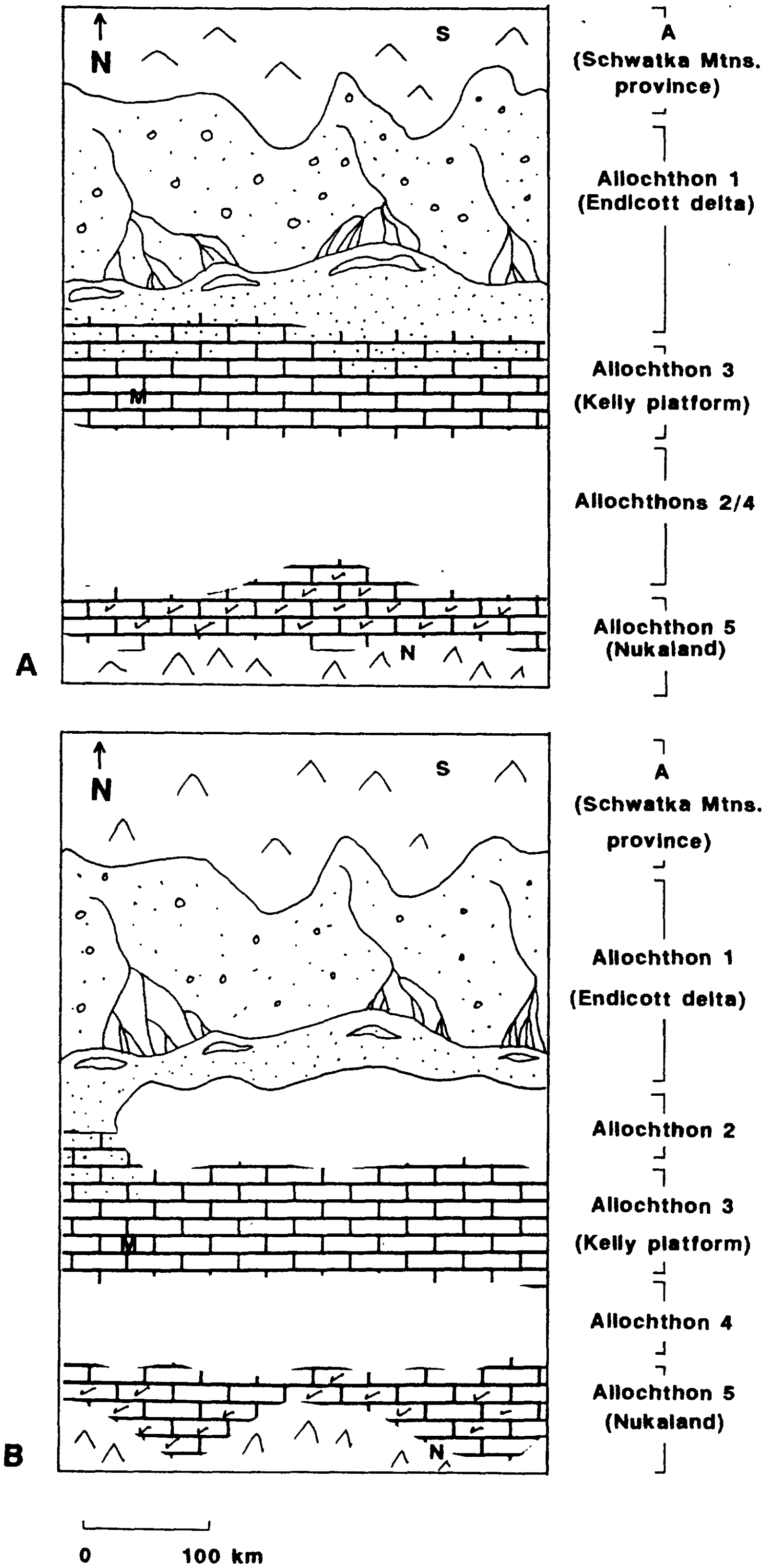


Figure 29. Alternate paleogeographic reconstructions of northwestern Alaska in Late Devonian-Early Mississippian time. Allochthons, geographic features, and symbols as in Fig. 28. **A.** Reconstruction based on ideas of C. G. Mull (written commun., 1990); sequences of allochthon 3 are restored directly south of sequences of allochthon 1. **B.** "Basin" between Kelly platform and Endicott delta is an embayment, open to the east.

data suggest that the Kelly platform was not completely cut off from the Endicott delta by a marginal sea, but only partially separated by an embayment that deepened to the east and (or) may not have formed until late Late Mississippian time. Further testing of these hypotheses requires tighter age control on cherts in the sequences of allochthon 2, and paleocurrent data from the Utukok Formation and other mixed carbonate and clastic deposits in the western Brooks Range.

The relationship between the Utukok Formation and the Kayak Shale in the western Brooks Range also has paleogeographic implications. The Utukok Formation is as much as 1000 m thick, generally light colored, and contains an abundant fauna indicative of shallow-water depositional environments. The Kayak Shale, in contrast, is typically less than 100 m thick, black to dark gray, and contains little indigenous fauna; fossils are broken, abraded, hydraulically sorted, and occur concentrated in rare limestone beds that appear to have been redeposited. Black shales like the Kayak Shale often occur near the base of transgressive sequences that blanket areas of irregular topography; these shales form at a variety of depths controlled by regional topographic restrictions on bottom-water circulation and are commonly deposited in local areas where sea floor subsidence is relatively rapid (Hallam and Bradshaw, 1979). The Kayak Shale in most sequences in the allochthon belt is succeeded by black chert and (or) siliceous shale interpreted as basinal deposits, whereas the Utukok Formation is generally overlain by fossiliferous carbonate rocks formed in shallow water. Thus, the Utukok Formation probably accumulated on topographic highs within the overall northwestern Alaska depositional basin, whereas Kayak Shale was deposited primarily in adjacent lows, subbasins, or embayments.

Demise of Kelly Platform

Thin-bedded spiculitic limestone forms the upper part of the Kogruk Formation in the Maiyumerak Mountains and appears to have been deposited in an outer shelf or basinal setting; this is a deeper water depositional environment than that indicated for any other part of the Maiyumerak sequence. Similar deeper water facies (Tupik Formation, unnamed "black Lisburne" units) overlie Upper Mississippian platform carbonate rocks in all sequences of allochthon 3 and are in turn overlain by condensed basinal deposits (chert and shale of the Pennsylvanian-Jurassic Etivluk Group) (Mayfield and others, 1988). The spiculitic limestone in the Maiyumerak Mountains is not tightly dated but is probably late Meramecian or early Chesterian in age. In other sequences of allochthon 3, the transition from shallow-water dolomitic limestone to spiculitic cherty limestone occurs in the latest Meramecian, about the level of foraminifer zone 15.

Few platform carbonate rocks younger than Meramecian have been found anywhere in the De Long Mountains allochthon belt; the exceptions are the Kogruk? Formation in the Lisburne Hills sequence (allochthon 1?) and the Nuka Formation in the Bogie sequence (allochthon 5). Both these units include neritic carbonate rocks which are at least as young as Chesterian and may be in part Pennsylvanian, and these younger carbonates differ in other ways from the Kogruk Formation in the sequences of allochthon 3. For example, the Kogruk? Formation in the Lisburne Hills contains distinct shallowing-upward cycles not found elsewhere in the Kogruk Formation, and the Nuka Formation is unique among Carboniferous carbonate rocks in northwestern Alaska in containing abundant detrital feldspar. These stratigraphic and lithologic differences suggest that carbonate rocks in the Lisburne Hills and Bogie sequences formed on discrete carbonate platforms that were not connected to the Kelly platform and that experienced separate histories of subsidence and clastic input.

Inundation of the Kelly platform probably reflects a variety of factors, both tectonic, ecologic, and eustatic. Long-term tectonic processes, such as thermal subsidence of passive margins, are an order of magnitude slower than typical sedimentation rates of neritic carbonates and thus are not usually sufficient in themselves to drown healthy carbonate platforms (Kendall and Schlager, 1981). However, ecologic shifts may depress the growth potential of carbonate benthos to levels that can be outpaced by long-term subsidence (e.g., Davies and others, 1989). Plate motion to higher latitudes, and out of the realm most favorable to carbonate production, is one such adverse environmental change that may have affected the Kelly platform. Recent paleogeographic reconstructions (Crane, 1987; Smith, 1987) suggest that northern Alaska lay at about 40^{o} north latitude at the start of Carboniferous time and moved progressively farther north throughout the late Paleozoic.

Paleontologic evidence indicates that Carboniferous rocks of northern Alaska were deposited in relatively cool water and supports the notion of increasingly adverse climatic conditions. Foraminifers of the Lisburne Group are characteristic of the Alaska-Taimyr faunal subrealm and are interpreted as temperate-water faunas on the basis of their low diversity, high genus/species ratios, and high number of cosmopolitan forms (Armstrong and Mamet, 1970). The Lisburne Group lacks features such as dasycladacian algal banks that are common in Carboniferous strata deposited in warm-water environments. As noted above, sedimentation rates in the Utukok and Kogruk Formations in the Maiyumerak sequence are low compared to other ancient neritic carbonate successions, and are consistent with a depositional environment only marginally conducive to carbonate accumulation. Deteriorating climate may have been responsible for the otherwise unexplained extinction, documented by Armstrong (1972), of the Lisburne Group lithostrotionid coral fauna near the end of Meramecian time but somewhat prior to cessation of neritic carbonate production. Limited persistence of latest Mississippian carbonate platform sedimentation in northwestern Alaska may reflect niceties of paleolatitudinal position; although the exact paleogeographic position of the Lisburne Hills sequence is uncertain, the palinspastic model of Mayfield and others (1988) restores the Nuka sequence farther south than any other sedimentary sequence in the De Long Mountains belt.

Eustatic changes may also have played a role in the demise of the Kelly platform. Long-term global sea level fell throughout the Late Mississippian (e.g., Vail and others, 1977), but this general decline was punctuated by a number of short-term sea level rises (Ross and Ross, 1988). One such rise took place during the late Meramecian (upper part of Mamet foraminifer zone 15); this is precisely the age of the transition from shallow to deeper water carbonate facies on the Kelly platform where this transition has been most tightly dated. Rapid pulses of relative sea level rise can outpace even optimally producing carbonate platforms, but will be even more likely to inundate platforms whose growth potential is already in decline as a result of other factors, i.e., drift to higher latitudes; demise of carbonate platforms along the Atlantic margin of North America during the Early Cretaceous has been ascribed to just such a superposition of effects (Kendall and Schlager, 1981).

Thus, the Kelly platform appears to have drowned about the end of the Meramecian, and deposition of neritic carbonate rocks was never reestablished in this region. Carbonate platform sedimentation persisted into the late Late Mississippian only in limited areas of northwestern Alaska, such as adjacent to Nukaland and on the Lisburne Peninsula. The inundation of the Kelly platform at the end of Meramecian time is probably primarily attributable to northward drift of northern Alaska, although eustatic changes may also have been a factor.

CONCLUSIONS

Middle Devonian through Upper Mississippian carbonate rocks of the Maiyumerak Mountains represent essentially continuous deposition in a variety of open middle shelf to more restricted inner shelf environments. Episodic terrigenous input occurred throughout Late Devonian-Early Mississippian time and consisted mostly of clay in the Devonian and quartz and lesser chert sand in the Mississippian. Fossil assemblages, chiefly conodonts, indicate that any hiatus in this sequence is less than a stage in duration. Detailed lithologic and biostratigrapic comparisons of the Maiyumerak sequence with coeval rocks throughout the western Brooks Range confirm that the Maiyumerak rocks are most similar to Devonian-Mississippian rocks in sequences of allochthon 3, as proposed by Mayfield and others (1988), and suggest that these rocks accumulated on a single carbonate platform, the Kelly platform.

Middle Devonian carbonate rocks in the Maiyumerak Mountains correlate well with coeval rocks in the central Baird Mountains quadrangle, but Upper Devonian rocks in these areas display contrasting facies and suggest that these rocks were not contiguous during deposition. No rocks correlative with the Devonian part of the Maiyumerak sequence are known to occur within the Schwatka structural province in the northeastern Baird Mountains quadrangle; at least some parts of the Schwatka province may have been subaerially exposed throughout the Middle and (or) Late Devonian. No evidence of unconformity has been found within the Maiyumerak sequence, but intertidal and supratidal environments prevailed towards the end of the Middle Devonian. These are the shallowest depositional environments that have been documented in the Maiyumerak sequence, and correspond to a period of uplift and (or) regression throughout northern Alaska.

Terrigenous material in the Maiyumerak carbonate sequence matches the Endicott Group in age and composition and was probably derived from the same source. This conclusion necessitates certain modifications of the paleogeographic model proposed by Mayfield and others (1988) for the western Brooks Range. Their model implies a Devonian-Mississippian paleogeography similar to that of present-day northeastern Australia, with the Endicott delta separated from the Kelly carbonate platform by a trough 50-100 km wide. A common provenance for the Endicott Group and terrigenous detritus reaching the Kelly carbonate platform suggests that any trough between the two was only an embayment, and (or) did not form until Late Mississippian time. The Kelly platform was drowned in late Meramecian time, and neritic carbonate deposition was never reestablished in this part of northwestern Alaska; demise of the carbonate platform most likely reflects long-term tectonic factors, such as northward drift of northern Alaska, in conjunction with a short-term eustatic rise.

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