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Preliminary Geologic Map of eastern Leffingwell Ridge, northeastern Arctic National Wildlife Refuge, Brooks Range, Alaska

by

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Abstract

Leffingwell Ridge is the northern flank of the regional anticlinorium that defines the range front of the Brooks Range of the northeastern Arctic National Wildlife Refuge (ANWR). The anticlinorium is cored by deformed and slightly metamorphosed pre-Mississippian rocks of the Franklinian sequence, with the north and south flanks defined by Mississippian through Triassic rocks of the Ellesmerian sequence. These Mississippian and younger rocks are very similar to the age-equivalent stratigraphy at Prudhoe Bay, and are the northernmost exposed rocks south of the ANWR coastal plain.

The structural character of the Mississippian and younger rocks of Leffingwell Ridge varies along strike from a steeply north-dipping homocline in the west to a series of detachment folds to the east. Between the Aichilik River and the Ekaluakat River, a laterally extensive klippe is preserved in synclinal lows between Leffingwell Ridge and a series of small en echelon folds to the north. The klippe duplicates almost the entire Ellesmerian sequence and was emplaced from the south prior to, and subsequently deformed by, the formation of the regional anticlinorium. Existence of the klippe suggests that shortening within the Ellesmerian sequence has been primarily by large-scale thrust duplication of most of the Ellesmerian section above a detachment in the Mississippian Kayak Shale.

Pre-Mississippian rocks of the core of the anticlinorium display two generations of structures: an early foliation sub-parallel to bedding and a later, steeply south-dipping cleavage. Regionally, these rocks can also be divided into three distinct and laterally extensive east-trending stratigraphic packages that are separated by thrust faults. At least one of these faults involves the Kayak Shale, suggesting that these stratigraphic packages may be horses in a duplex within the pre-Mississippian Franklinian sequence beneath a roof thrust in the Kayak Shale. The discordance in trends between the horses and the regional anticlinoria may reflect a pre-existing east-trending structural grain within the Franklinian sequence that was reactivated during Late Cretaceous to Tertiary formation of the anticlinoria.

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Introduction

Leffingwell Ridge is a long and narrow ridge that defines the topographic range front of the Brooks Range in the northeastern Arctic National Wildlife Refuge (ANWR). The ridge marks the northern flank of a regional, east-northeast trending anticlinorium that extends from the Canadian border in the east to the Jago River in the west. This anticlinorium defines the range front in eastern ANWR and consists of a core of highly deformed pre-Mississippian rocks, with north and south flanks of Mississippian through Triassic sedimentary rocks (Reiser et al., 1980). These Mississippian and younger rocks are similar to the age-equivalent stratigraphy at Prudhoe Bay to the west (Reiser, 1970; Bird and Magoon, 1987). The Mississippian to Jurassic rocks at Leffingwell Ridge are the northernmost exposed rocks south of the ANWR coastal plain.

The structural geometry and evolution of Leffingwell Ridge and the associated regional anticlinorium are being studied as part of a Ph.D. dissertation at the University of Alaska, Fairbanks. Leffingwell Ridge between the Aichilik and Egaksrak Rivers, as well as a portion of the pre-Mississippian core of the anticlinorium, was mapped at 1:25,000 scale during the summer of 1986 (Hanks, 1987). Detailed mapping of Leffingwell Ridge from the Egaksrak River to the Ekaluakat River continued during 1987 and is the subject of this report.

Mississippian through Jurassic rocks

Stratigraphy

The Mississippian through Jurassic rocks exposed at Leffingwell Ridge are very similar to rocks of the same age encountered in the subsurface of the North Slope, and can be considered equivalent to the autochthonous stratigraphy of the North Slope (Reiser, 1970; Armstrong and Mamet, 1975; Detterman et al., 1975). This stratigraphy formed on a south-facing passive continental margin that existed from Mississippian through Early Cretaceous time. This continental margin experienced similar depositional conditions throughout the North Slope subsurface and the northeastern Brooks Range, with lateral variations in stratigraphy being easily explained by variations within the depositional environment. These lateral changes in stratigraphy can have

significant implications for the structural evolution and geometry of subsequent deformational events (Wallace and Hanks, 1988 a & b).

The Endicott Group is poorly exposed in the 1987 map area and consists of a basal sequence of shales and thin siliceous siltstones and sandstones and an upper carbonate-dominated sequence. There are no good exposures of the lower Mississippian unconformity, although the location of the unconformity and the nature of the rocks both above and below it can be fairly precisely defined in several localities (for ex., Sheet 1, S12, T2N, R39E). There are no indications that the Kekiktuk Conglomerate is a significant stratigraphic unit east of the Egaksrak River, and if present at all, it is probably less than 5 meters thick.

Where exposed, the lower part of the Endicott Group consists of siliciclastic sediments, primarily shales grading up into interbedded thin siltstones and fine-grained sandstones. Where this unit can be defined, it has been mapped as Mes. This part of the Endicott Group is very poorly exposed. Where it can be roughly measured, Mes appears to be over 150 meters thick. However, some of this apparent thickness may be due to structural thickening near the unconformity surface. Lithologically and stratigraphically, this unit is equivalent to the Mississippian Kayak Shale (Reiser et al., 1980) and will be refered to as the Kayak Shale later in this report.

The upper part of the Endicott Group consists of carbonate grainstones and boundstones with interbedded carbonate mudstones and local siliceous shales. Where it can be identified, this sequence has been mapped as Mel. The boundstones within this sequence vary abruptly in thickness along strike, and are commonly totally absent. This carbonate interval appears to be gradational with the overlying Alapah Limestone of the Lisburne Group, but is easily distinguished from it by the lateral variability in lithology and fossilifereous nature of the limestones of the Endicott Group.

The Mississippian Lisburne Group is the primary ridge-forming unit of the Mississippian and younger rocks of northeastern ANWR, and essentially defines the backbone of Leffingwell Ridge. Despite this, the actual exposure of the Lisburne Limestone is quite poor, consisting mainly of frost-riven rubble. In the structurally intact sections which occur between the Egaksrak and Ekaluakat Rivers, exposure of measurable Lisburne Group is less than 30%. The Lisburne Group can be divided into two units for mapping purposes--the Alapah Limestone, and the Wahoo Limestone. The Alapah Limestone consists primarily of peloidal packstone with minor grainstones, while the overlyng Wahoo consists of skeletal grainstones and bryozoan packstones. The Alapah remains fairly constant in thickness, while the Wahoo appears to increase in thickness to the east.

The Sadlerochit Group is poorly exposed between the Egaksrak and Ekaluakat Rivers, although exposure was good enough to determine the location and approximate attitude of the various mappable horizons within the group. There are no measurable sections of the Sadlerochit

Group in the 1987 map area.

The Triassic Shublik Formation and Triassic Karen Creek Sandstone are present between the Egaksrak and Ekaluakat Rivers, but very poorly exposed. Due to poor exposures, neither the sandstone interval within the Shublik Formation (Trss, Hanks, 1987) nor the Karen Creek Sandstone could be reliably distinguished east of the Egaksrak River and so were not mapped separately. There were indications immediately east of the Egaksrak River (Sheet 1, S29 & 30, T3N, R39E) that the Shublik Formation may become sandier to the east.

The Jurassic Kingak Shale is not exposed east of the Egaksrak River, although it is exposed to the west, along the Aichilik River (Hanks, 1987).

Structural Stratigraphy

The stratigraphy of the Leffingwell Ridge area can be divided into several structurally distinct packages of structurally competent rocks separated by relatively incompetent shale horizons. These shales have acted as detachment horizons during the structural development of Leffingwell Ridge, resulting in variations in structural style throughout the stratigraphic column.

The two most important detachment horizons are the Mississippian Kayak Shale and the Jurassic Kingak Shale. The existence of these two detachment horizons has permitted large-scale duplication of the entire intervening sequence (MP Lisburne through Tr Karen Creek Sandstone) in the Egaksrak River klippe. Detachment of the Lisburne Limestone from the underlying Kayak Shale has also resulted in some detachment folding of the Lisburne Group (for ex., Sheet 1, S31, T3N, R40E).

Other structural detachments of minor importance include the Triassic Kavik Shale and shales within the Triassic Shublik Formation. Detachment along the Kavik Shale has resulted in local disharmonic folding between the Permian Echooka Formation and the Triassic Ledge Sandstone (for ex., Sheet 1, S23, T3N, R39E).

Structural Geology

Leffingwell Ridge is the northern flank of the large, basement-cored east-northeast trending anticlinorium that forms the major range-front structure of northeastern ANWR from the Jago River to the Canadian border. West of the Okerokovik River, Leffingwell Ridge is defined by a north-dipping homocline (Reiser et al., 1980). East of the Okerokovik River, a series of east-trending, doubly-plunging anticlines occurs north of the homocline and are the last structural highs south of the coastal plain. These anticlines are generally less than 6 miles (10 km) in length and, where best exposed, involve the Mississippian Lisburne Limestone through Triassic Karen

Creek Sandstone (for ex. Aichilik River, Hanks, 1987; possibly Ekaluakat River, Sheet 1, S22, T3N, R40E, this report). Most commonly these folds are defined by the Triassic Ledge Sandstone. The folds may be fault-bend folds associated with thrust ramps in the underlying pre-Mississippian basement (cross-section A, Hanks, 1987; Sheet 2, cross-sections C and D, this report). These anticlines are oriented on a slightly more easterly trend than that of Leffingwell Ridge itself and appear to occur in a left-stepping en echelon configuration. Two, possibly three, of these anticlines can be recognized between the Egaksrak and Ekaluakat Rivers.

East of the Egaksrak River, the homocline which defines Leffingwell Ridge broadens into an asymmetric, north-vergent syncline/anticline pair. Lateral variations in smaller structures (ie. tight detachment folding and/or thrusting) in the hinge area of the anticline reflect lateral variations in the accomodation of shortening. This fold pair extends as far east as the Ekaluakat River, where the syncline disappears due to the exposure of deeper structural levels.

The Egaksrak River klippe, first recognized between the Aichilik and Egaksrak Rivers (Hanks, 1987; Hanks and Wallace, 1987), is preserved in the synclinal low between the anticline/syncline pair that forms Leffingwell Ridge and the system of frontal anticlines to the north. The klippe is best exposed between the Aichilik and Egaksrak Rivers and extends east of the Egaksrak where it eventually disappears due to increasing depth of erosion. The klippe reappears immediately west of the Ekaluakat River. Here, the geometry of the klippe has been modified slightly by the development of a minor thrust and associated fault-propagation fold along the northern flank of the anticline south of the klippe (Sheet 2, cross-section D).

The relationship of the northernmost exposure of Lisburne Limestone along the Ekaluakat River to the rest of Leffingwell Ridge is equivocal. In this location, the Lisburne Limestone is very well exposed and is highly imbricated with at least four discernable thrust slices. This may represent the structurally complex core of a frontal anticline, similar to the small Lisburne-cored anticline on the Aichilik River (Hanks, 1987; Reiser et al., 1980). Alternatively, this imbricated Lisburne section may represent the lateral equivalent of the Egaksrak River klippe.

Pre-Mississippian rocks

Stratigraphy and structure

Pre-Mississippian rocks are moderately to poorly exposed in the 1987 map area and immediately to the south. For the purposes of this report, the pre-Mississippian rocks immediately south of Leffingwell Ridge between Redwacke Creek and the Ekaluakat River have been divided into three map units: a siltstone unit of presumed Ordovician age (Os); a phyllite unit of undetermined age (ph) and an undifferentiated pre-Mississippian unit (pC?).

The Ordovician siltstone unit is well exposed along the Ekaluakat River and consists of thinly bedded siltstones and fine-grained sandstones. This unit corresponds to the unit mapped as Os by Reiser et al. (1980). The Ordovician age reported by Reiser et al. (1980) is based on a graptolite locality along the Canadian/US border 20 miles to the east. No graptolites were found along the Ekaluakat River, although the siltstone did contain abundant trace fossils. For the purposes of this report, a volcanic unit associated with Os along the Ekaluakat River (Ov of Reiser et al., 1980) has also been included in Os. No lithologies similar to Os were seen in the pre-Mississippian rocks west of the Aichilik River during the 1986 field season (Hanks, 1987).

At least two deformational episodes have affected Os. The first deformation (D1) resulted in the development of a micaceous foliation (S1) subparallel to bedding. The second deformation (D2) is represented by an east-trending, steeply south-dipping spaced cleavage.

The phyllite of undetermined age is also well exposed along the Ekaluakat River and vicinity and consists of silvery-green and maroon phyllites. This is essentially the same unit mapped as 'ph' by Reiser et al. (1980). No fossils have been recovered from this phyllite and its depositional age is therefore unknown.

The phyllite records at least two, and possibly three, deformational events. Original bedding is locally preserved and has been deformed into isoclinal, recumbent folds. This deformational event (D1) may or may not be the same as the deformational event that resulted in a pervasive, mostly south-dipping phyllitic foliation. A later, near-vertical crenulation and dissolution cleavage cross-cuts the pervasive foliation, and may represent D2.

The contact of the phyllite with the underlying Os is obscured, but the phyllite immediately adjacent to the contact is highly deformed and sheared, with numerous sheared quartz veins subparallel to the pervasive foliation. This suggests that the contact between Os and the phyllite is tectonic in nature.

The final pre-Mississippian map unit, pC (?) undifferentiated, includes several individual units that have been combined for the purposes of this report. These rocks are very similar to the majority of pre-Mississippian rocks exposed west of the Ekaluakat River--interbedded tan limestones, dolomitic limestones and sandy dolomites and limestones. These rocks are highly deformed, with the style of deformation somewhat controlled by the percentage of interbedded shales. In general, these rocks have also experienced at least two deformations, although evidence of both deformational events are not necessarily present in all exposures, and are best preserved in the finer-grained and thinner-bedded lithologies. In general, D1 is recorded by a pervasive foliation subparallel or parallel to bedding. D2 is reflected by a more steeply dipping, albeit sporadic, spaced cleavage.

The contact between pC (?) and the underlying ph along the Ekaluakat River is fairly well exposed and consists of a 'broken formation' of highly deformed shales, siltstones and thin

sandstones. This unit has been tentatively correlated as Os, and has been interpreted as a thrust slice between the overlying pC (?) and ph.

Regional Structural Interpretation and Conclusions

The Mississippian through Jurassic rocks of Leffingwell Ridge are in the northern flank of a large regional anticlinorium that forms the range-front of the Brooks Range in northeastern ANWR. The structural character of these Ellesmerian sequence rocks varies along strike from a steeply north-dipping homocline in the west to a series of detachment folds to the east. A series of small, en echelon left-stepping, possibly basement-involved, folds develop to the north of the ridge proper. A laterally extensive klippe duplicating most of the Ellesmerian sequence is preserved from the Aichilik River to the Ekaluakat River in synclinal lows between these frontal anticlines and Leffingwell Ridge. This klippe was emplaced from the south and subsequently deformed by the formation of the regional anticlinorium. Based on the range of possible footwall cutoffs, the klippe may have been displaced as few as 6 kilometers, or as many as 26 kilometers (Hanks and Wallace, 1987). Regardless of the amount of displacement, the existence of the klippe suggests that shortening within the Ellesmerian sequence has been primarily by large-scale thrust duplication, with the Mississippian Kayak Shale and the Jurassic Kingak Shale acting as major detachment surfaces. This contrasts with the deformational style within the Ellesmerian sequence in northwestern ANWR, where shortening within the Mississippian through Jurassic rocks is by detachment folding above the Kayak Shale detachment (Wallace and Hanks, 1988 a & b).

It has been difficult to determine the degree and nature of the involvement of the pre-Mississippian rocks in the formation of the anticlinorium because of poor exposures of both the pre-Mississippian rocks themselves and of the pre-Mississippian unconformity. The Kayak Shale, which has acted as a detachment horizon between the Ellesmerian cover and Franklinian basement, is only sporadically and generally poorly exposed. However, at least 2 generations of pervasive structures exist in the pre-Mississippian rocks: an early foliation sub-parallel to bedding and a later, steeply south-dipping pervasive cleavage. The apparent truncation of the later pervasive cleavage and related structures by the pre-Mississippian unconformity and the consistent south dip of all pre-Mississippian lithologies have led earlier workers to conclude that all the pervasive structures within the Franklinian sequence predate the unconformity. This in turn suggests that there may have been a Devonian or older north-vergent deformational event.

In contrast, Oldow et al. (1987) have observed that, in western ANWR, the later, steeply-dipping pervasive cleavage shares essentially the same trend as pervasive structures in the overlying Kayak Shale. This relationship has been interpreted to mean that the pervasive structures in both the pre-Mississippian rocks and the overlying Ellesmerian sequence developed during the

same deformational event, specifically the formation of the regional anticlinoria. From this, Oldow et al. conclude that all of the north-vergent folds, faults and penetrative fabrics within the pre-Mississippian rocks of the northeastern Brooks Range are of latest Cretaceous to Tertiary age. The earlier, bedding-parallel foliation and related structures are interpreted as remnants of a south-vergent, Devonian or older event.

These conclusions are based on reconnaissance studies of mesoscopic and microscopic fabrics within the pre-Mississippian rocks of western ANWR and should be testable. The interpretation requires that the Mississippian Kekiktuk Conglomerate, the basal conglomerate immediately above the pre-Mississippian unconformity, be penetratively deformed during the formation of the anticlinoria along with the underlying pre-Mississippian rocks. Alternatively, the Kekiktuk Conglomerate could itself be duplexed between a roof thrust in the Kayak Shale and a floor thrust in the pre-Mississippian rocks. Studies of the deformational history of both the pre-Mississippian rocks and the Mississippian Kekikuk Conglomerate in various areas of ANWR are currently in progress in order to address these problems.

Several additional observations can be made in the Leffingwell Ridge area of northeastern ANWR that may have bearing on this problem. The pre-Mississippian rocks in the core of the anticlinorium can be divided into three distinct stratigraphic packages that are separated by thrust faults based on mapping during the 1986 and 1987 field seasons (Hanks, 1987; this report), and on the 1:250,000 geologic map of Demarcation Point quadrangle (Reiser et al., 1980). Kayak Shale is imbricated between pre-Mississippian rocks along at least one of these faults, suggesting that these stratigraphic packages may be horses in a duplex within the pre-Mississippian Franklinian sequence beneath a roof thrust in the Kayak Shale. These stratigraphically and structurally distinct packages are fairly large (5-10 km wide, 30+ km long) and trend eastward, in contrast to the east-northeast orientation of the anticlinorium. This discordance in trends may reflect a pre-existing east-trending structural grain within the Franklinian sequence. This pre-existing structural grain may have controlled the development of the individual structural packages or 'horses' during the formation of the regional anticlinorium. The relationship between these horses and the pervasive structures within the pre-Mississippian rocks is unclear, and will be a major focus of the 1988 field season.

Implications for the ANWR coastal plain

Pre-existing structural trends and variations in lithology within the pre-Mississippian Franklinian sequence have had a strong influence on the formation and geometry of the exposed regional anticlinoria. This relationship can be logically inferred to extend north into the subsurface of the ANWR coastal plain.

The exact nature and degree of involvement of the pre-Mississippian rocks in the Late

Cretaceous and Tertiary development of the anticlinoria also has implications for the distribution and reservoir quality of the Mississippian Kekiktuk Conglomerate, if it is present in the subsurface to the north. If formation of the regional anticlinoria was accompanied by pervasive deformation of the Franklinian sequence and overlying Mississippian Kekiktuk Conglomerate, the basal conglomerate may occur as a relatively continuous horizon, but its reservoir potential would, in all likelihood, be significantly diminished. Alternatively, if there was no development of pervasive structures associated with the formation of the anticlinoria, the reservoir quality of the basal conglomerate may remain high, although the conglomerate may be structurally imbricated with pre-Mississippian rocks.

Lateral variations in structural style of the Ellesmerian sequence have direct implications for the structural style and distribution of potential reservoir horizons within the 1002 area. In northeastern ANWR, the existence of the Egaksrak River klippe at Leffingwell Ridge documents major thrust duplication within the Ellesmerian sequence. This contrasts markedly with northwestern ANWR, where shortening within the Ellesmerian sequence is primarily by detachment folding. If similar lateral changes in structural style occur to the north, the Ellesmerian sequence may be structurally duplicated in the subsurface of the eastern 1002 area.

Aknowledgements

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UNIT DESCRIPTIONS

Qal Quaternary alluvium

Trkc Triassic Karen Creek Sandstone

Dark gray-weathering, sooty gray, fine- to medium-grained quartz lithic phosphatic sandstone. Massive, highly bioturbated with few preserved sedimentary structures. Approximately 30 to 45 meters thick.

Trs Triassic Shublik Formation

Black, thinly bedded, phosphatic shale, siltstone, fine-grained sandstones and minor black fossiliferous limestones. Locally highly deformed. Thickness cannot be determined in study area.

Trsk Triassic Shublik Formation and Karen Creek Sandstone, undifferentiated

Dark gray-weathering very fine- to fine-grained quartz lithic sandstone. Commonly bioturbated and locally phosphatic.

Trlf Triassic Ledge Sandstone/Fire Creek Siltstone (Undifferentiated) members of the Ivishak Formation

Tan- to orangish tan-weathering, fine- to medium-grained pyritic quartz sandstone and siltstone, with local grit and pebble conglomerates. Massive with few sedimentary structures, except for local low-angle crossbedding. Bedding generally <.5 meters thick. Forms prominent ridges of frost-riven rubble. Approximately 65 to 90 meters thick.

Trks Triassic Kavik Shale member of the Ivishak Formation

Brown, thinly bedded siltstone and shale. Poorly exposed in study area. Approximately 130 meters thick.

Pe Permian Echooka Formation

Reddish-brown, thinly bedded (10 cm) calcareous bioclastic limestones, calcareous sandstones and bioturbated siltstones. Approximately 50-100 meters thick.

Pw Pennsylvanian Wahoo Formation

Light gray- to buff-weathering skeletal and oolitic grainstones and bryozoan packstones. Contains prominent orange-weathering horizons toward top. Thickens from 200 meters in the west to approximately 300 meters in east.

Ma Mississippian Alapah Formation

Light gray-weathering peloidal packstones. Approximately 400meters thick.

Mel Mississippian Endicott Group--limestones

Overlies Mes. Thin-bedded skeletal grainstones with locally well-developed coral boundstones. Very fossiliferous, with abundant corals, brachiopods and crinoids. Gradational contact with overlying Alapah Limestone. Thickness laterally variable from < 50 meters to > 200 meters.

Mes Mississippian Endicott Group--siliciclastic sediments

Black, locally deformed shales and siltstones with minor thin-bedded (<30 cm), fine- to course-grained, quartz lithic sandstones. Poorly exposed in study area. Approximate thickness of 150 meters, but this may include some structural thickening.

Meu Mississippian Endicott Group undifferentiated.

Includes both the Mes and Mel. Generally poorly exposed, with Mel not well developed.

Os Ordovician sediments

Thinly bedded dark gray siltstones, shales and fine-grained sandstones. Locally highly bioturbated on bedding surfaces. Locally pyritic. Polydeformed and slightly metamorphosed. Thickness indeterminate. Well-exposed on the Ekaluakat River. Ordovician age based on graptolite locality on the U.S.-Canada border to the east (Reiser et al. 1980).

ph phyllite

Polydeformed silvery green and maroon phyllites of unknown depositional or metamorphic age. Well-exposed on the Ekaluakat River. Thickness indeterminate.

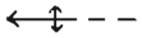
pC (?) Pre-Cambrian (?) sediments, undifferentiated.
Interbedded tan limestones, dolomitic limestones, sandy dolomites and limestones and green and black shales. Highly deformed. Age and thickness unknown.

GEOLOGIC MAP SYMBOLS

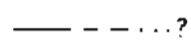

Strike and dip of beds


Strike and dip of overturned beds


Strike and dip of foliation or cleavage


Trend and plunge of trace of fold axis, dashed where approximately located.


Trend of axial surface of flexure where dip changes magnitude but not direction


Contact: solid where known, dashed where approximate, dotted where covered, queried where questionable.

Thrust fault: solid where known, dashed where approximate, dotted where covered, queried where questionable.


Fault: solid where known, dashed where approximate, dotted where covered, queried where questionable.