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DISTRIBUTION AND CHARACTER OF FRACTURES IN DEFORMED CARBONATES OF THE LISBURNE GROUP, NORTHEASTERN BROOKS RANGE, ALASKA

by

C.L. Hanks and A.P. Krumhardt
Geophysical Institute, University of Alaska

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Abstract

The distribution and orientation of naturally-occurring fractures in the Lisburne Group exposed in the northeastern Brooks Range fold-and-thrust belt can provide a clearer understanding of the origin of and geologic controls on fractures in the Lisburne Group of the North Slope subsurface. The Lisburne Group is involved in a wide variety of map-scale structures in the exposed parts of the range, providing a series of natural experiments where various models for the formation and distribution of fractures in the Lisburne Group can be tested. Structural settings and associated fracture patterns investigated in during the 1994 field season included: high-angle transverse faulting in the eastern Sadlerochit Mountains; moderate folding in the Clarence River syncline; and tight folding with minor thrust faulting in the Fourth Range.

Preliminary analysis of field results confirm that early regional fractures that form in front of a fold-and-thrust belt are overprinted or reactivated by subsequent deformation. New fractures that form in response to local structures either utilize the preexisting fracture set and/or obscure it. In the Sadlerochit Mountains, for example, young fracture sets do not necessarily developed parallel to the high angle faults (strike ~20°), but appear to reactivate and form new fractures parallel to the regional fracture set (strike ~340°). Increase in the intensity of the fault-related fractures is limited, however, to within 50-100 m of the fault itself.

In examples of folded Lisburne Group, the intensity of the folding, the position with respect to the fold hinge, and the intensity of bedding-parallel slip govern what fracture set dominates. For example, while the early regional fracture set is well-preserved on the limbs of the Clarence River syncline, extensional and shear fractures related to folding are dominant near the core of the fold. However, because the fold is relatively open, there is not abundant evidence of fracturing related to bedding-parallel slip. In contrast, in the Fourth Range where the Lisburne is deformed into tight detachment folds, the early regional fracture set can not be reliably identified, and there is abundant evidence of bedding-parallel slip and related fracturing of individual beds throughout the Lisburne Group. Large, through going NS extensional fractures are present, but appear to be relatively young and are probably related to the local fold.

Introduction

The carbonate rocks of the Carboniferous Lisburne Group are widely exposed throughout northern Alaska as an important element of the Brooks Range fold-and-thrust belt. The Lisburne Group is also a major reservoir of the North Slope. As in many carbonate reservoirs, most of the hydrocarbon production from the Lisburne Group in the subsurface is from naturally-occurring fractures (Missman and Jameson, 1991). While natural fractures play an important role in how the reservoir is produced, the geologic factors controlling the fracture distribution, character and origin are poorly understood. In the Lisburne oil field, less than 10% of the 2 billion barrels in place is recoverable at the present time (Missman and Jameson, 1991). A clearer understanding of the nature and origin of these fractures has the potential to aid in the development of secondary and tertiary recovery programs for this large, but difficult to produce, reservoir.

The Lisburne Group is widely exposed in the nearby northeastern Brooks Range fold-and-thrust belt. The Lisburne Group is involved in a variety of map-scale structures in the fold-and-thrust belt, providing a series of natural experiments where various models for the formation and distribution of fractures in the Lisburne Group can be tested. The results of this field-based study can then be applied to the origin, character and distribution of fractures in the Lisburne carbonates of the subsurface.

Regional geologic setting

The Lisburne Group is a thick sequence of platform carbonates that developed on a south-facing passive continental margin during Carboniferous time. The northernmost exposures of the Lisburne Group are in the northeastern Brooks Range of the Arctic National Wildlife Refuge (ANWR) (figure 1). The Lisburne exposed in the northern part of the range, in the Sadlerochit and Shublik Mountains, is the closest exposed stratigraphic equivalent to the reservoir of the Lisburne oil field, located approximately 75 miles to the northwest.

The Lisburne oil field is located on the south side of a major structural high that extends the length of northern Alaska margin, the Barrow Arch. The trapping mechanism of the field is a southwest-dip underneath a Lower Cretaceous unconformity (LCu). This southwest dip is most likely due to extension prior to the LCu, with additional tilting during the Tertiary (Jamison and others, 1980; Edrich, 1987). Production from the Lisburne field is strongly influenced by two sets of naturally-occurring fractures that parallel the fault trends in the field: an east-northeast striking set and a north-northwest striking set. The NNW-trending fractures are often open or only partially filled (Sampson and Marcou, 1988; Missman and Jameson, 1991).

The overall structural style of the northeastern Brooks Range fold-and-thrust belt is controlled by a north-vergent regional duplex in basement rocks between a floor thrust at depth and a roof thrust near the base of the overlying cover sequence (figure 2). Regionally, the roof thrust is localized in a major shale underlying the Lisburne Group, the Mississippian Kayak Shale (figure 3). This shale has acted as a very effective detachment horizon, permitting the Lisburne and overlying rocks to deform independently of the underlying basement rocks during Cenozoic thrusting. Throughout most of the northeastern Brooks Range, the Lisburne and overlying rocks have deformed primarily by detachment folding and/or thrusting (Wallace and Hanks, 1990).

Local variations in the extent of the detachment horizon, the amount of shortening, and the presence of high angle faults have resulted in local variations in the gross structural style of the Lisburne limestone. In the eastern Sadlerochit Mountains, for example, the Kayak Shale is depositionally thin and/or absent, and the Lisburne Group has remained structurally coupled to the

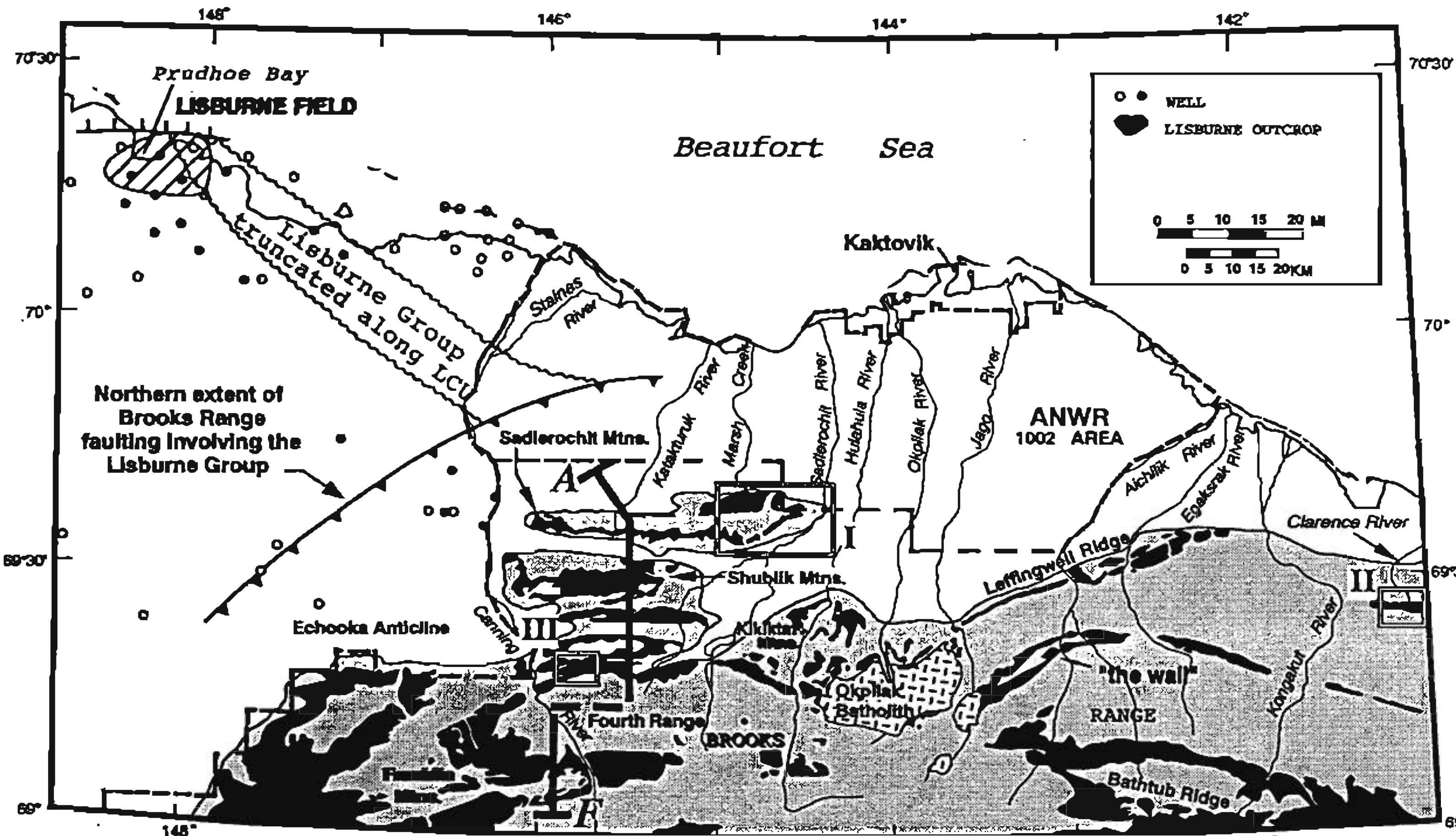


Figure 1. Generalized geologic map of the northern part of the northeastern Brooks Range showing the distribution of Lisburne Group exposures. The three outlined areas are: I. Southeastern Sadlerochit Mountains, figure 5; II. Clarence River, figure 8; III. Fourth Range, figure 16. Cross section A-F is the location of the balanced section shown in Figure 2. Map modified from Watts, 1990.

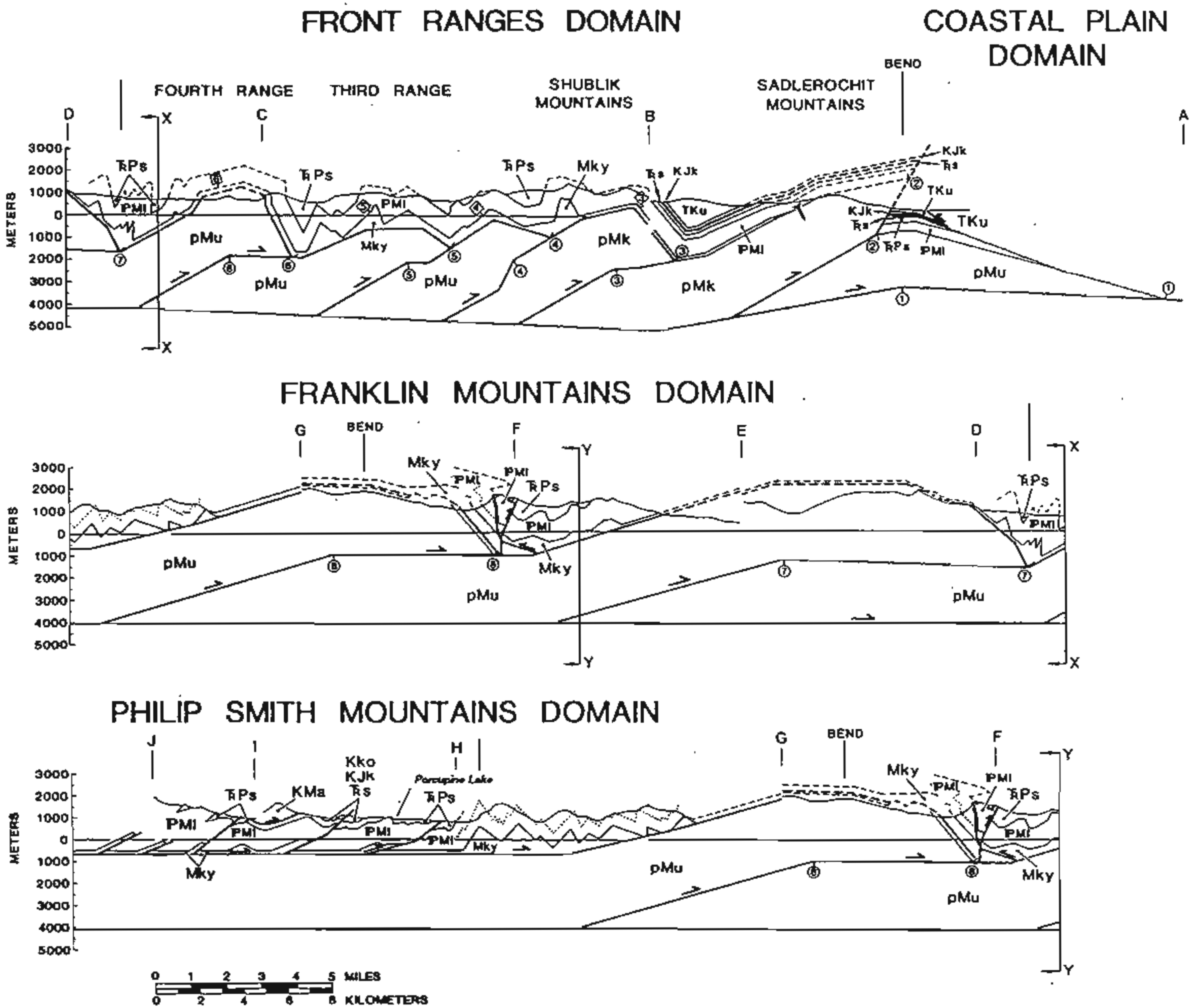


Figure 2. Balanced cross section through the western portion of the northeastern Brooks Range as shown on Figure 1. From Wallace, 1993.

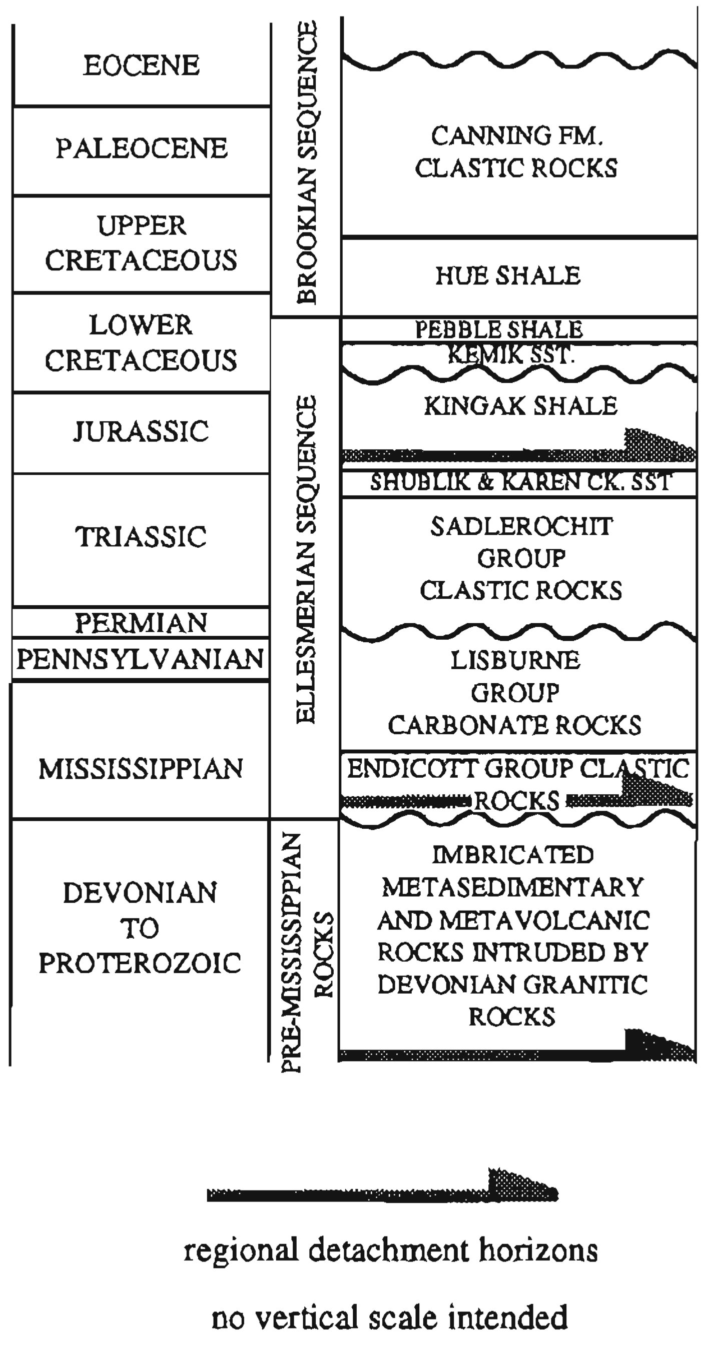


Figure 3. General stratigraphy of the northeastern Brooks Range.

underlying basement rocks during Cenozoic deformation. Consequently, the Lisburne has behaved as a passive structural member in a large thrust sheet cored by basement rocks (figure 2) and possible structural complexities due to thrusting and detachment folding are absent.

Preliminary fracture analysis of the Lisburne Limestone exposed in the eastern Sadlerochit Mountains (Hanks and others, 1994) indicates there are there are two fracture sets in the eastern Sadlerochit Mountains: an early, regional set that strikes NNW and a younger, ENE-striking set that is related to the local structure. The early NNW striking set of fractures appears to be similar in character and orientation to the younger NS striking set present in the subsurface of the Lisburne field. In addition, there is a strong correlation between fracture density and the host lithology, with dolomitized mudstones being much more intensely fractured than nearby grainstones.

The eastern Sadlerochit Mountains is the simplest of all the deformational settings of the Lisburne Group in the northeastern Brooks Range. Deformational styles within the Lisburne Group range from minor high-angle faulting (e.g.southeastern Sadlerochit Mountains), to slightly detached Lisburne folded into an open regional syncline (e.g.Clarence River) to strongly detached Lisburne deformed into tight detachment folds (eg. Fourth Range). This range in deformational styles and intensity provide an opportunity to determine if the early NNW-striking fracture set remains consist across the range in a variety of structures; if new fracture sets develop in the more complex structures or if old fracture sets are reactivated and/or enhanced; and if lithology continues to control fracture character and distribution in a variety of structural settings.

Regional Lisburne stratigraphy

In the northeastern Brooks Range and subsurface of the North Slope, the Lisburne Group is divided into two formations: the Mississippian Alapah Formation (Chesterian) and the Mississippian to Pennsylvanian Wahoo Formation (Chesterian to Morrowan/Atokan) (figure 3). The Alapah formation generally consists of a lower, thickly-bedded sequence of grainstones and packstones, and an upper, recessive-weathering sequence of wackestones and mudstones. In contrast, the overlying Wahoo formation consists of a lower, massive, cliff-forming series of primarily thickly-bedded grainstones and packstones, and an upper, more thinly-bedded and cyclic series of grainstones, packstones, wackestones, and mudstones. This thick carbonate sequence has been interpreted to have been deposited on a broad south-dipping ramp (Watts and others, 1994).

In any discussion of the structural style and consequent fracture pattern of the Lisburne Group, the presence, character and thickness of the underlying Kayak Shale should be noted. Presence of the Kayak Shale permits detachment and deformation of the overlying Lisburne into detachment folds and related thrusts. However, the Kayak Shale does not remain consistent in lithology or thickness throughout the range (figure 4). Note that in the eastern Sadlerochit

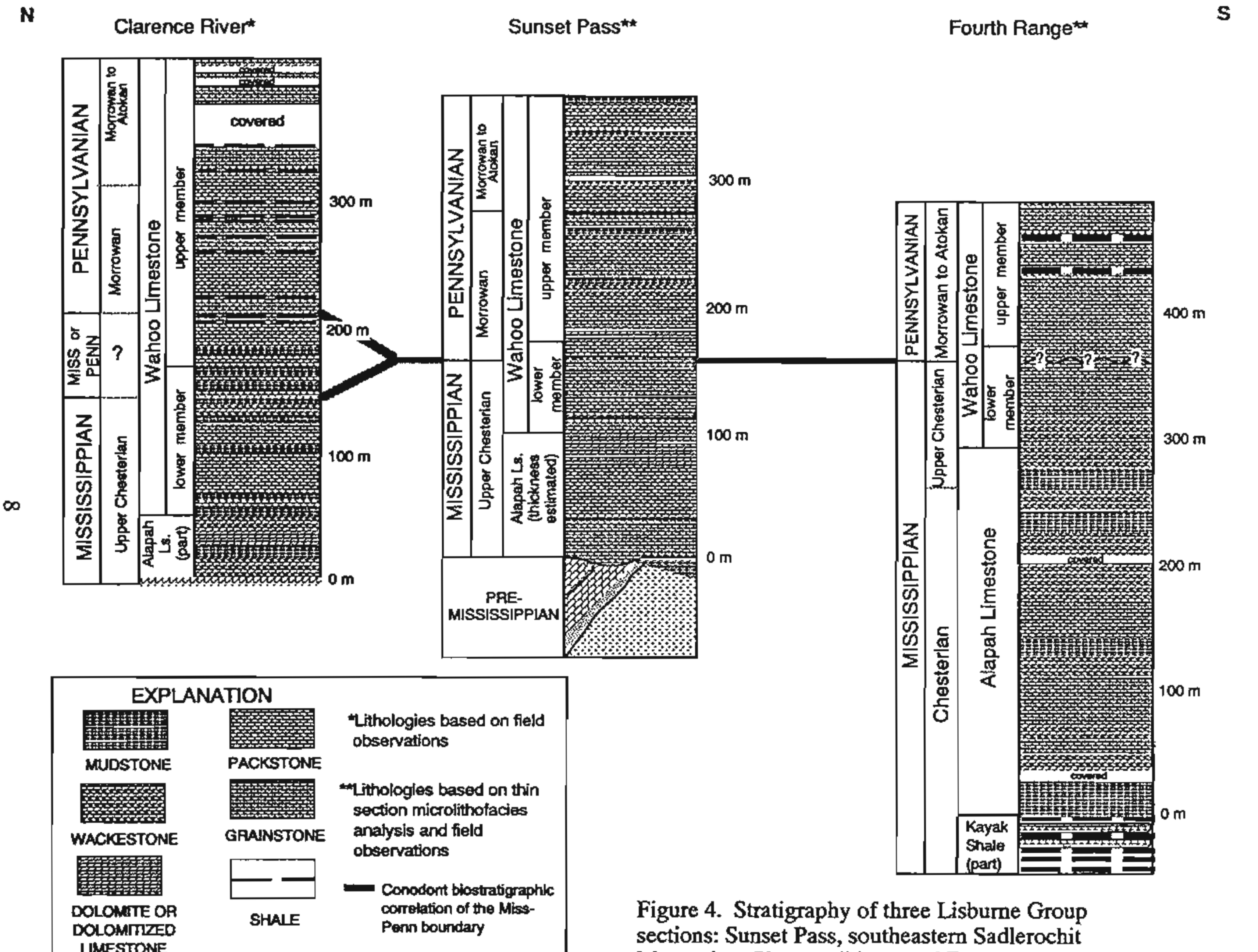


Figure 4. Stratigraphy of three Lisburne Group sections: Sunset Pass, southeastern Sadlerochit Mountains; Clarence River; and Fourth Range.

Mountains the Kayak Shale is depositionally absent, but is present in the Clarence River area, and very thick in the Fourth Range.

Southeastern Sadlerochit Mountains--high angle faulting

Structure

The southeastern side of the Sadlerochit Mountains is a homocline that dips moderately to the south (figs. 2 and 5). This homocline is the surface expression of the southern flank of a Cenozoic-age horse in the regional, northward propagating duplex. Normally, this regional duplex is bounded by a floor thrust at depth and a roof thrust in a shale near the base of the Ellesmerian sequence. However, in the Sadlerochit Mountains, this shale (the Mississippian Kayak Shale) is depositionally absent (figure 4), and the roof thrust for the duplex is located in stratigraphically higher in the Ellesmerian sequence, in the Jurassic to Cretaceous Kingak Shale. Consequently, in the Sadlerochit Mountains the majority of the Ellesmerian sequence has remained structurally attached to the underlying pre-Mississippian rocks, and have deformed with them as a coherent structural unit. Structural disruption of the Lisburne and Sadlerochit Groups is minimal.

The exception to this is a series of northeast-trending, low displacement, high angle faults that offset stratigraphy within both the pre-Mississippian carbonate sequence and the overlying Ellesmerian sequence (figure 5; Robinson and others, 1989). The absolute age of the faulting is not known, but the faults clearly cut Permo-Triassic rocks, making the latest movement on them post-Triassic in age. The faults generally strike northeast, approximately 30°-40° east of the interpreted NNW transport direction during Cenozoic thrusting (Wallace and Hanks, 1990). The presence of these high-angle faults provide an opportunity to evaluate the effect of high-angle faults have on fracture distribution within the Lisburne carbonates.

Stratigraphy

The stratigraphy of the Lisburne group along the southeastern flank of the Sadlerochit Mountains is essentially the same as that seen at the 'Sunset Pass' section in the eastern Sadlerochit Mountains (figure 4).

Fracture orientations and distribution across structure

Two high angle faults and the associated fracture distribution in the Lisburne are exposed in the vicinity of Camp 263 Creek (figure 5). The first, a high angle fault with apparent left-lateral offset, displaces rocks of the Lisburne Group on Camp 263 Creek and strikes ~25°. The actual fault surface is not exposed, but reasonably good exposures of Lisburne Group exist <100 meters

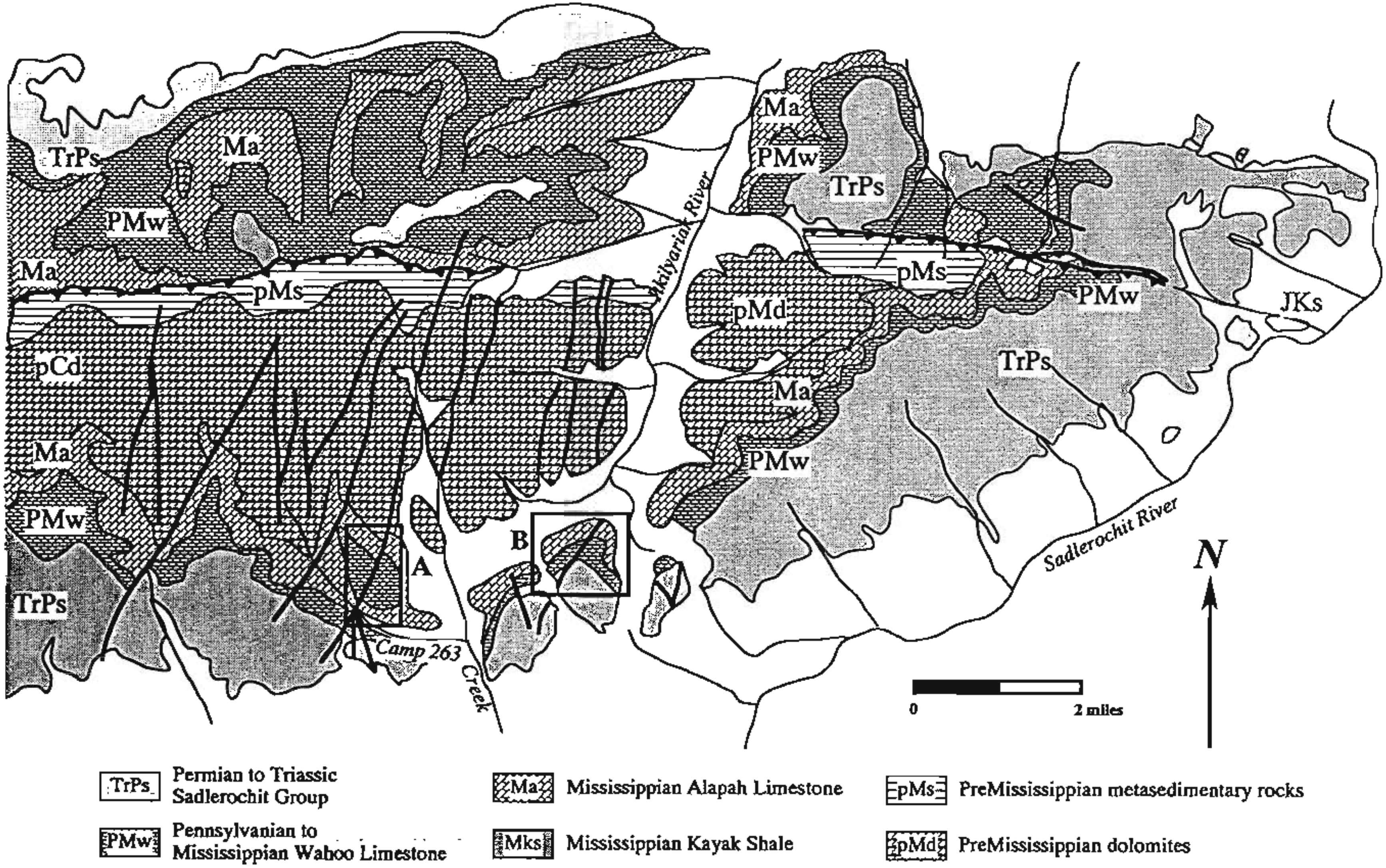


Figure 5. Geologic map of southeastern Sadlerochit Mountains. The fracture pattern of the Lisburne Group adjacent to high-angle transverse faults was studied in the two outlined areas. Observations are discussed in the text. **A.** Camp 263 Creek; **B.** Headwaters of Itkilyariak River and Camp 263 Creek. Map modified from Robinson and others, 1989.

on either side of the fault. The orientation of fractures adjacent to the fault are summarized in figure 6.

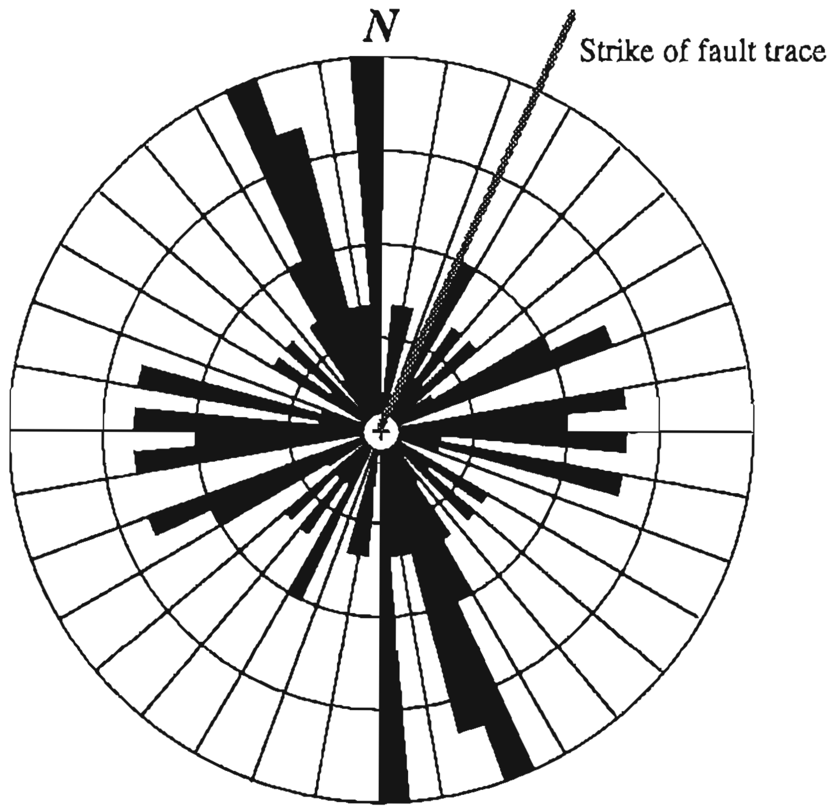


Figure 6. Fracture orientations in Lisburne Group adjacent to Camp 263 fault. Strike of fault trace is N 25 E. N = 70.

A second fault is well- exposed between Camp 263 Creek and the headwaters of Itkilyariak Creek. This fault also has apparent left-lateral offset, strikes ~30°, and dips moderately to the east. This fault offsets both the Lisburne and Sadlerochit Groups, and is fairly well-exposed. The orientation of fracture associated with and adjacent to this fault are illustrated in figure 7.

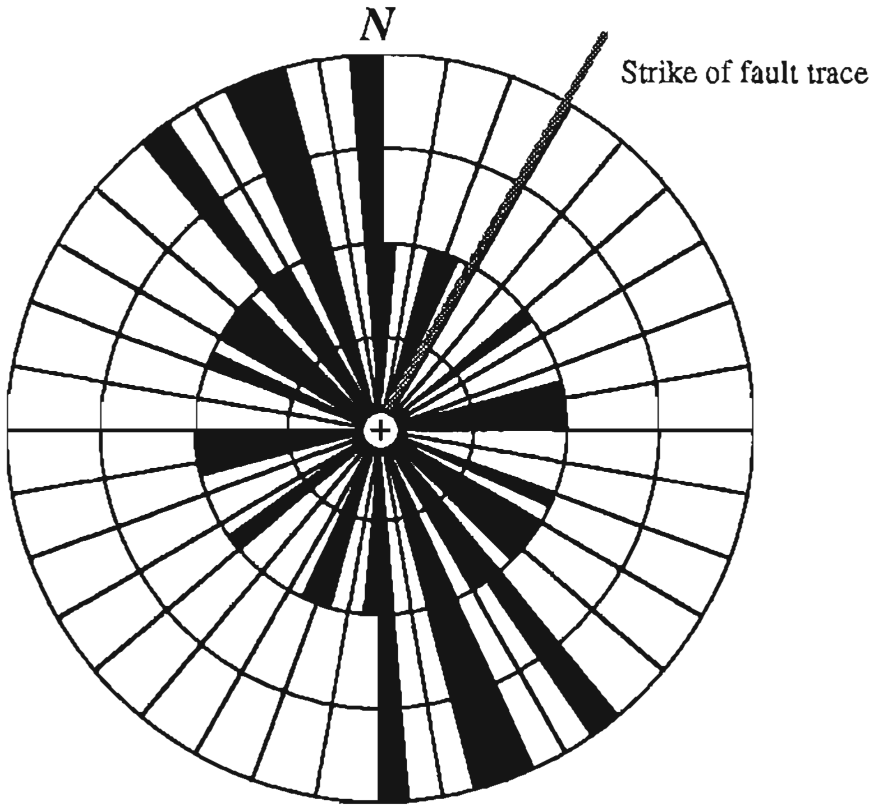


Figure 7. Fracture orientations in Lisburne Group adjacent to Itkilyariak Creek fault. Strike of fault trace is N 30 E. N = 20.

In the case of both of these faults, few fractures have developed parallel to the actual fault trend. On Camp 263 Creek, a set of fractures did develop that were approximately parallel to the fault trend, but these fractures were not consistently developed throughout the section, and were limited to exposures <50 meters from the fault trace. On the Itkilyariak Creek fault where the actual fault surface was exposed, fractures developed during faulting did not parallel the fault itself, but were at an angle to it.

In both examples, the most obvious effect of the fault on the fracture pattern was an increase in fracture density. In general, this increase is limited to the area immediately adjacent (within 100 m) of fault.

Few carbonate mudstones were exposed in the vicinity of either fault, but fracture distribution with respect to other lithologies was similar to that seen in the structurally less-disrupted section in the Sunset Pass section to the east (table 1; Hanks and others, 1994)

Fractures related to folding--Clarence River

Structure

The Lisburne carbonates exposed in the Clarence River area are folded into an east-west trending, open, asymmetric syncline (figure 8). The syncline is a structural low between two thrust-related structural highs to the north and south (see figure 2 for an equivalent structural position along the Canning River transect to the west). In this area, the Lisburne Group is underlain by a significant thickness of Kayak Shale, permitting the Lisburne Group and overlying rocks to deform independently of the underlying preMississippian basement.

Stratigraphy

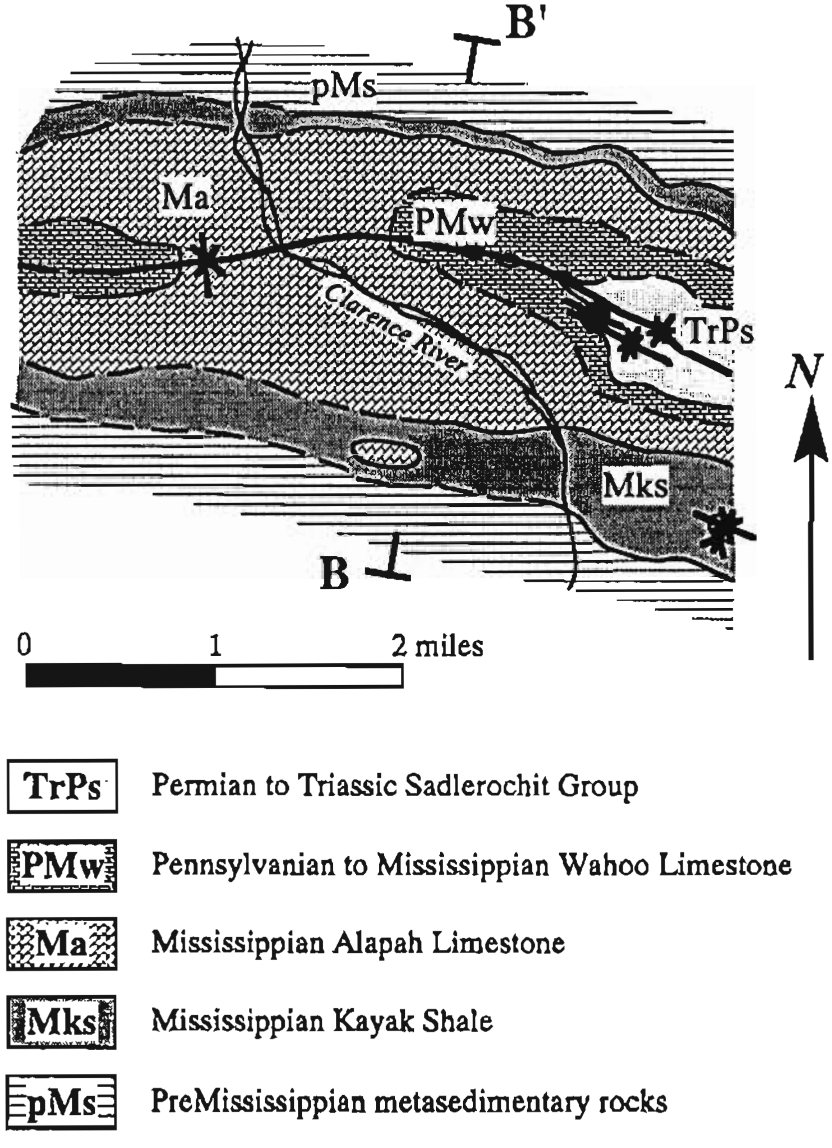
The stratigraphy of the Lisburne Group exposed in the Clarence River area is considerably different from that seen in the Sunset Pass section to the west. While similar lithologies are exposed in both the Clarence River and the Sunset Pass sections (figure 4), the Clarence River section has shale intervals in the upper Wahoo that are not present at Sunset Pass. Similar shale intervals occur in the Lisburne carbonates of the Lisburne field. Both the Clarence River and Lisburne field sections have been interpreted as having been deposited further up on the carbonate ramp than the section exposed at Sunset Pass (Watts and others, 1994).

Fracture character, orientations, relationship to lithology, and distribution across structure

Two planar fabrics occur in the Lisburne carbonates in the Clarence River area. Steep, generally north-south trending extension fractures occur consistently throughout the section (figure 9). This fracture set is overprinted by a younger, generally east-west trending axial planar cleavage and extensional shear fractures (figure 10). Both fracture sets strongly influence the outcrop pattern (figures 11 & 12).

Early NS trending fractures

Where preserved, the NS trending fractures are calcite-filled, with individual fractures varying in width from <1/4" to 1". In most cases, weathering has removed the original fracture fill and destroyed all surface ornamentation. There was one observed NS surface with slicks, suggesting at least some minor shear. Similar fractures in underlying siliciclastic rocks have



<u>Figure 8.</u> Geologic map and cross section of the Clarence River area.

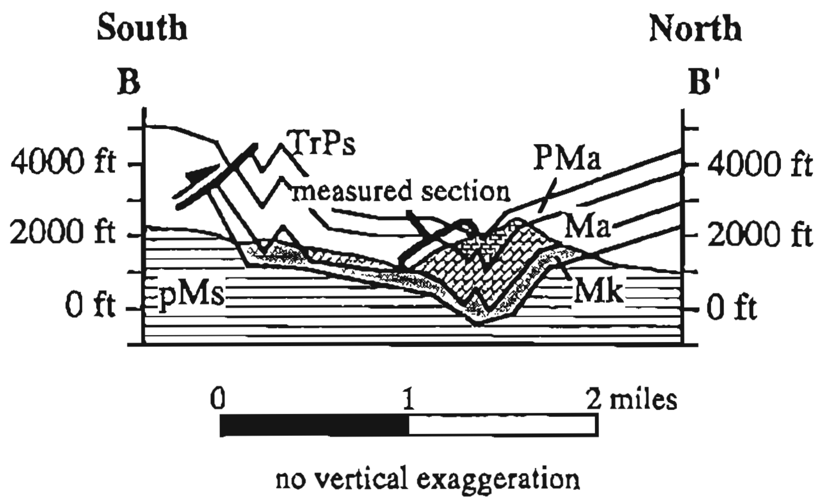


Figure 8. Continued.

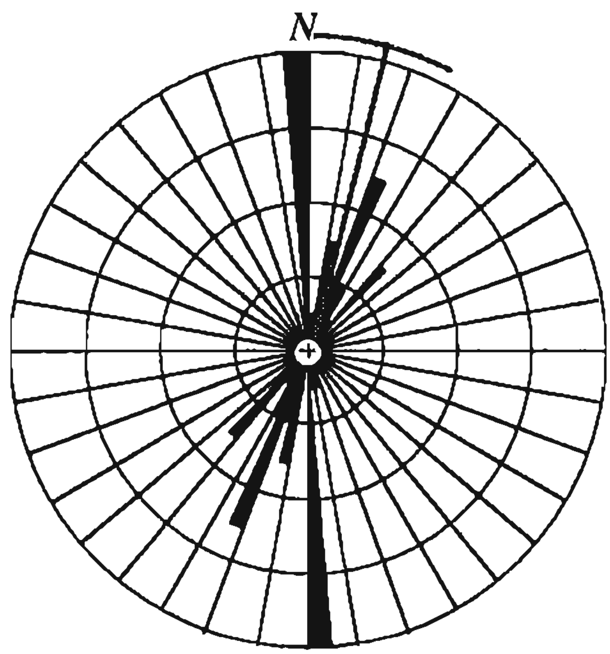


Figure 9. Orientation of the first fracture set in the Lisburne Group exposed at the Clarence River.
Mean vector direction = 14°; N = 28; 5° intervals.

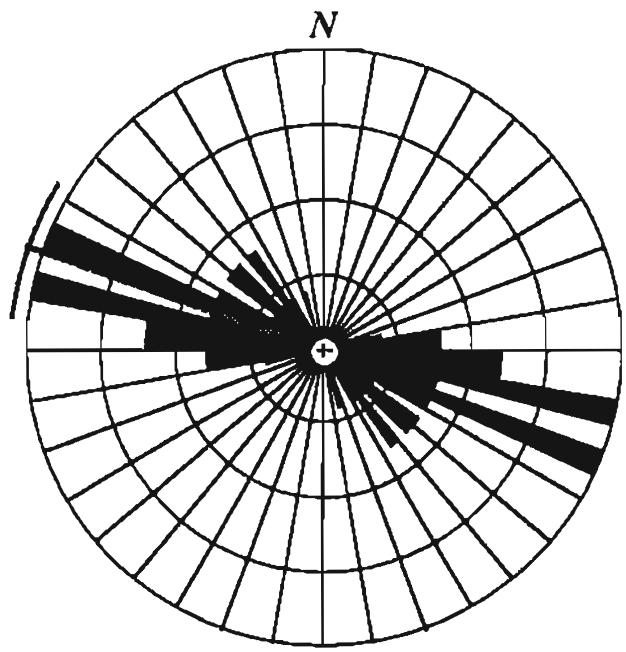


Figure 10. Second generation planar fabric (primarily axial planar dissolution cleavage) exposed in the Lisburne Group of the Clarence River section. Mean vector direction = 289°; N = 35; 5° intervals.

<u>Figure 11.</u> North-south trending extension fractures within the Lisburne Group of the Clarence River section. Fractures of this orientation strongly influence the weathering pattern of the Lisburne Group, with individual fractures extending vertically for several 10's of meters. West is to the right.

Figure 12. Westward facing view of the Wahoo limestone of the Lisburne Group, Clarence River. The strong influence of east-west planar fabrics on the outcrop pattern of this part of the Lisburne is clearly seen in this photo. The east-west fabric in the lower part of the Wahoo is dominated by dissolution cleavage that varies in dip with lithology (see figure 14). Further upsection, extension fractures and shear fractures are dominant. North is to the right.

plumose structures indicating origin as extension fractures.

The relationship of the early fracture set to lithology is similar that seen at Sunset Pass in the eastern Sadlerochit Mountains (figure 13, Table 1; Hanks and others, 1994). Fracture density is greatest in the finer grained and dolomitic lithologies, such as wackestones and cryptalgal laminates, where fracture densities can be as high as 17 fractures/foot. Fracture density is considerably less in the coarser lithologies, such as grainstones, where fracture density can be as low as 1 fracture/3 feet. While major through going fractures of this fracture set can extend several 10's of meters vertically, the majority of these fractures are limited in vertical extent and/or restricted to individual beds, with the majority of fractures terminating on bedding planes, internally within beds or on erosional surfaces. Fractures within the more densely fractured finer-grained lithologies are more likely to be evenly distributed. In less-densely fractured lithologies such as grainstones, the fractures are not evenly distributed and occur in 'swarms.'

Siliciclastic shale horizons in the Wahoo limestone had fracture densities similar to that seen in the finer-grained carbonate lithologies (Table 1). However, in general fractures did not continue from overlying or underlying beds through the shale--unless the shale was very thin Frequently fractures terminated at the boundary of the shale with the carbonate bed, or terminated with the shale horizon itself.

Detailed observation suggests variations within the NS fracture set with respect to stratigraphic and structural position. The NS fractures can be subdivided into an early NNE trending set and a later NNW trending set (figure 9). NNE-trending fractures dominate in the dolomitized algal mudstones Alapah at the base of the section and on the south limb of the syncline. NNW-trending fractures become more common in the interbedded grainstones and wackestones/mudstones of the lower Wahoo. Near the core of the syncline where the carbonates are dominantly massive grainstones with interbedded shales of the upper Wahoo, the dominate fracture set is again NNE-trending, with the NNW-trending set appearing to be a minor, and later, conjugate set.

Later EW trending planar fabrics

While the NS fracture set appears to be primarily extensional in origin, the younger east-west trending planar fabric is dominated by compressional and shear features. At the base of the section in the upper Alapah and lower Wahoo, this fabric is an east-west trending axial planar cleavage that changes character and dip with varying lithologies (figure 14).

While this fabric is densely spaced (up to 34/ft in muddier lithologies), individual cleavage planes rarely extend beyond an individual bed. The relationship between cleavage density and lithology is not as clear as with the purely extensional NS fractures (figure 15). While higher cleavage densities do occur in the muddier lithologies, grainstones also can have fairly high cleavage densities (densities as high as 12/ft were observed). This difference in densities between

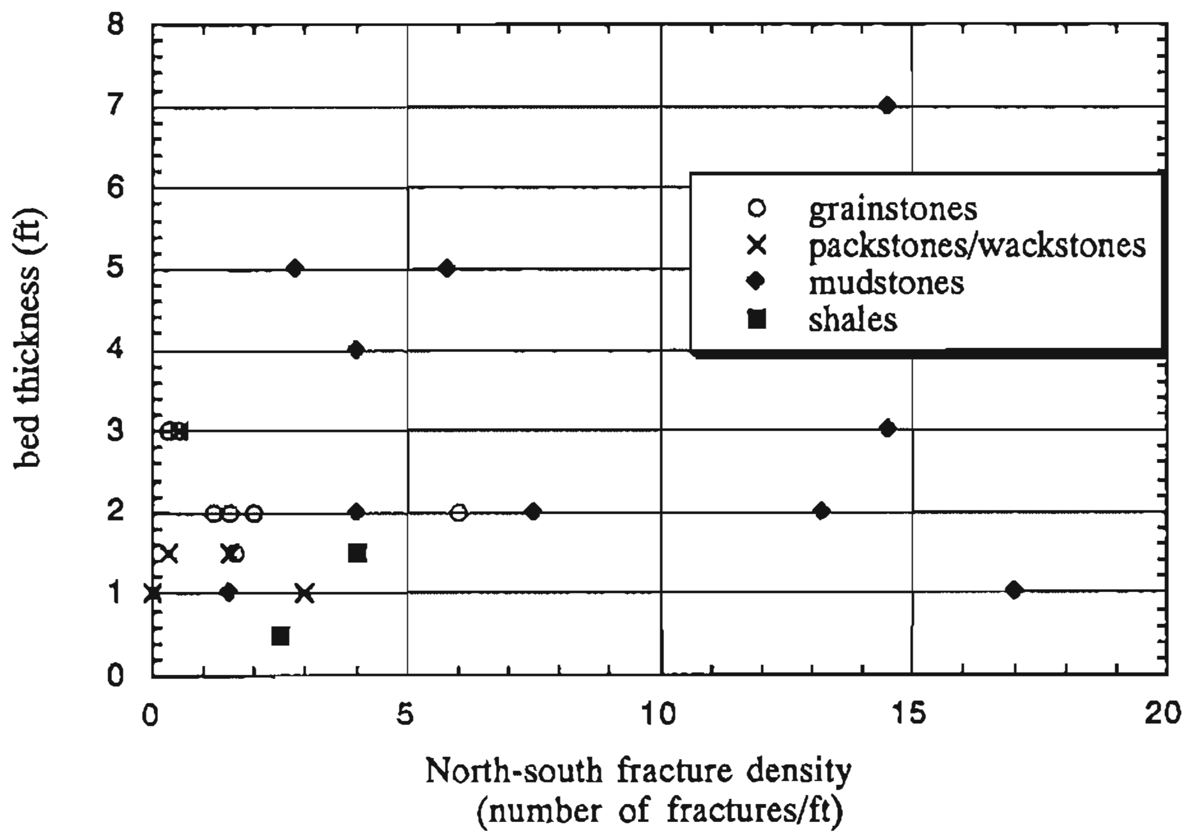


Figure 13. North-south fracture density vs bed thickness, Lisburne Group, Clarence River area

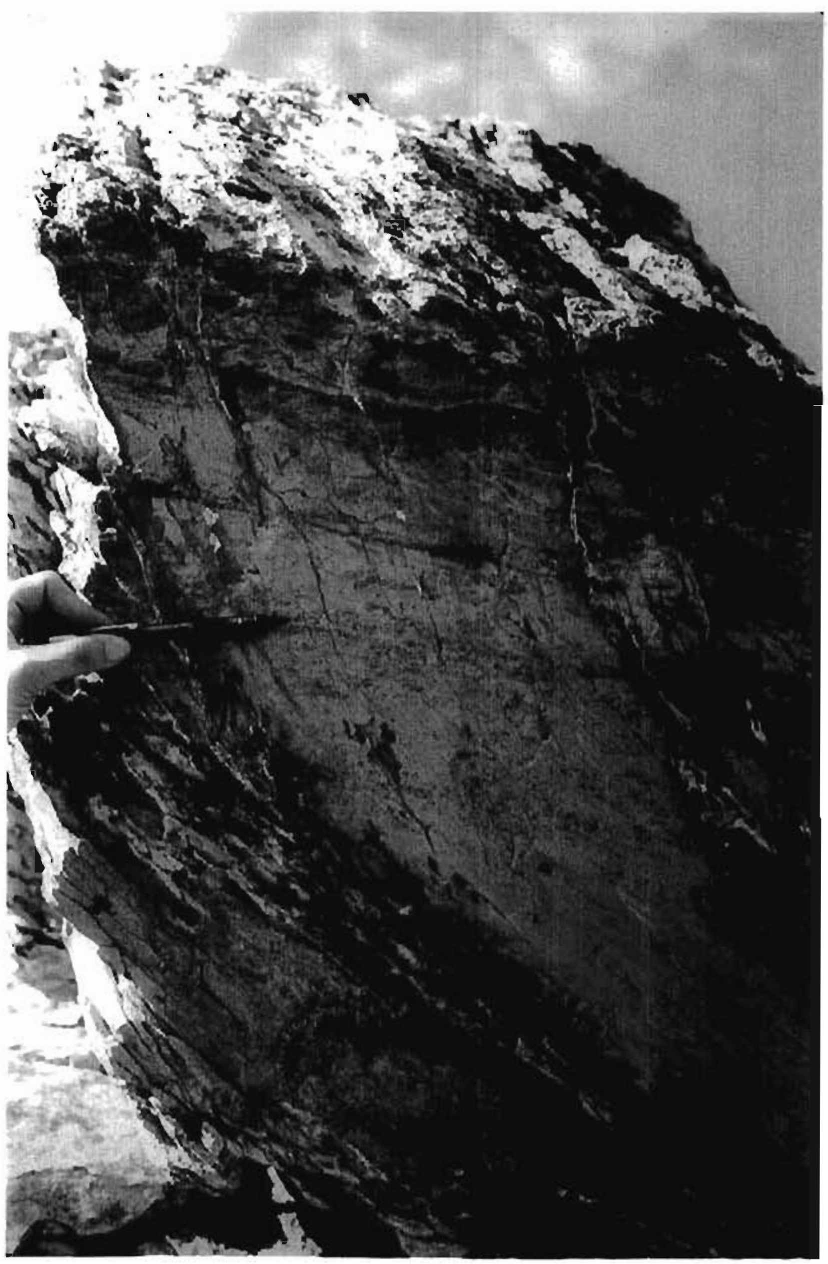


Figure 14. East-west trending dissolution cleavage in the Wahoo limestone, Clarence River. Note the change in dip and density of the cleavage from the packstone (top) to mudstone (bottom). North is to the right.

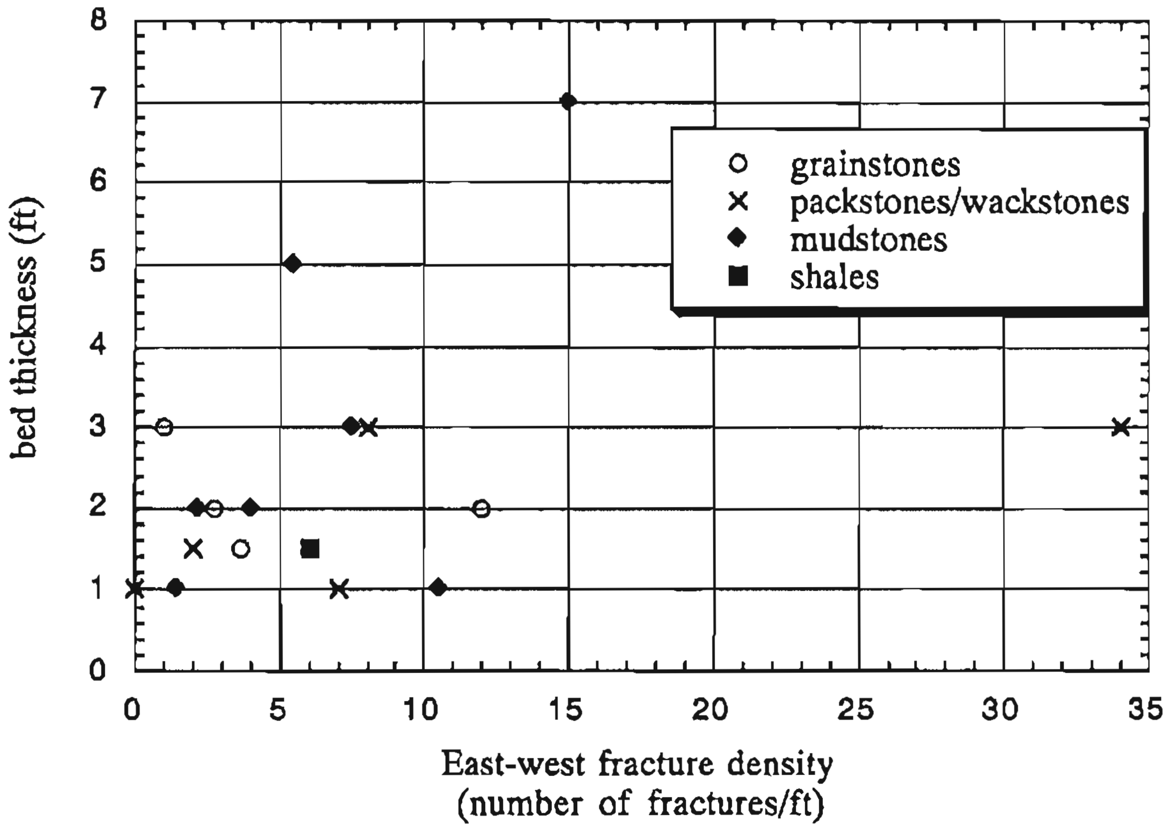


Figure 15. East-west fracture density vs bed thickness, Lisburne Group, Clarence River area.

NS fractures and EW fractures and cleavages is probably due to the differences in the mode of origin of the two features.

There is some evidence that this EW axial planar cleavage was succeeded by a later, generally EW-trending set of conjugate shear fractures with a component of extension. This is more evident in shales and coarser carbonate lithologies of the upper part of the Wahoo, where the dissolution cleavage becomes increasingly rare, and the conjugate shear fractures more common. While this change corresponds to a change in lithology, it could also be related to increasing proximity to the fold hinge.

Ambiguities in timing and sequence of fracture development at Clarence River

There are some ambiguities in the relative age of these EW dissolution cleavages, and the NS extension fractures. In the packstones and wackestones of the lower Wahoo, earlier NS fracture planes locally appear crenulated by the EW dissolutions fabric, suggesting that the cleavage did indeed postdate the NS extension fractures. However, NS fractures occasionally extend into shales that appear to have undergone significant shearing associated with folding and development of the dissolution cleavage in surrounding carbonates.

Some of the ambiguities can be resolved by successive periods of extension that reactivate and enhance older fabrics. Early regional NS extensional fractures that formed before formation of the Clarence River syncline may have been reactivated during or immediately after folding as extension fractures perpendicular to the fold axis. The preexisting NS regional fractures would have provided a preferred plane of weakness that would have reopened during subsequent deformation. Reactivation of these early fractures could account for NS extension fractures cutting the deformed shales, for example. A weakly developed set of conjugate shear fractures oriented approximately NS could also have developed during or immediately after folding, and would account for the occurrence of this type of NS fracture in the upper part of the section, near the core of the syncline. Likewise, EW dissolution cleavages could have also been reactivated later in the fold's history as extensional fractures parallel to the fold axis. This would have most likely occurred in the parts of the fold undergoing the most extension, such as the synclinal core. This is where most of the extensional EW fractures are presently observed at Clarence River.

Fourth Range

Structure

The majority of the Lisburne Group exposed in the northeastern Brooks Range has been folded into tight detachment folds above a detachment in the Kayak Shale. This folded Lisburne is exposed on the flanks of regional, basement cored anticlinoria that are interpreted to reflect horses within the regional north-vergent duplex (figure 2). The Fourth Range is one such anticlinorium where erosion has not yet stripped off most of the deformed Lisburne from above the crest of the regional fold (figures 2 & 16). In this phase of the study, we focused on a particularly well-exposed section of Lisburne Group that forms the back limb of a large, inclined detachment fold (figure 16). The upper part of the section has been disrupted by minor thrust faulting.

Stratigraphy

The section exposed in the Fourth Range has been described in detail by Gruzlovic (1991). The Lisburne in this area is dominated by a thick (~300 meters) sequence of mudstones, wackestones and grainstones of the Alapah (figure 4). The Wahoo is dominated by grainstones, and may be cut by one or more intraformational unconformities. Overall, the lower Lisburne section exposed at the Fourth Range is thicker than that seen at Clarence River and in the Sadlerochit Mountains, and was deposited on a deeper part of the Lisburne shelf.

Fracture orientations and character

At first glance, the Fourth Range Lisburne section looks remarkably coherent and relatively undeformed. Closer inspection reveals, however, that the rocks are highly shattered. While stratigraphic integrity is for the most part maintained, individual beds are commonly highly fractured. Fractures are not always of consistent orientation from bed to bed, and frequently do not extend beyond individual beds. Bedding planes show abundant evidence of bedding parallel shear, suggesting that bedding parallel slip during folding and related fracturing of individual beds probably played a major role in fracture development.

As observed in other sections of Lisburne in the northeastern Brooks Range, north-south fractures are abundant at the Fourth Range section (figure 17). However, the character of these fractures is highly variable. Very few NS fractures clearly predate all other fractures; those that do are narrow (<5 mm) and filled with calcite (figure 18). Most NS fractures appear to post-date other fractures. While a few of these late NS fractures have slicked surfaces, others have twist hackles indicative of an extensional origin. NS fractures with slicks occasionally curve and merge into a bedding plane that is also slicked. Most of the NS fractures in overlying and underlying siliciclastic rocks have plumose structures, also suggesting an extensional origin.

The second main set of fractures is oriented approximately east-west, parallel to the axis of the fold but with a wide range in variability (figure 17). These fractures appear to be generally confined to individual beds or groups of beds, are perpendicular to bedding, and occasionally show evidence of extensive shear. These fractures parallel axial planar cleavage in underlying shales of the Kayak Shale. In the sandstones of the Echooka Formation immediately overlying the Lisburne Group, EW fractures appear to predate extensional NS fractures; in the lower part of the

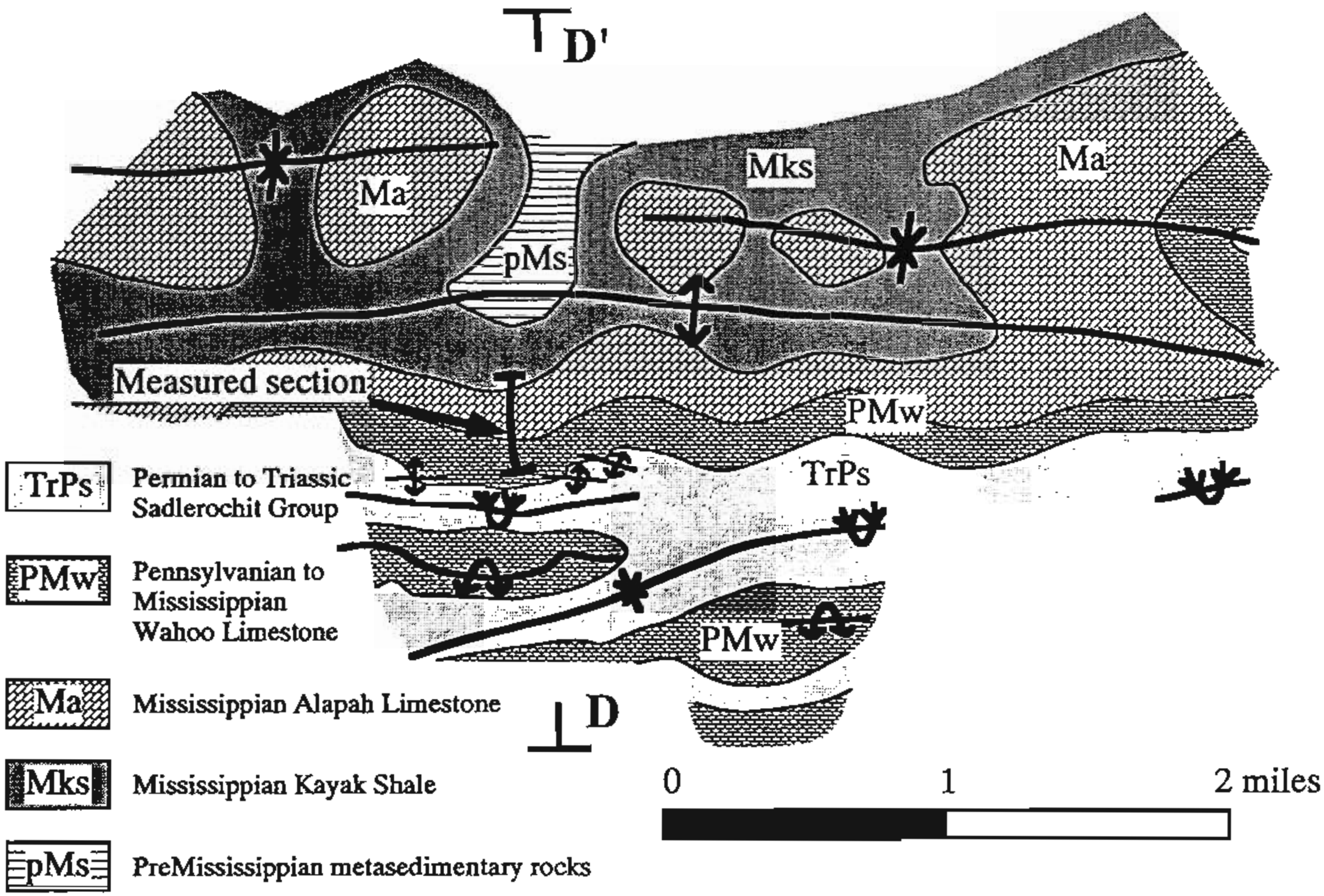


Figure 16. Geologic map and cross section of Fourth Range. Modified from Gruzlovic, 1991.

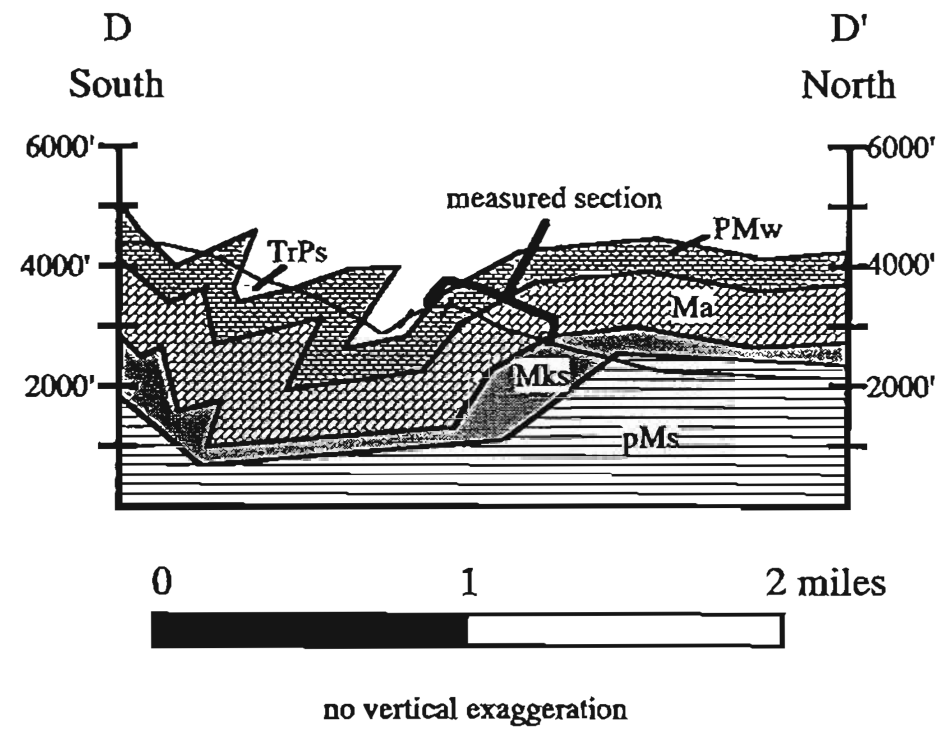


Figure 16. Continued.

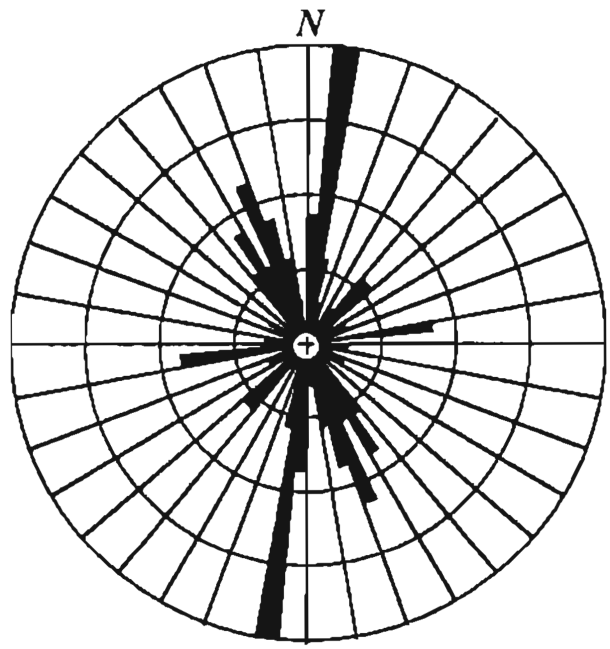


Figure 17. Fractures exposed in the Lisburne Group of the Fourth Range section.
N = 43; 5° intervals.

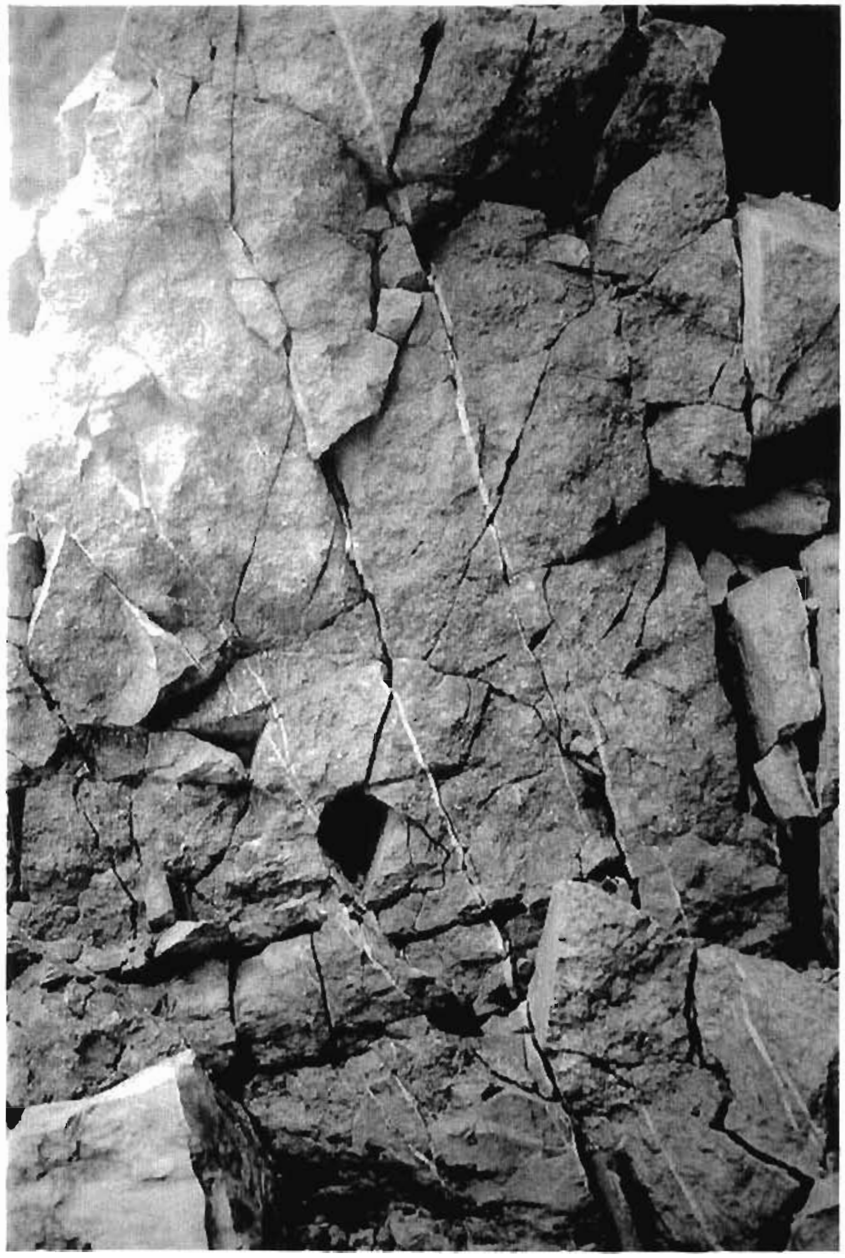


Figure 18. Several generations of fractures occur within the Lisburne Group exposed in the Fourth Range. This photo of the base of a grainstone bed illustrates three different fracture sets. An early set of filled extension fractures trends north-south (upper left to lower right in photo) and probably represents regional fractures that developed prior to formation of the current local structure. Later fractures include a set trending northwest-southeast (upper right to lower left), perpendicular to local fold axes, and east-west (left to right), parallel to local fold axes. West is to the right.

Alapah limestone, EW fractures appear to predate both shear and extensional NS fractures.

Role of lithology on fracturing

Time and the complexity of the fracturing did not permit an extensive evaluation of the relationship between fracture density and lithology. However, qualitatively, the bedding architecture did appear to play a role in fracture development and character. Thick sequences of interbedded lime mudstones in the lower Alapah typically shared the same fracture pattern, even though individual fractures may not extend beyond the boundaries of individual beds. These fractures were generally limited to three sets--a pervasive NNW striking, steeply dipping fracture set; a later, approximately EW striking pervasive set that was perpendicular to bedding; and a non-pervasive, possibly contemporaneous set of extension (?) fractures oriented NS or NNE. Evidence of shear on any of these fractures or on bedding planes was minimal.

In contrast, thick grainstone beds immediately overlying the lower Alapah mudstones appeared to be highly shattered, with abundant evidence of shear on the bedding planes and on NS fractures. The fracture pattern was not nearly as consistent or as simply categorized as that seen in the underlying mudstones. This pattern held throughout the remainder of the section, but was particularly noticeable in those parts of the section where thick grainstone beds were interbedded with mudstone beds.

Discussion of Fourth Range fracture pattern

The complexity of the fracture patterns in the Fourth Range reflects the complexity of the map scale structure. The early, regional NS extension fractures that dominated the Sunset Pass section (Hanks and others, 1994) are difficult to reliably identify in the Fourth Range section, and may be totally masked by later deformation. The dominant NS and EW fracture sets in the Fourth Range section both probably are related to the folding of the carbonates into the map scale detachment fold and concurrent bedding parallel slip of individual beds and sequences of beds. During this deformation, extensional fractures would develop perpendicular to the fold axis while shear fractures would develop at other orientations. The high number of NS fractures at this section could be due to reactivation and/or enhancement of preexisting NS regional fractures during folding.

The heterogeneous nature of the stratigraphy at the Fourth Range section probably promoted widespread bedding parallel slip during folding which in turn enhanced fracture development. Thick, coarse-grained beds such as grainstones and packstones became detached from underlying and overlying mudstones. This detachment and bedding parallel slip led to widespread internal fracturing within the grainstones and packstones, with associated shear on both internal fractures and bedding surfaces. In contrast, the more evenly bedding and lithologically homogeneous mudstones experienced far less bedding parallel slip and shear.

Discussion--Distribution and character of fractures in deformed carbonates

These preliminary observations of fracture distribution within the Lisburne Group exposed in the northeastern Brooks Range illustrates the high variability of fracture character and intensity possible within carbonate rocks with changing structural position. Since the orientation and intensity of the in situ stress state (ie. structural position) is highly variable in an evolving fold-and-thrust belt, understanding the relationship between fractures and structural position is important for developing predictive models both for hydrocarbon exploration and production.

As might be expected, relatively gently and/or simply deformed carbonates have the most simple fracture patterns. Structures in this category include gentle, open folds, such as those found in the foreland of a fold-and-thrust belt. Most of the rocks exposed in the northeastern Brooks Range and immediately to the north in the subsurface of the coastal plain are involved in the fold-and-thrust belt proper, and consequently have experienced more deformation than might be expected of rocks further to the foreland. However, because of a combination of stratigraphy and its relatively forward position, the Lisburne Group exposed in the Sadlerochit Mountains have undergone relatively gentle deformation (Hanks and others, 1994). The early north northwest striking, vertical extension fractures seen at the Sunset Pass section are interpreted to be due to compression and development of low differential stresses under high pore pressure conditions in front of the advancing fold-and-thrust belt (Lorenz and others, 1991; Hanks and others, 1994). These fractures were subsequently overprinted by extensional and shear fractures that developed during formation of the Sadlerochit Mountains. Because of the relatively low amounts of strain and simple structural history, lithology played the primary role in the determining the character and density of the fractures. Coarse grained lithologies such as grainstones have relatively few, straight, and through going fractures while dolomitized mudstones are the most intensely fractured, with individual fractures irregular and anastomosing, but generally confined to individual beds.

As the map scale structures become increasingly more complex, so do the fracture patterns. While lithology continues to play a role in determining the fracture character and density, it is no longer the major factor, as structural position and the degree of bedding parallel slip also come into play.

Fracture patterns within the Lisburne Group varied with structural position both within an individual fold and between different types of folds. In the footwall syncline exposed at the Clarence River, early regional NS extension fractures were overprinted near the core of the fold by extension and extensional shear fractures parallel and subparallel to the fold axis. However, on the southern limb of the fold near the thrust fault, EW fabrics were primarily dissolution cleavage, indicating compression and not extension in this part of the fold. However, the fracture patterns remained fairly coherent and the relative age relationships clear.

In contrast, the fracture patterns of the Lisburne Group in the Fourth Range were far more complex. Here the Lisburne Group is folded into a large tight detachment fold, and the section examined was on an anticlinal limb. Early regional NS fractures were difficult to reliably identify; NS extension fractures were synchronous or postdated the folding. Both NS and EW fractures varied in orientation, showed indications of both shear and extension, and appeared to be related in part to extreme bedding parallel slip during folding. Lithology did not appear to exert as strong an influence in fracture density here as was seen in other sections--the lime mudstones were only slightly more fractured than grainstones. To the contrary, grainstones appeared more susceptible to fracturing due to bedding parallel slip.

As might be expected, location with respect to high angle transverse faulting also plays a role in fracture density. Fracture intensity increases in the immediate vicinity of a fault (within 50-100 m) but has little effect at significant distances from the fault. New fractures do not necessarily form parallel to the fault--preexisting fractures (in the case of the eastern Sadlerochit Mountains, the NS regional fractures) can be reactivated and/or enhanced by later transverse faulting.

Implications for hydrocarbon exploration and production within the Lisburne Group

Results from this study suggest that understanding fracture origin and distribution could be critical for successful exploration and production of the Lisburne Group. Even within the relatively little deformed Lisburne Group of the Lisburne Field, fractures play a critical role in providing permeability for the reservoir (Teufel and others, 1993; Teufel and Lorenz, 1995). The relative age, degree of cementation, and distribution of the open fractures with respect to productive horizons all play important roles (Missman and Jameson, 1991). Recent studies indicate that the orientation of the open fractures with respect to the current stress field may be critical--fractures kept open by low differential regional stresses may close with a drop in formation pressure due to production (Teufel and Lorenz, 1995). The resulting loss of permeability is irreversible.

It is therefore critical to establish the relative age, origin, character and distribution of fractures early in the exploration and production process. In this study, we have established the following for the Lisburne Group exposed in the range:

•in most examples of Lisburne limestones exposed, there are two main orientations of fractures: an early NS regional set and a later set, generally oriented EW and related to the local structure. The early set is through going, relatively evenly distributed, and consistent in orientation; the younger set can vary in character and distribution depending upon structural position.

•the early NS fracture set can be obscured with deformation, but is often reactivated by late extension fractures that form perpendicular to the structural axis. This relationship could be relatively common, especially if transport direction remains fairly consistent over time and/or the axis of the map scale folds are approximately 90° to the early regional fractures. These late NS fractures could provide good permeability, but caution during production would be advisable in order to avoid closing of the fractures during production.

•There is a strong relationship between lithology and fracture distribution in the more gently deformed Lisburne, with finer-grained, more dolomitic horizons more densely fractured than coarse-grained grainstones and packstones. However, in more deformed Lisburne, the grainstones may be preferentially fractured during folding and related bedding parallel slip.

•Fracture density may be unexpectedly high in the limbs of anticlines as well as the hinges, if there is abundant bedding parallel slip. However, the orientation of fractures on the limbs of the folds may not be entirely consistent with those in the hinge areas.

•Increase in permeability due to fault-induced fracturing may be limited to the area immediately adjacent to high-angle transverse faults, depending upon the density and degree of faulting.

These observations may be directly applicable to similar structures in the subsurface of the coastal plain of ANWR, and in deformed Lisburne Group in the subsurface of the central and western Brooks Range. Observations regarding the relationship between lithology, fracture density, and fracture character are applicable to relatively undeformed Lisburne Group in the North Slope subsurface.

Conclusions

Fractures commonly provide a major source of porosity and permeability in carbonate rocks. Developing a good descriptive and predictive model of fracture development in potential carbonate reservoirs can therefore be essential for a successful exploration and production program. However, study of fractures in the subsurface is restricted to core data and log analysis. While detailed core analysis can be very useful, it is difficult to arrive at a three dimensional model for the origin and distribution of fractures. Large, open, and/or widely spaced fractures may be difficult to evaluate because of the limited sampling of such fractures by the core barrel. Cross-cutting and abutting relationships critical for determining the relative age relationships between different fracture sets are also difficult to ascertain in core.

This pilot study focused on the fracture distribution, density and character within variably deformed Lisburne Group exposed in the northeastern Brooks Range of northern Alaska.

Although the structural setting of the Lisburne exposed in the range differs from that of the subsurface of the Prudhoe Bay area, some general observations are applicable to both exposed and subsurface Lisburne Group.

•In mildly deformed Lisburne Group, there is a strong relationship between lithology and fracture density, with muddier and dolomitic lithologies, such as dolomitic mudstones, more intensely fractured than grainstones.

•In more intensely deformed Lisburne Group, the difference in fracture density between grainstones and dolomitic mudstones becomes less pronounced, with grainstones experiencing a relative increase in fracture density with respect to the mudstones.

•Within a fractured sequence of carbonate rocks, even thin (<1 ft) shale horizons can act as significant impediments to vertical permeability.

•Fractures related to local faults are limited in areal extent and frequently localized to the area immediately adjacent to the fault. Fault-related fracture sets do not necessarily developed parallel to the high angle faults, but may reactivate and/or form new fractures parallel to a preexisting fracture set.

•Regional fractures that develop prior to major thrusting and are overprinted by later structures may be difficult to distinguish from later fractures in even moderately deformed rocks. However, these early fractures may be reactivated by later fractures and could act as effective permeability conduits in deformed carbonates.

These observations, while directly applicable to the Lisburne Group, can be applied to predicting the distribution and density of fractures in other carbonate sequences. Information on the orientation and relative timing of fractures within the Lisburne Group is also applicable to predicting the orientation and relative age of fractures within underlying and overlying siliciclastic reservoir horizons, such as the Mississippian Endicott Group, the Permo-Triassic Sadlerochit Group, and various Cretaceous sandstones of the Brookian sequence.

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Camp 263 Creek, Sadlerochit Mts

Lithology	Bed thickness	Distance from fault	NNW fractures		ENE fractures		Other fractures	
			number	comments	number	comments	number	comments
grainstone	1.5 ft	50 ft	5/4 ft	clean, 3 go thru	4/3 ft	clean, thrugoing	10/ft	postdate Fx1 & 2 cc filled
grainstone	1 ft	75 yds	5/4 ft	conjugate set developed	6/2ft	all truncated within bed		
pkst/ grainstone		75-100 yds	6/ft	No obvious conjugates	4/5ft			

TABLE 1. Carbonate lithology, fracture density, and fracture character

Clarence River: Wahoo Limestone

Lithology	Bed thickness	NS fractures number/ft	NS fractures comments	EW fractures number/ft	EW fractures comments	Other fractures number	Other fractures comments
grainstone	< 3 ft	2-3/6 ft	cc filled	5/5 ft, with swarms of 10/ft			
mudstone	1 ft			46/ft	show deflection and dip changes with minor changes in mud content		
mudstone gradational into:	<2 ft	66/5 ft	cc filled; up to 2 cm (1") wide				
grainstone	< 2 ft	30/5 ft	fractures grouped in swarms, with ~3 swarms/5 ft; nearly all fractures in this coarser grained lithology continue into finer grained lithologies, but not visa versa				
packstone	1-2 ft	9/6 ft	6 cont into underlying shale;<1-2 frax/6 ft cont more than 10 ft.	2/ft			
shale	<6 inches	15/6ft	~1frax/foot extends thru shale	22/ft			
dolomitic mud/wackstone	1 ft	18/6 ft	6 go through entire dol. bed;8 cont. thru shale	6-8/ft			

TABLE 1. Continued.

Lithology	Bed thickness	NS fractures number/ft	NS fractures comments	EW fractures number/ft	EW fractures comments	Other fractures number	Other fractures comments
mudst				29/ft	Steep dissolution cleavage (?) flattens into underlying shale. Shale has abundant folded, crenulated cc stringers (mylonitic shear zones?)		
grnst/pkst	1-2 ft	1/3ft	while rare in outcrop, NS frax control overall weathering pattern				
pkst/grnst	3 ft	4/9 ft	1 thrugoing; rest terminate internally or on bedding plane	8/ft	3 thrugoing		
wackstone	3 ft	5/9 ft	1 thrugoing	34/ft			
shale	1.5 ft	4/ft		6/ft	cc-filled extension frax that postdate dissolution cleavage		
grnst		3/2 ft	none thrugoing; all three penetrate overlying shale, but don't go all the way thru	12/ft	all but two terminate internally; remaining two terminate against overlying shale		
grnst		4/2 ft	none continuous thru underlying shale				

TABLE 1. Continued.

Lithology	Bed thickness	NS fractures		EW fractures		Other fractures	
		number/ft	comments	number/ft	comments	number	comments
ooid grainstones	1-2 ft	8/5 ft		11/3 ft		8/3 ft	conjugate to EW frax but younger?
grnst	2 ft	5/4 ft		11/3 ft		6/3 ft	conjugate to EW frax but younger?
grainstone	3 ft	1/3 ft	These fairly cont. thru bed; possibly late en echelon extension?			6/ft	conjugate set assoc. with NS frax, due to en echelon extension of NS? Suggests that NS are reactivated?

TABLE 1. Continued.

Clarence River: Alapah Limestone

Lithology	Bed thickness	NS fractures number/ft	NS fractures comments	EW fractures number/ft	EW fractures comments
mudst/wkst	5 ft	29/5 ft	9 continue thru entire bed; only 3 of those continue into overlying bed; cc filled	11/2 ft	only 4 continue thru entire bed
mudst., sl. dol.	4 ft	8/2 ft	2 go thru entire bed, but terminate at bedding plane		
mudst	5 ft	14/5 ft	4 go all the way thru		
mudst, sl. dol., evap nodules	7 ft	29/2 ft	all terminate at bedding planes	30/2 ft	all terminate at bedding planes
skeletal, oncolitic wkst	1 ft		poor fracture development		
skel. mudst	2 ft	15/2 ft		8/2 ft	
cryptalgal mudst with thin shale stringers	< 1 ft	2-3/2 ft	few frax extend beyond individual beds	2-3/2 ft	few frax extend beyond individual beds

TABLE 1. Continued.

Lithology	Bed thickness	NS fractures		EW fractures	
		number/ft	comments	number/ft	comments
cryptalgal mudst with fenestral fabric & layering	< 1 ft	34/2 ft	All terminate against erosion surfaces; occ. evidence of shear	21/ 2 ft	most terminate agains bedding planes; undulatory; probably axial planar cleavage
oncolitic cryptalgal laminate	1-4 ft	12/3 ft	Occ. large, thrugoing frax extend > 20 ft (~1/15 ft) but generally confined to 1-2 beds; some filled with euhedral quartz	11/5 ft	1-2 of these > 20 ft high
mudst with cryptalgal laminate & evaporite nodules		29/2 ft		15/2 ft	

TABLE 1. Continued.

Fourth Range: Wahoo & Alapah Limestones

Lithology	Bed thickness	NS fractures		EW fractures		Other fractures	
		number/ft	comments	number/ft	comments	number	comments
grnst (Wahoo)	2+ ft	1.5	1/3 extend 15-20 ft	1.5	few extend beyond individual bed		
mudst (Alapah)	1 ft	24	1/ft throughgoing	3		4	NS frax contempor-aneous with EW?
mudst (Alapah)	1.5 ft	11		2		1.5	"
grnst (Alapah)	2+ ft			6.5		3.5	"

TABLE 1. Continued.