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Preliminary Geologic Map of Central Leffingwell Ridge, Arctic National Wildlife Refuge, Northeastern Brooks Range, Alaska

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Abstract

Leffingwell Ridge is the northern limb of a regional east-northeast trending anticlinorium and forms the range front of the northeastern Brooks Range in the eastern Arctic National Wildlife Refuge (ANWR). Pre-Mississippian rocks of the Franklinian sequence form the core of the anticlinorium, with Mississippian through Triassic rocks of the Ellesmerian sequence forming the north and south limbs. Detailed mapping of pre-Mississippian rocks immediately south of Leffingwell Ridge suggests the possibility of Mesozoic to Cenozoic small scale duplexing of the pre-Mississippian rocks beneath a roof thrust in the Mississippian Kayak Shale. The regional anticlinorium would have been the result of this duplex formation, and may have occurred as recently as Tertiary time.

Detailed mapping of central Leffingwell Ridge between the Okerokovik and Egaksrak Rivers has documented a previously unmapped thrust that emplaces Mississippian Kayak Shale through Triassic Karen Creek Sandstone over Karen Creek Sandstone, with a minimum of 5 kilometers of displacement. The thrust sheet has been preserved as a klippe in the vicinity of the Egaksrak River and documents major detachment within both the Kayak Shale and the Kingak Shale. This represents a major change from the structural syle in the western part of the northeastern Brooks Range, where major thrust duplication of the Ellesmerian section has not been recognized.

Introduction

Leffingwell Ridge is the northern flank of a large east-northeast trending, west-plunging anticlinorium that forms the range front of the Brooks Range in the eastern Arctic National Wildlife Refuge (ANWR). The anticlinorium is cored by pre-Mississippian rocks of the Franklinian sequence (Reiser etal, 1980). Mississippian through Jurassic rocks of the Ellesmerian sequence define the northern and southern limbs of the structure. The northern flank of the anticlinorium, Leffingwell Ridge, is the last exposure of the Ellesmerian stratigraphy south of coastal plain of ANWR.

During the summer of 1986, a portion of Leffingwell Ridge was mapped at a scale of 1:25,000 as part of a Ph.D. project being done in the Department of Geology and Geophysics of the University of Alaska-Fairbanks. The preliminary map covers Leffingwell Ridge proper from the east bank of the Okerokovik River to the west bank of the Egaksrak River. Also included in the mapping were the pre-Mississippian rocks immediately to the south of Leffingwell Ridge between the Okerokovik and Aichillk Rivers.

Pre-Mississipplan rocks and structure

The pre-Mississippian rocks exposed south of Leffingwell Ridge consist primarily of limestones, with local calcareous sandstones and argillaceous shales. The exposure is exceedingly poor and the rocks highly deformed. The rocks have been mapped as pre-Cambrian, based on Cambrian fossils found in a belt of limestones on Whale Mountain to the south (Dutro etal, 1972). However, the structural relationship of the dated limestones to the limestones immediately south of Leffingwell Ridge is poorly constrained, thus leaving the age of the northern belt of pre-Mississippian limestones in some doubt.

Three fairly distinctive units can be defined in the area immediately south of Leffingwell Ridge, west of the Aichilik River (see map legend at end of text). The structurally lowest unit consists of thin-bedded, tan-weathering rippled limestones and sandy limestones. These rocks generally dip to the south and are tightly folded into north-vergent isoclinal folds.

The rippled limestones are structurally overlain by thick-bedded, black, peloidal, commonly recrystallized limestones. The thick-bedded limestones generally display open, upright folds, having behaved as a structurally more competent unit than the rippled limestones.

A reddish-tan weathering, argillaceous shale, grading to phyllite, is associated with both of the limestone units. This shale is penetratively deformed, with a generally south-dipping cleavage. The shale occurs structurally both above and below the massive black limestone. The shale is commonly poorly exposed, but where it is seen, it becomes more penetratively deformed approaching the contact with the black limestone.

The poor exposure and an indeterminate original stratigraphy limit the confidence level at which the pre-Mississippian structure can be interpreted. In the area mapped, there is a definite structural stratigraphy: rippled limestones overlain by shales overlain by thick-bedded black limestones overlain by shales. However, black limestones with intervening thin limestones and shales occur repeatedly above this basal stratigraphy. Whether this repetition is due to the original depositional stratigraphy, or alternatively is due to structural repetition is presently unclear. The rocks are obviously highly deformed, with a generally south-dipping, east-west trending structural grain. Most of the lithologic contacts presently appear to be structural contacts, but the amount of displacement on these faults is unknown. It is conceivable that some, if not all, of the lithologic contacts were originally stratigraphic, but later acted as slip surfaces due to rheologic contrasts between the different lithologies. However, the repetition of the black limestone suggests the possibility of repeated structural duplication of a specific stratigraphic interval, perhaps in a duplex.

Mississippian and younger rocks

The Mississippian and younger rocks exposed at Leffingwell Ridge are broadly equivalent to the autochthonous stratigraphy of the North Slope, including Prudhoe Bay (Reiser, 1970; Detterman etal, 1975; Armstrong and Mamet, 1975). The gross stratigraphy is essentially the same as that seen elsewhere in the North Slope autochthon. Several units within the Ellesmerian sequence have particular structural significance in the Leffingwell Ridge area, either as probably detachment horizons, or as good marker horizons.

The Endicott Group in the eastern portion of Leffingwell Ridge consists almost entirely of Kayak Shale. A significant amount of Kekiktuk Conglomerate is present to the west, near the Jago River (Pavia, 1986; Sable, 1977), but very little is exposed east of the Okerokovik River. The Kekiktuk is probably depositionally thin or missing in this area. The Kayak shale is a thick unit that underlies most of the talus-covered south-facing slopes of Leffingwell Ridge. The Kayak is very poorly exposed west of the Aichilik River. However, east of the Aichilik river the

Kayak is better exposed and consists primarily of siltstones, minor carbonaceous shales and abundant limestones, specifically grainstones, packstones and locally thick coral boundstone sequences. Exposures are not good enough, however, to measure a complete section of Kayak shale.

The Mississippian and Pennsylvanian Lisburne Limestone is the major ridge former at Leffingwell Ridge. The Mississippian Alapah Formation is generally poorly exposed although in a few areas fairly continuous sections are preserved. The Alapah consists primarily of a monotonous sequence of peloidal packstones. The Pennsylvanian Wahoo Formation is moderately well exposed and consists of shallowing-upward cycles of bryozoan baffiestones and skeletal grainstones.

Most of the Sadlerochit Group is poorly exposed, with local good exposures of all the formations of the group. The Echooka Formation, the Kavik members and Ledge/Firecreek (undifferentiated) members of the Ivishak Formation were mapped as distinct horizons. The Ledge Sandstone forms prominent ridges, but the ridges are almost entirely mantled with rubble.

The Shublik Formation as a whole is very poorly exposed with only a few scattered outcrops in the entire field area. However, a thin (<15 meters thick) sandstone layer within the Shublik is mappable throughout the field area and provides a good marker horizon.

Overlying the Shublik Formation, the Triassic Karen Creek Sandstone is a prominent minor ridge former and is a mappable horizon throughout the field area. Although the Shublik sandstone and the Karen Creek are lithologically very similar, they both provide good marker horizons above the Ledge Sandstone and therefore were critical in delineating the structure.

The Jurassic Kingak Shale overlies the Karen Creek Sandstone, but is very poorly exposed in this area. Only minor rubblecrops are visible along most of the range front. However, there is a fairly good exposure of the Kingak Shale that forms the west bank of the Aichilik River for almost 2 miles north of Leffingwell Ridge. Although the best outcrop of Kingak Shale in the area, the Kingak along the Aichilik River is highly deformed and bedding is very difficult to discern.

Several stratigraphic intervals stand out as being potential detachment horizons due to their lithology. These include: the Kayak Shale; the Kavik Shale of the Ivishak Formation; the shale of the Shublik Formation; and the Kingak Shale.

Structural Geology of Leffingwell Ridge

To the west, near the Okerokovik River, Leffingwell Ridge forms a

steeply north-dipping homocline involving Mississippian through Triassic rocks. However, the regional west plunge of the structure results in progressively deeper structural levels being exposed to the east. The homocline at the OkerokoviK River rapidly gives way to the tight anticline that forms the range front immediately west of the Aichilik River. This fold also plunges to the west and involves Mississippian Alapah Limestone through Triassic Karen Creek Sandstone. The geometry of this structure suggests that it is a fault-bend fold related to the ramping of a thrust fault from the pre-Mississippian basement up into the Kingak Shale (see cross-section A, sheet 2). The tightness of the fold, the relatively short back limb and the need to maintain constant bed thicknesses suggest that the ramp is fairly steep, possibly 45^{o} or greater. Ramps normally dip $10\text{-}20^{o}$ (Suppe, 1983). The steepness of this ramp could be due to the reactivation of an older structure, such as a normal fault.

The overall steep northward dip of bedding at Leffingwell Ridge abruptly gives way to gentle dips east of the Aichilik River. The westward plunge of the range front fold changes east of the Aichilik River to an easterly plunge and progressively higher structural levels are preserved. The entire Mississippian through Triassic sequence is exposed in this area, from Kayak Shale thru Karen Creek Sandstone. Disharmonic folding and minor thrusting within the Ledge Sandstone as compared to broad open folding within the underlying Lisburne Limestone and Echooka Formation suggest minor detachment within the Kavik Shale. Other than this minor structural complication, the entire sequence from the Alapah Limestone up to Karen Creek Sandstone appears fairly coherent. Local tight folding within the Kayak Shale does suggest the possibility of some detachment of the Lisburne Limestone and overlying rocks from the underlying pre-Mississippian rocks. However, the amount of displacement, if any, along a detachment in the Kayak cannot be determined at present. Therefore, the Mississippian through Triassic sequence of Leffingwell Ridge may be considered parautochthonous.

Progressively higher structural levels are preserved further to the east, exposing a major klippe, the 'Egaksrak River klippe'. This klippe is a preserved remnant of a once extensive thrust sheet with significant displacement. This thrust emplaces a well preserved, stratigraphically intact sequence of Kayak Shale thru Triassic Karen Creek Sandstone over Karen Creek Sandstone of the underlying parautochthonous rocks of Leffingwell Ridge. The Egaksrak River klippe appears to continue for some distance east of the Egaksrak River and is thus areally quite extensive. This klippe is significant in that it documents major thrust duplication within the Ellesmerian sequence involving significant horizontal displacement. The exact amount of the displacement is as yet

undetermined, but is probably greater than five kilometers. The Egaksrak River klippe also documents significant detachment in both the Kayak Shale and the Kingak Shale.

Immediately to the south of the Egaksrak River klippe, an out-of-sequence thrust and related fault-propagation fold is developed in the Lisburne Limestones of the parautochthonous rocks. This fault, although fairly spectacular, has relatively minor displacement. Where its stratigraphic throw is greatest, the thrust has emplaced Alapah Limestone over the Ledge/Firecreek (undifferentiated) members of the Ivishak Formation.

A third fault that may be significant is a steep, north-northwest trending fault immediately west of the Egaksrak River. This fault cuts the parautochthonous rocks of Leffingwell Ridge and possibly the Egaksrak River klippe with apparent right-lateral displacement. If this is a tear fault related to transport of the parautochthonous rocks, it may reflect the direction of transport.

Regional Structural Interpretation of Leffingwell Ridge

In the gross sense, Leffingwell Ridge can be described as the northern limb of a regional anticlinal structure that is cored by pre-Mississippian rocks. However, the age, origin and details of that structure are unclear, as is its relationship to deformation to the north in the subsurface of the ANWR coastal plain.

Map-scale structural patterns within the pre-Mississippian rocks appear to be truncated by the pre-Mississippian unconformity, suggesting that much of the deformation within the anticlinal core occurred prior to the unconformity. However, the possibility also exists that these structures are much younger than the unconformity. Structures within the pre-Mississippian rocks are similar in trend and vergence to the regional trend of the late Mesozoic to Cenozoic structures of northeastern Alaska (Mull, 1983; Reiser, 1970). Although the regional map pattern suggests truncation of the structures in the pre-Mississippian rocks by the pre-Mississippian unconformity, the overlying Mississippian Kayak Shale is poorly exposed in the Leffingwell Ridge area, and what little is seen is highly deformed. The possibility then exists that faults originating within the pre-Mississippian rocks flatten into a detachment within the Kayak Shale. A detachment within the Kayak would permit seemingly unrelated deformation above and below the detachment horizon. The deformation withing the pre-Mississippian rocks would therefore postdate the pre-Mississippian unconformity.

Another structural element that must be accounted for is the

existence of the regional anticlinorium itself. This structure has elevated pre-Mississippian through Triassic rocks with respect to the Tertiary sediments of the coastal plain. These same Tertiary sediments are themselves highly deformed. The structural relief of the anticlinorium and possibly related deformation in the sediments of the coastal plain suggests that the structure is younger than the Late Jurassic to Cretaceous Brookian orogeny and in fact may be as young as Tertiary in age.

With this evidence in mind, the anticlinal structure has been tentatively interpreted as the product of duplexing in the pre-Mississippian rocks (see cross-sections A and B, sheet 2). A duplex may have already existed in the Franklinian sequence prior to Mississippian time and may merely have been tightened during a younger (Tertiary?) deformational event. This younger event resulted in the development of a roof thrust in the overlying Kayak Shale and the formation of the regional anticlinorium.

An alternate interpretation is that there is no duplexing in the core of the anticlinorium, but the entire anticline is a fault-bend fold related to a ramp in the pre-Mississippian sequence. The first interpretation is presently favored because of the similarity in regional trend between the structures in the pre-Mississippian rocks and the structures in the Mississippian and younger rocks and because the thin bedding and strong competency contrasts of the pre-Mississippian rocks would lend themselves to duplexing.

The answer to this question of Mississippian vs younger duplexing of the Franklinian basement may lie in the distribution and deformation of the Kekiktuk Conglomerate. If the Kekiktuk is depositionally present in the area and was glued to the basement during formation of the duplex, the Kekiktuk Conglomerate should occur as carapaces on the individual horses in the duplex and thus be structurally interleaved with the pre-Mississippian rocks.

The Egaksrak River klippe has been deformed by the folding in the Mississippian and younger stratigraphy related to the formation of the basement duplex. The klippe therefore represents an event that predates formation of the regional anticlinorium. The roots of the klippe must lie south of the present-day Leffingwell Ridge. The klippe cannot have originated from the out-of-sequence thrust immediately to the south of it, although proximity makes this interpretation tempting. The Alapah/Kayak contact in the hanging wall is truncated by the out-of-sequence thrust. This same contact also is truncated by the thrust that emplaced the Egaksrak River klippe. Since the same contact cannot be truncated twice in the hanging wall of a single thrust, there can be no direct relationship

between the two faults.

The origin of the Egaksrak River klippe therefore remains speculative. It may have originated from now eroded Ellesmerian sequence rocks that once overlay the pre-Mississippian core of the regional anticlinorium, or may have come from even farther south. In either case, the existence of the klippe documents major thrust duplication within the Ellesmerian sequence involving significant horizontal displacement, as well as major detachment in both the Kayak Shale and the Kingak Shale.

Implications for the ANWR coastal plain

The existence of the Egaksrak River klippe documents major thrust duplication of the Ellesmerian sequence in northeastern ANWR. Thrusting of this magnitude and style has not been seen in the Ellesmerian sequence in northwestern ANWR. This structural duplication of potential hydrocarbon reservoirs immediately south of the coastal plain has direct implications for reservoir distribution in the subsurface to the north.

Regional structure as well as detailed mapping suggests the possibility of small-scale duplexing within the pre-Mississippian rocks of eastern ANWR. Although this hypothesis remains to be tested, such duplexing could have implications for the interpretation of the structural style, degree of shortening and potential reservoir distribution in the subsurface of ANWR coastal plain.

Aknowledgements

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UNIT DESCRIPTIONS

Qal Quaternary alluvium

JKk Lower Jurassic to Lower Cretaceous Kingak Shale
Black, thinly bedded, commonly highly deformed shale with calcareous concretions. Poorly exposed in map area.

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, thinnly bedded, phosphatic shale and siltstone. Rarely exposed in field area. Locally deformed. Approximately 175 meters thick (including Shublik Sandstone).

Trss Triassic Shublik Sandstone
Dark gray-weathering, sooty gray, fine-grained quartz lithic sandstone within the shale of the Shublik Formation. Highly bioturbated with abundant phosphate nodules. Approximately 15 to 20 meters thick with three individual sandstone layers separated by thin (1-2 meters thick) shales.

Trlf Triassic Ledge Sandstone/Firecreek Siltstone (Undifferentiated) members of the Ivishak Formation
Tan- to orangish tan-weathering, fine- to medium-grained pyritic quartz sandstone and siltstone. Locally conglomeratic. Massive with few sedimentary structures, except for occasional 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, thin bedded siltstone and shale. Coarsens upward into basal Ledge Sandstone. Occasionally contains Lingula. Approximately 130 meters thick

Pe Permian Echooka Formation

Reddish-brown, thin bedded (10 cm) calcareous bioclastic limestones and calcareous sandstones grading up to bioturbated siltstones. Basal limestones contain brachiopod fragments. Occasional thin (<10 cm) basal conglomerates containing Lisburne clasts. Approximately 90 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. Approximately 200 meters thick.

Ma Mississippian Alapah Formation

Light gray-weathering peloidal packstones, with occasional skeletal grainstones and coral boundstones. Approximately 415 meters thick.

Mks Mississippian Kayak Shale

Black, locally deformed shales and siltstones. Occasional iron stained, thin bedded (<30 cm), medium-grained, quartz lithic sandstones Local skeletal grainstones and coral boundstones towards upper part of section. Very fossiliferous, with abundant corals, brachiopods, crinoids and pelecypods. Thickness undetermined.

Mkc Mississippian Kekiktuk Conglomerate

Massive quartzite and quartz, chert pebble conglomerate. Locally iron-stained. Generally missing throughout study area due to non-deposition or poor exposure.

Mk Mississippian Endicott Group undifferentiated.

Includes both the Kayak Shale and Kekiktuk Conglomerate. In the field area, consists almost entirely of Kayak Shale.

pCbl Pre-Cambrian (?) black limestone

Black-weathering, massive, thick- to medium-bedded peloidal limestone. Commonly recrystallized. Thickness varies from 15 to 100 m.

pCrl Pre-Cambrian (?) rippled limestone

Tan- to orangish tan-weathering thinly bedded, crossbedded sandy limestones. Interbedded thin argillaceous stringers. Occasionally grades into calcareous sandstones. True thickness unknown, observed thickness generally less than 300 m.

pCsh Pre-Cambrian (?) shale

Greenish tan- and reddish tan-weathering, thinly bedded argillaceous shales. Highly deformed with a penetrative cleavage. Commonly grades into phyllite. True thickness unknown, observed thickness less than 50 meters

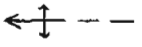
pC Pre-Cambrian (?) undifferentiated

GEOLOGIC MAP SYMBOLS

Strike and dip of beds

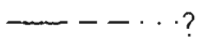
Strike and dip of overturned beds

Strike and dip of foliation or cleavage



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

Trend of axial surface of flexure where dip changes degree 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.