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MECHANICAL STRATIGRAPHY OF THE LISBURNE GROUP, EASTERN SADLEROCHIT MOUNTAINS: A PRELIMINARY REPORT OF FIELD RESULTS

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Abstract

The Carboniferous Lisburne Group is an important naturally-fractured reservoir in the subsurface of the North Slope of Alaska. The closest exposed section of Lisburne is in the northern part of the northeastern Brooks Range fold-and-thrust belt, approximately 75 miles to the southeast. Lisburne carbonates of the 'Sunset Pass' section of the eastern Sadlerochit Mountains have two dominant sets of fractures: an early, through-going set striking NNW and a later, more restricted set striking ENE. Both sets of fractures are calcite filled. In general, fracture density increases in calcareous mudstones and/or dolomitic horizons. There is no obvious correlation between fracture density and bed thickness.

Although the structural setting of the Lisburne Group exposed in the northeastern Brooks Range and that of the Lisburne in the subsurface to the northwest are very different, they both share the NNW striking fracture set. This suggests that both sections of Lisburne fractured under similar (possibly the same) NNW compressional stresses, probably related to NNW-directed thrusting. In both the surface and subsurface, the ENE striking set is most likely related to local structures. This similarity in fracture pattern between the Lisburne of exposed in the Sadlerochit Mountains and the Lisburne in the subsurface suggests that fracture patterns in surface exposures of the Lisburne Group can be used to study subsurface fracture characteristics.

Introduction

The Carboniferous Lisburne Group of northern Alaska is the thick, heterogeneous and highly fractured reservoir of the Lisburne oil field of the North Slope. It also is widely exposed throughout northern Alaska as an important element of the Brooks Range fold-and-thrust belt. The Lisburne Group was recognized to be a potential reservoir horizon very early during petroleum exploration of northern Alaska and was considered by many to be the primary exploration target during exploratory drilling of the North Slope (Paige and Dayton, 1987).

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). Within the Lisburne reservoir, the distribution and density of fractures are highly variable and may depend on the lithology of the host rock, the structural setting of the reservoir and/or other as yet unidentified factors. 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 distribution, character 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 purpose of this pilot study is to define a mechanical stratigraphy of the Lisburne Group exposed in the northeastern Brooks Range of Alaska. This mechanical stratigraphy would relate lithology to mechanical properties and fracture patterns in a well-documented section of the Lisburne Group. In the subsurface, the upper part of the Lisburne Group (the Pennsylvanian Wahoo Limestone) is the productive horizon, and the focus of the initial phases of this study will be on that interval. The section chosen for the first phase of the project, the 'Sunset Pass' section, was chosen for its relative structural simplicity, good exposure of the Wahoo Limestone and proximity to Lisburne field.

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) (Fig. 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. 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).

However, in the eastern Sadlerochit Mountains, the Kayak Shale is depositionally thin and/or absent, and the Lisburne Group has remained structurally coupled to the 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 (Fig. 2) and possible structural complexities due to thrusting and detachment folding are absent.

Besides its structural simplicity, the 'Sunset Pass' section is one of the best documented sections of the Wahoo Limestone, with several studies focusing on the stratigraphy, carbonate sedimentology, and biostratigraphy (Carlson, 1987; Krumhardt, 1992; Watts, 1990; Morgan, 1992). This information provides a means of correlating observations on the fracture distribution and density with lithology and bed thickness within the section as well as with other sections in both surface exposures and in the subsurface.

The 'Sunset Pass' section:

The 'Sunset Pass' section is located at the eastern end of the Sadlerochit Mountains (Figs. 1 & 4). The section is not actually at Sunset Pass, but approximately 6 miles to the east. However, the section has been referred to as the 'Sunset Pass' section for many years and will be referred to as such in this report.

Stratigraphy

Figure 3 is a generalized stratigraphic section of the Lisburne Group exposed at the 'Sunset Pass' section. The uppermost member of the Lisburne Group, the Wahoo Limestone (Mississippian and Pennsylvanian in age), is well-exposed at this location and has been subdivided into two informal members: 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.

In contrast, the Alapah Limestone (Mississippian in age) is not well-exposed at the section. However, the Alapah Limestone is well-exposed along strike to the west, and in the footwall below the range-front fault to the north. The Alapah generally consists of a lower, thickly-bedded sequence of grainstones and packstones, and an upper, recessive-weathering sequence of wackestones and mudstones. The Alapah was not examined in detail in this preliminary study.

Structure

The Sadlerochit Mountains consist of a single, large, east-west trending, doubly-plunging anticlinorium, interpreted to reflect a Cenozoic-age horse within the regional duplex in the pre-Mississippian rocks (Fig. 2; Wallace and Hanks, 1990; Wallace, 1993). In the Sadlerochit Mountains, these pre-Mississippian rocks are structurally competent Lower Paleozoic and Proterozoic carbonate rocks underlain by siliciclastic metasedimentary rocks intruded by a mafic sill. The northern margin of the anticlinorium is truncated by an out-of-sequence range-front fault that thrusts these pre-Mississippian rocks over Mississippian and younger rocks of the Ellesmerian sequence to the north (Fig. 2). The Ellesmerian sequence rocks in the footwall are themselves deformed into a broad east-west trending fold that is also interpreted to reflect a Cenozoic-age pre-Mississippian horse at depth.

The range-front fault that is such a prominent structure in the western and central Sadlerochit Mountains gradually loses displacement towards the eastern end of the range. As the fault loses displacement, a series of folds develop within the hanging wall. These folds are probably fault-propagation folds related to thrust faults climbing up-section from the pre-Mississippian sequence and dying out in the overlying Lisburne Group (Wallace, pers. comm.) There are several of these small thrust faults in the vicinity of the 'Sunset Pass' section, resulting in a kinked hanging wall anticline (Fig. 5). One of these small faults eventually dominates east of the section and emplaces pre-Mississippian rocks over rocks of the Lisburne Group. The fault loses displacement upsection, however, and the clastic rocks of the Sadlerochit Group form the broad, east-plunging fold nose of the eastern end of the Sadlerochit Mountains only locally disrupted by faulting.

As mentioned earlier, the footwall also is cored by a Cenozoic horse within the pre-Mississippian sequence, resulting in broad folding of the overlying Ellesmerian rocks. In the eastern Sadlerochit Mountains, the Lisburne Group immediately underlying the range-front thrust fault is deformed into an inclined to slightly overturned anticline with an axial plane dipping moderately to the south (Fig. 5). This fold is itself thrust over Lisburne along a low-angle thrust fault. Clastic rocks of the Sadlerochit Group are deformed into more open, upright folds immediately to the north.

These structural complexities are probably in part due to small-scale thrust faulting within the phyllites and metasandstones of the pre-Mississippian sequence. The 'Sunset Pass' section lies on the south-dipping panel of the hanging wall anticline, well south of the frontal thrust fault and associated subsidiary structures. The fracture patterns seen at the section should therefore reflect both the regional and local structure.

Fracture patterns

Fracture sets and orientations

The Pennsylvanian Wahoo Limestone is well exposed in the 'Sunset Pass" section (Fig. 3) and a variety of lithologies are available for study. The Mississippian Alapah Limestone, although not well-exposed in the hanging wall, is reasonably well-exposed in the footwall immediately north of the range-front fault. The fracture pattern, distribution and relationship to lithology for several of the major lithologies within the Alapah Limestone were studied in the footwall.

There are two distinctive fracture sets in both the Wahoo Limestone in the hanging wall and the Alapah Limestone in the footwall. The earliest fractures are steeply dipping, normal to bedding and strike north-northwest (Fig. 6). These fractures are generally evenly and widely spaced, and are throughgoing. Individual fractures commonly cut across several beds (Figs. 7 and 8). Most of the NNW-striking fractures probably were originally filled with calcite, although they are locally unfilled at present because of weathering.

Fractures of the second set are steeply dipping and strike east-northeast (Figs. 8 & 9). These fractures are more variable in orientation, commonly more closely spaced than the earlier NNW striking fractures, and often terminate vertically at bedding planes. Some of these fractures are filled with calcite, suggesting that most of the fractures were originally mineralized. Fractures of this second set have maintained a bed-normal orientation where beds have been folded by the map-scale overturned fold in the footwall, indicating that both fracture sets predate the fold and related structures, including the range-front fault.

Relationships between fractures and lithology

The fracture type, density, and character in a variety of different carbonate lithologies and bed thicknesses in both the hanging wall and footwall are summarized graphically in Figure 10 and Table 1.

In both the Wahoo Limestone of the hanging wall and the Alapah Limestone of the footwall, there appears to be a strong correlation between fracture density and lithology. In general, the density of fractures increases with increasing carbonate mud content, with grainstones being the least densely fractured and carbonate mudstones the most densely fractured (Figs. 10 and 11). This may be due to the increase in mud, an increase in dolomitization of the muddier lithologies, or more complete cementation of the grainstones and packstones. Chert nodules and lenses also fracture more readily than the surrounding matrix, with fractures within the chert commonly not extending into the surrounding rock (Fig. 12)

The character of the fractures also changes with lithology. While fractures are abundant in the carbonate mudstones, they generally terminate at bedding boundaries (Fig. 11). In mudstones that are not as highly dolomitized, the fractures are commonly very narrow, anastomosing and multistranded, suggesting multiple episodes of fracturing opened new fractures and did not reactivate old ones (Fig. 13). In contrast, while fractures are fewer in number in the grainstones, they are frequently wider, more planar and throughgoing, especially the early NNW-striking fractures (Fig. 7). A high percentage of both NNW and ENE-striking fractures terminate within the thicker grainstone beds, specifically against stylolitic horizons. This is true for both skeletal and oolitic grainstones. Clast composition in the grainstones appears to affect the morphology of the fractures, however, with oolitic grainstones having more planer, 'cleaner' and more evenly spaced fractures than those in the skeletal grainstones.

There appears to be no obvious correlation between bed thickness and fracture density (Fig. 10). Increased bed thickness within the grainstone horizons does seem to increase the possibility of fractures terminating against stylolitic horizons.

Relationship between fractures and structural position

Both sets of fractures occur in both the Wahoo Limestone of the hanging wall and the Alapah Limestone of the footwall. The overall fracture character, distribution and relationship to lithologies appear to remain consistent in both structural positions.

In both the hanging wall and footwall, anomalously large calcite-filled ENE-striking fractures are commonly associated with major changes in lithologies. In the footwall, this occurs at the base of the Alapah Limestone, where carbonate rocks overlie pre-Mississippian phyllitic shales. These fractures are often fairly wide (1"-3") and show evidence of shear and/or displacement. The most striking examples are large en echelon shear fractures, but small amounts of displacement are visible in large planar ENE-striking fractures as well. The sense of shear displacement varies but is generally consistent with bedding-parallel slip associated with the formation of the footwall fold.

In the hanging wall, similar large, throughgoing calcite-filled ENE-striking fractures occur in the lower Wahoo Limestone, where the massive grainstones and packstones of the lower Wahoo overlie carbonate mudstones and wackestones of the upper Alapah. However, these fractures do not show obvious evidence of shear or significant offset.

Discussion: Origin of the fractures seen at Sunset Pass

The early and dominant NNW-striking set of fractures seen at Sunset Pass are common throughout the northeastern Brooks Range. They are consistently perpendicular to the axes of the large, regional anticlinoria and of smaller folds. In the past these fractures have been referred to by geologists working in the region informally as the 'AC joints.' Their consistent orientation with respect to regional structures has suggested that the fractures and larger structures both formed as part of the same stress regime. Similar fractures in the basal Mississippian Kekiktuk Conglomerate underlying the Mississippian Kayak Shale seen elsewhere in the northeastern Brooks Range have been suggested to have formed synchronously or shortly after formation of the regional anticlinoria as a dilatancy effect (Hanks and Wallace, 1992). In general, however, the timing of fracture formation vs development of the map-scale structures within the Lisburne Group has been not been a focus of study.

In this study, preliminary evidence in the eastern Sadlerochit Mountains suggests that the NNW-striking fractures formed prior to the development of the local map-scale structures. This timing would rule out the possibility that the fractures were directly related to the local thrust fault or folds. To the contrary, the occurrence of similarly-oriented fractures in the subsurface of the North Slope suggest that these fractures are a regional phenomenon responding to a regional stress regime.

Recent work by Lorenz and others (1991) suggests that extensional fractures can form at depth parallel to regional tectonic compression. Such fractures can form experimentally at very low levels of differential stress under low confining pressures in brittle rocks (Griggs and Handin, 1960). Under natural conditions, these conditions can be achieved with high pore pressures and corresponding low effective confining pressures. The resulting fractures would remain open as long as pore pressure remains high and differential stresses exist, providing an opportunity for mineral precipitation and filling of the fractures. Based on our preliminary data, this method of fracture formation provides a reasonable explanation for the orientation, character and timing of these early fractures in the eastern Sadlerochit Mountains.

The ENE-striking fractures appear to parallel and either immediately predate or have formed synchronously with the local structures. For example, these fractures locally appear to be associated with shear fractures and en-echelon tension gashes and have occasional small amounts of offset in the footwall of the range-front fault, suggesting a genetic relationship with the fault. Increases in the size and width of the fractures at major lithologic boundaries also suggests that some of these fractures may have formed in response to bedding-parallel shear and extension of beds as the Lisburne Group was folded. This origin of the ENE fracture would imply a potentially significantly younger age than the earlier NNW-striking fractures as well as a more restricted areal extent.

Discussion: Implications of the observed fracture character for subsurface reservoir characteristics

At first glance, the gross fracture characteristics of both the surface exposures of the Lisburne Group and the Lisburne reservoir are remarkably similar--in both areas, there are two dominant fracture sets: an ENE-striking set and a NNW-striking set.

In the subsurface, the two fracture sets do not appear to play similar roles in the enhancement of permeability. At the Lisburne field, the NNW-striking fractures play a major role in directional conductivity within the reservoir. In contrast, the ENE-striking fractures probably have little effect on the directional conductivity through the Lisburne field, as they are preferentially held closed by the anisotropic horizontal in situ stresses (Teufel and others, 1993). Consequently, the character of NNW-striking fractures observed in the surface exposures may yield important information on the character, distribution and morphology of the NNW-striking set in the subsurface.

As noted in this report, the distribution of both fracture sets is a function of lithology, and thus ultimately a function of depositional environment. Fractures of both orientation are more widely and more evenly spaced in the cleaner, oolitic grainstones. Since this lithology becomes more frequent upsection in the Wahoo Formation at the 'Sunset Pass' section (Krumhardt, 1992) and elsewhere in the northeastern Brooks Range (Watts, 1990), better reservoir characteristics would be expected from the top of the formation. However, the 'Sunset Pass' section is not entirely lithologically analogous to the subsurface section, having almost no siliciclastic shale or quartz interbeds and displaying none of the karsted 'Subsurface Alteration Zone' that seems to dominate the upper zone in the subsurface (Missman and Jameson, 1991). It is not possible to evaluate the effect of these lithologies on the fracture distribution at this point.

With increasing amounts of lime mud, the fractures of both sets become more irregularly spaced and more easily terminated by bedding planes and horizontal stylolites. Beds consisting entirely of lime mudstone also commonly display multiple, parallel fractures (Fig. 13), suggesting that healed fractures in these beds were no less resistant to frequent fracturing than the matrix rock.

Finally, the thin dolomitized lime mudstones that occur at the top of individual depositional cycles in outcrop (Krumhardt, 1992) are the most heavily fractured (Fig. 11). Similar lithologies occur in the subsurface, and, if similarly fractured, may provide much of the permeability for the system by allowing drainage from the less intensely fractured, but volumetrically more important, carbonate grainstones, packstones and wackestones.

Bedding discontinuities, thin lime mudstone interbeds, and stylolites create locally important heterogeneities within the reservoir lithologies, and are capable of partitioning the reservoir horizontally despite fracturing. As noted, these features are less important in the oolitic grainstones, although measurements in even this lithology indicated that in an individual oolitic grainstone bed:

--65% of fractures that extended to a one-inch thick lime mudstone within the oolitic grainstone bed terminated at the mudstone;

--53% of fractures terminated at a small horizontal stylolite within the bed;

--95% of fractures terminated at a large internal horizontal stylolite.

The dependence of fracture character on lithology is best exemplified by the intensely fractured chert nodules surrounded by virtually unfractured limestone (Fig. 12). The brittle cherts fractured easily and often, and apparently were commonly unmineralized. Although they provide local high permeability and porosity, they are volumetrically unimportant: unfortunately, drilling for chert nodules would not be a rewarding exercise.

Lengths of the NNW-striking fractures, especially in the oolitic grainstones, are essentially unlimited. Although individual fractures may not extend for more than a few tens of feet, interconnected fracture systems can be traced a minimum of a hundred feet, limited only by the dimensions of exposed pavements (Fig. 8). Barring the presence of a fault, fracture permeability enhancement in the north-northwest direction should be limited only by the sized of the bed.

Widely spaced "megafractures," as postulated by Missman and Jameson (1991) for the subsurface reservoir, may or may not be present in the outcrop. The one to three-inch wide calcite-filled fractures noted at the base of both the Alapah and the Wahoo Formations trend east-northeast, and are spaced on the order of 25 to 150 feet. However, they are typically do not extend up from the base of the respective formations more than fifty or hundred feet; although they cross bedding boundaries indiscriminantly where they are present, the limited vertical extent as developed at the 'Sunset Pass' section would not provide vertical continuity throughout the formation. Although severely limited by bedding and stylolites, five percent of the largest fractures commonly do extend across such heterogeneities (Fig. 7), and may provide vertical conductivity sufficient to fit the Missman and Jameson model.

Conclusions

Preliminary observations on the fracture character and density in the Lisburne Group at the 'Sunset Pass' section of the eastern Sadlerochit Mountains suggest the following:

•There are two distinct fracture sets: an early, NNW-striking set and a later, ENE-striking set. Both are filled with calcite.

•The early, NNW-striking fracture set is similar in orientation and character to the open fracture set seen in the Lisburne oil field. This suggests that the two fracture sets may have originated under the same, or at least similar, stress regime. Similar fractures have been observed that developed parallel to the maximum stress direction under conditions of high pore pressure and low differential stress (Lorenz and others, 1991). This suggests that the NNW-striking fractures seen in the Lisburne in both the surface and subsurface may have formed in response to NNW compression far beyond the thrust front.

•While the later ENE-striking fracture set shares the same orientation as the range-front fault and appears to be related to it, both sets predate the folding associated with the fault. This suggests a complicated history of fracturing, folding and later faulting under the same stress regime.

•The early, NNW-striking set is more throughgoing while the later, ENE-striking set is more likely to be restricted to 1 or 2 beds.

•Both fracture sets show a strong correlation between fracture density and lithology. Fracture density increases with carbonate mud and/or dolomite content, with carbonate mudstones being the most densely fractured lithology.

•Bed thickness does not have any obvious effect on fracture density.

The positive correlation between lithology and fracture density at the outcrop scale suggests that a fracture stratigraphy of the Lisburne Group will be feasible. In addition, similarities between the orientation and character of the fractures seen in the exposed Lisburne of the eastern Sadlerochit Mountains and those seen in the subsurface of the North Slope suggest that study of exposed Lisburne Limestone will yield insights into the reservoir character of the unit in the subsurface.

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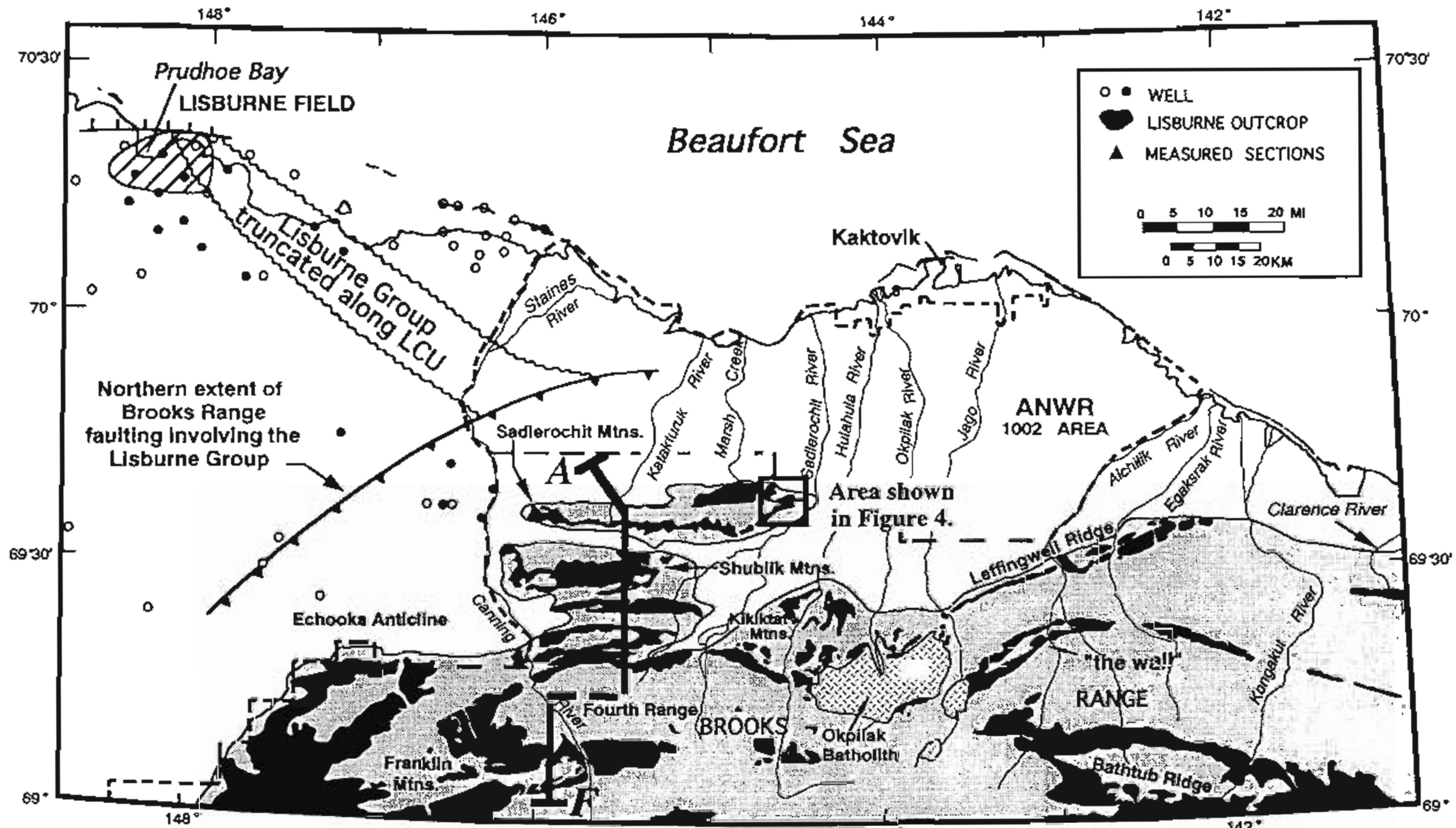


Figure 1. Generalized geologic map of the northern part of the northeastern Brooks Range showing the distribution of Lisburne Group exposures. The outlined area is shown in more detail in Figure 4. Cross section A-A' is the location of the balanced section shown in Figure 2. Map modified from Watts, 1990.

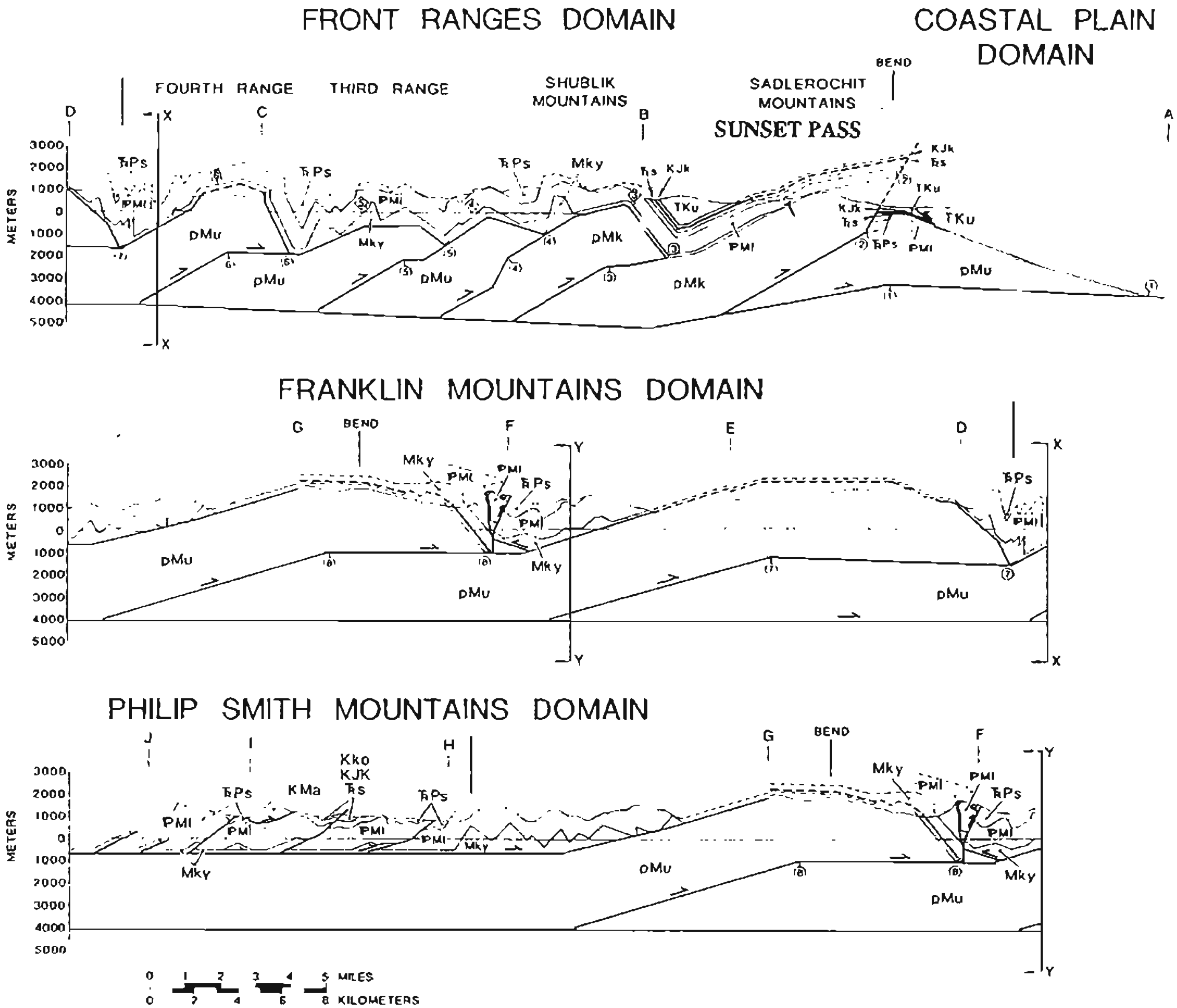


Figure 2. Balanced section through the western portion of northeastern Brooks Range as shown on Figure 1 (from Wallace, 1993).

EXPLANATION

TKu Kemik Sandstone, pebble shale unit, Hue Shale, & Canning Formatic
(Lower Cretaceous to Lower Tertiary)

KJk Kingak Shale
(Jurassic to Lower Cretaceous)

T̶R s Shublik Formation
(Triassic)

T̶R Ps Sadlerochit Group
(Permian to Triassic)

IPMl Lisburne Group
(Mississippian to Pennsylvanian)

Mky Kayak Shale
(Mississippian)

pMu Undifferentiated pre-Mississippian rocks and
unconformably overlying Mississippian Kekiktuk Conglomerate

Units restricted to the north (Sadlerochit & Shublik Mountains)

pMk Mafic volcanic rocks, Katakturuk Dolomite, and Nanook Limestone
(Proterozoic to Devonian)

Units restricted to the south (Porcupine Lake vicinity)

KMa Mt. Annette allochthon
(Mississippian to Lower Cretaceous)

Kko Kongakut Formation
(Lower Cretaceous)

Symbols

A – J Offsets in line of section

(3) Leading-edge cutoffs (Footwall & Hangingwall) for each horse
(numbered from North to South)

◇3 Point at base of IPMl originally overlying leading-edge cutoffs
for each horse

Figure 2. (continued)

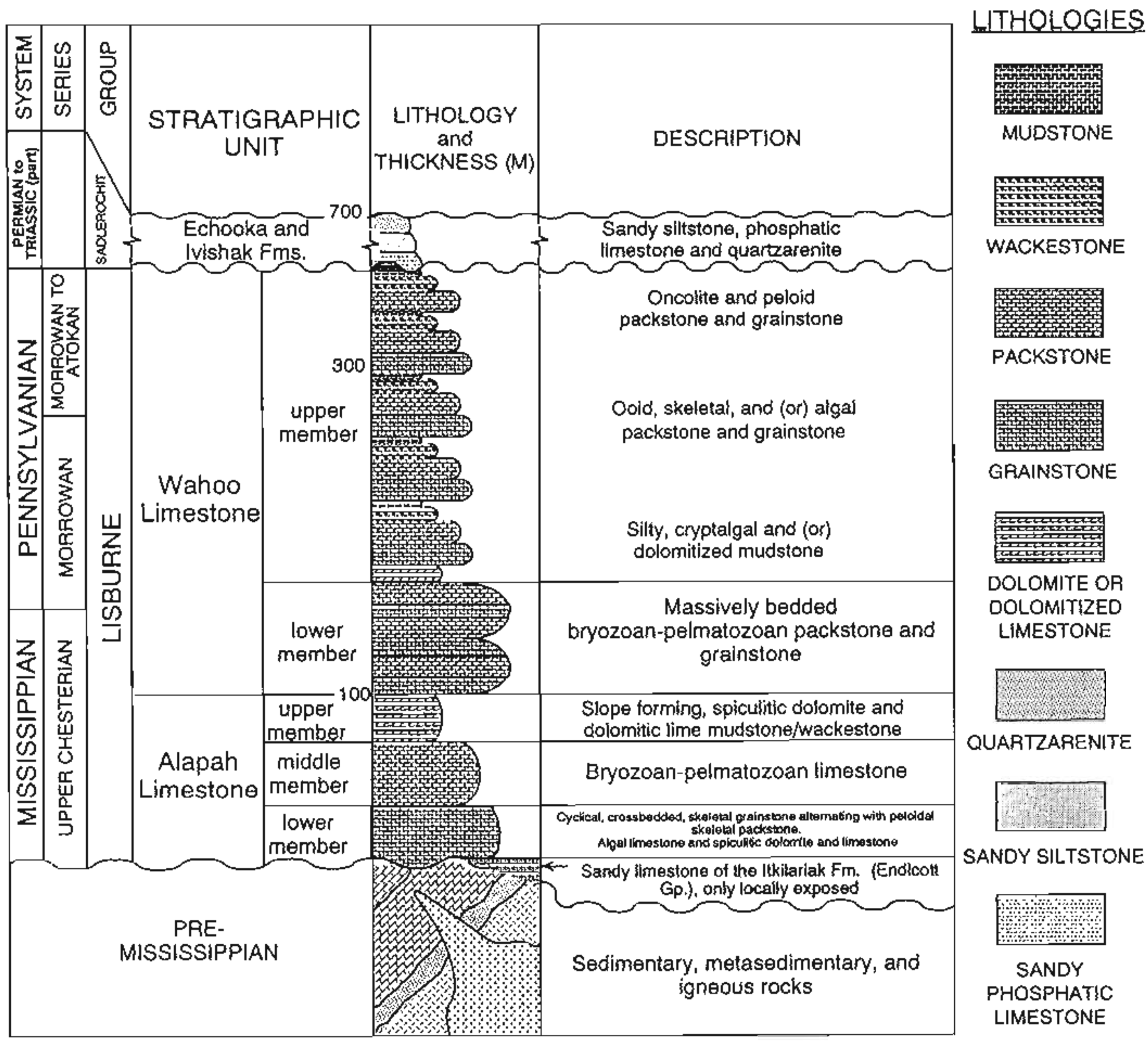
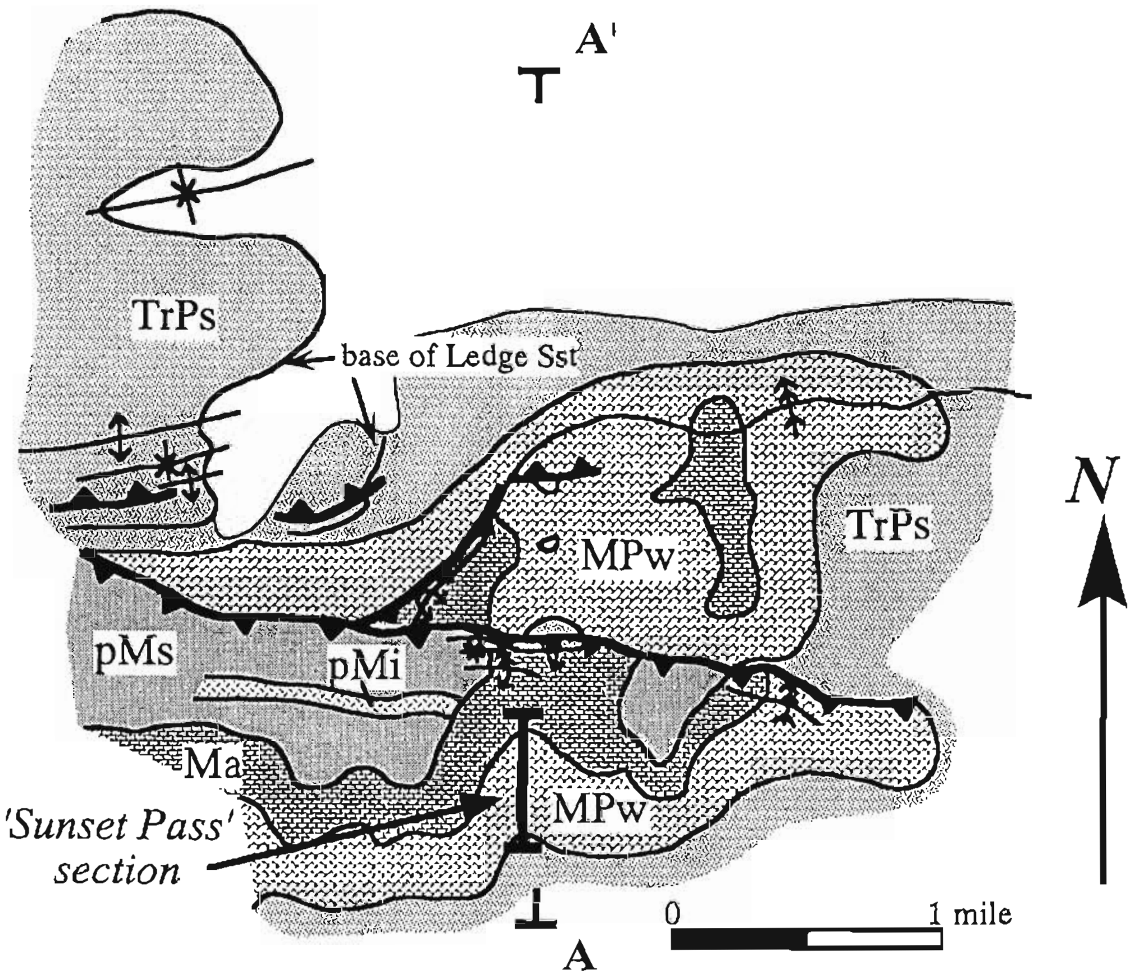


Figure 3. Schematic diagram showing stratigraphic relationship and lithology of the Lisburne Group in the eastern Sadlerochit Mountains. At the study section, the Endicott Group is missing and the Alapah Limestone rests with angular discordance on pre-Mississippian rocks. (Modified from Carlson, 1987; Crowder, 1990; Watts, 1990; Gruzlovic, 1991; and Krumhardt, 1992)



	TrPs	Permian to Triassic Sadlerochit Group
	MPw	Pennsylvanian Wahoo Lst
	Ma	Mississippian to Pennsylvanian Alapah Lst
	pMs	Pre-Mississippian sedimentary rocks
	pMi	Pre-Mississippian mafic intrusive rocks

Figure 4. Geologic map of eastern Sadlerochit Mountains. Map based on published maps by Bader and Bird (1986), Robinson and others (1987), and unpublished mapping by W. K. Wallace (1986, 1987) and C. Hanks (1993).

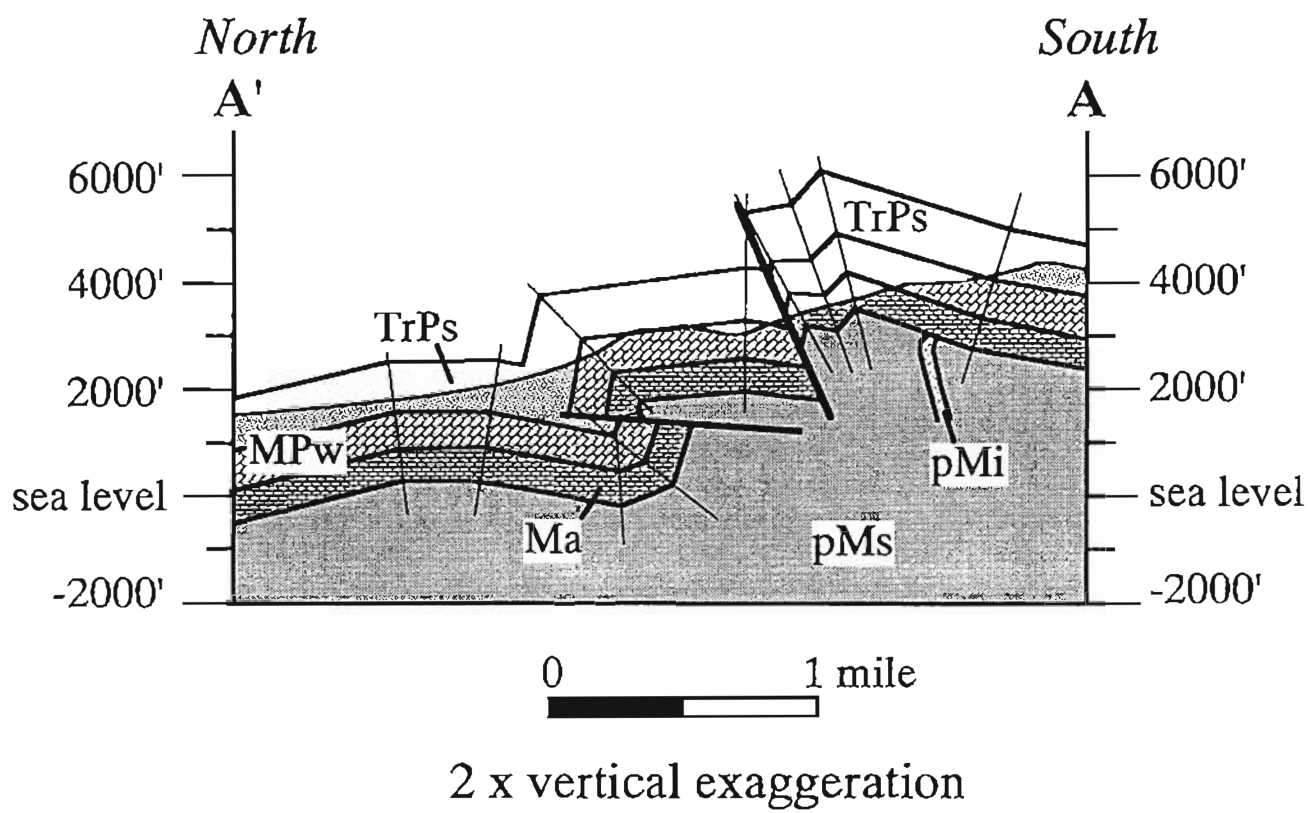


Figure 5. Cross section of eastern Sadlerochit Mountains.

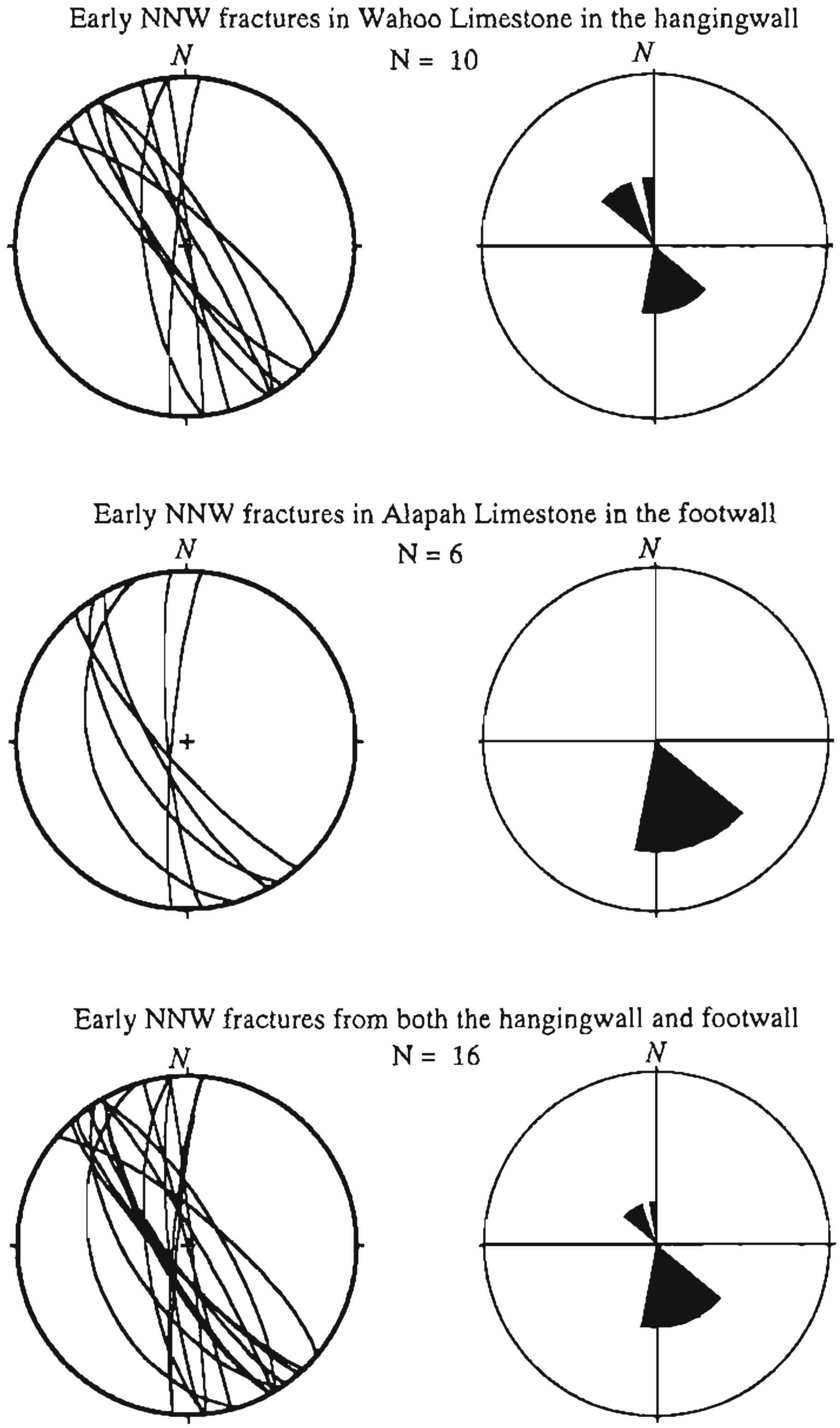


Figure 6. Lower hemisphere, equal area stereographic projects of the early, NNW-trending fractures in both the Wahoo Limestone in the hanging wall and the Alapah Limestone in the footwall. Data is also shown as rose diagrams of the strike of the fractures, with the outer circle equaling 25%.

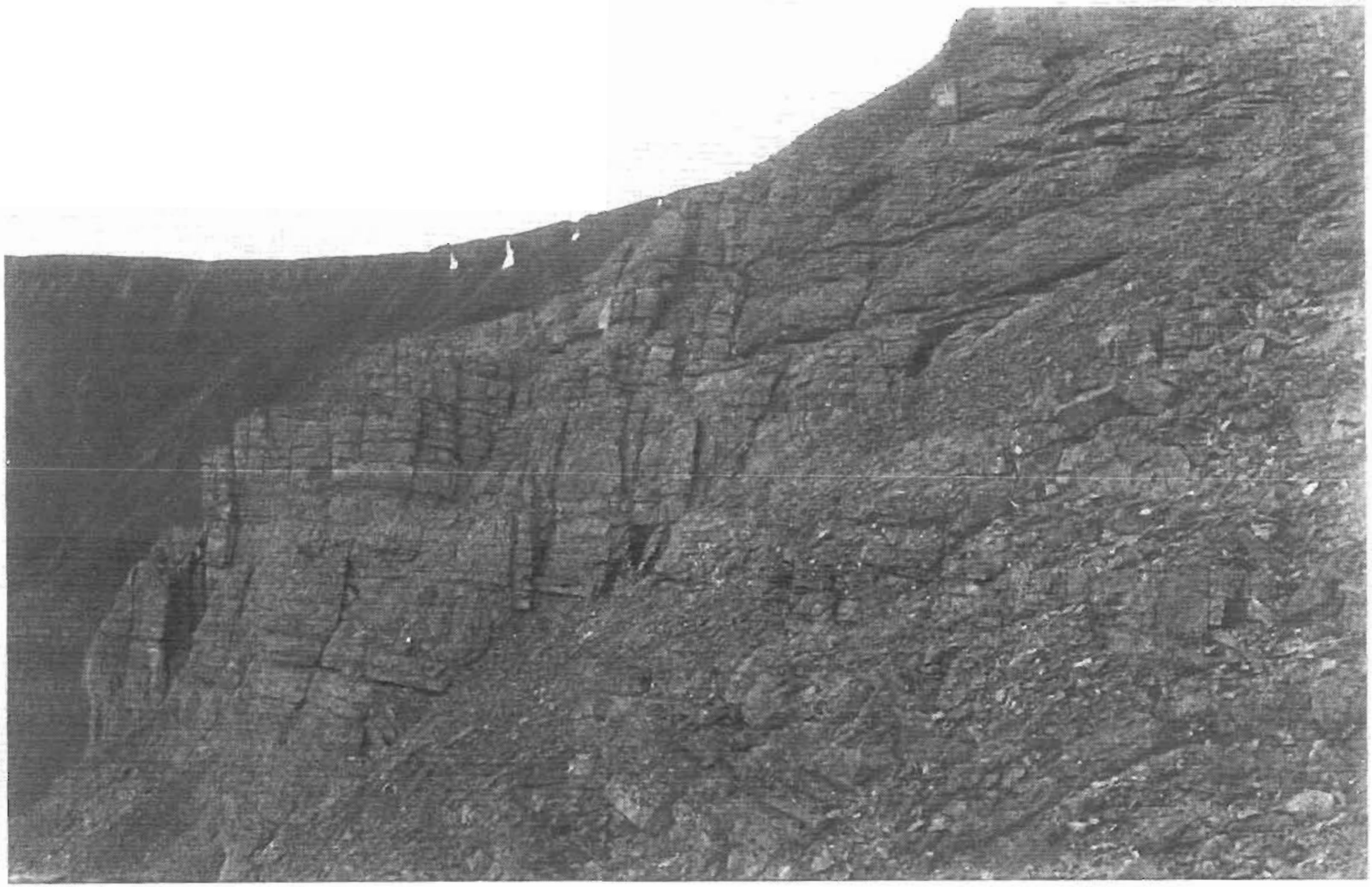


Figure 7. Photograph looking towards the south of NNW-trending fractures in the lower Wahoo Limestone. Individual beds are 6-15 feet thick. Note that while many of these fractures are throughgoing for several 10's of feet, individual fractures frequently terminate at bedding surfaces.

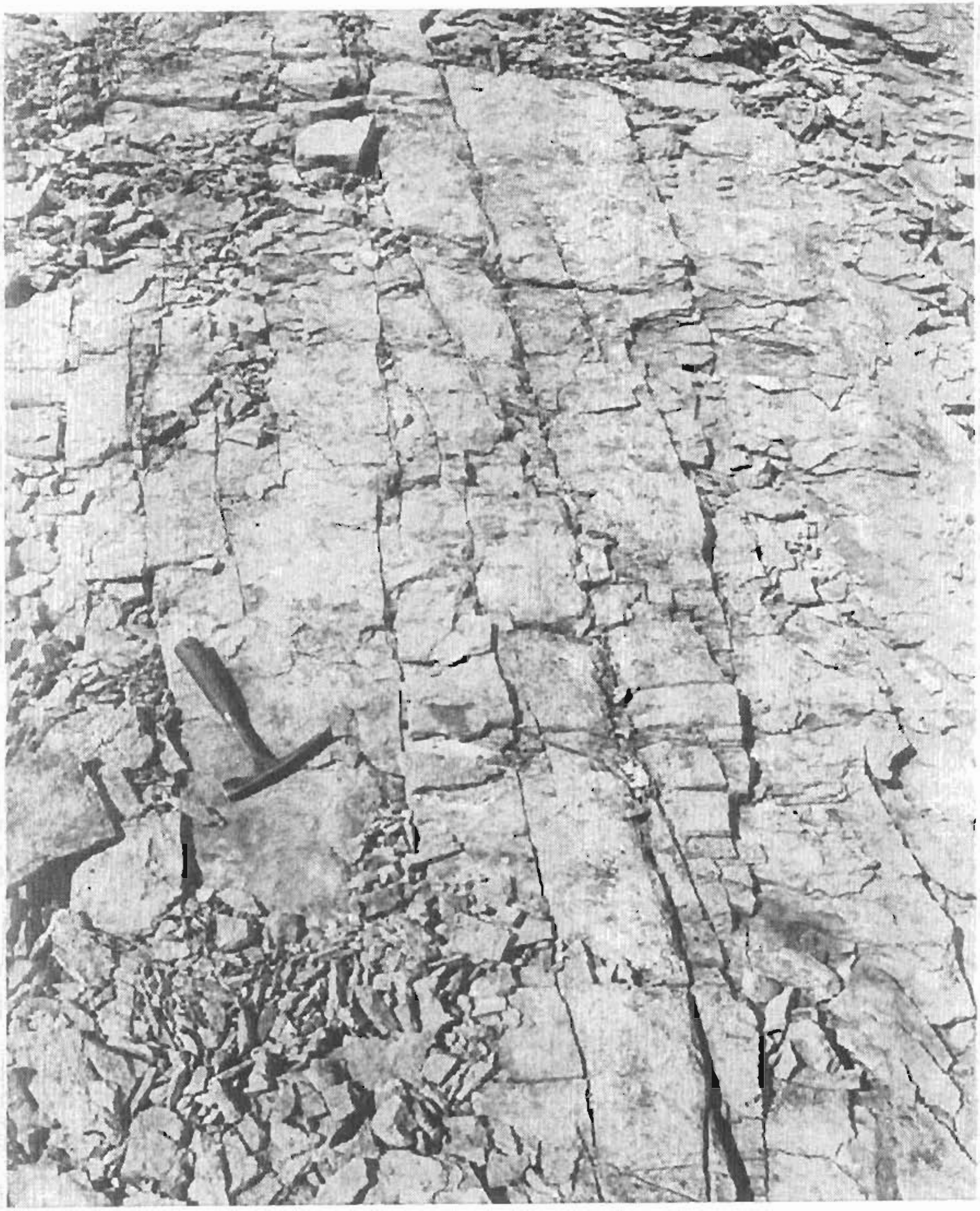
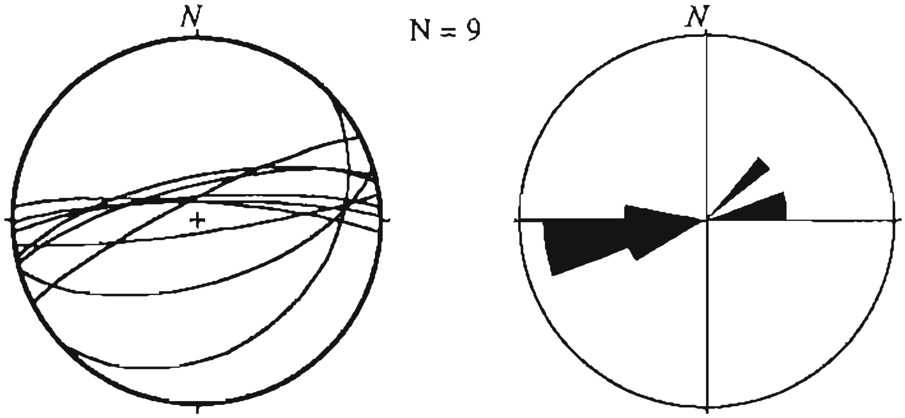
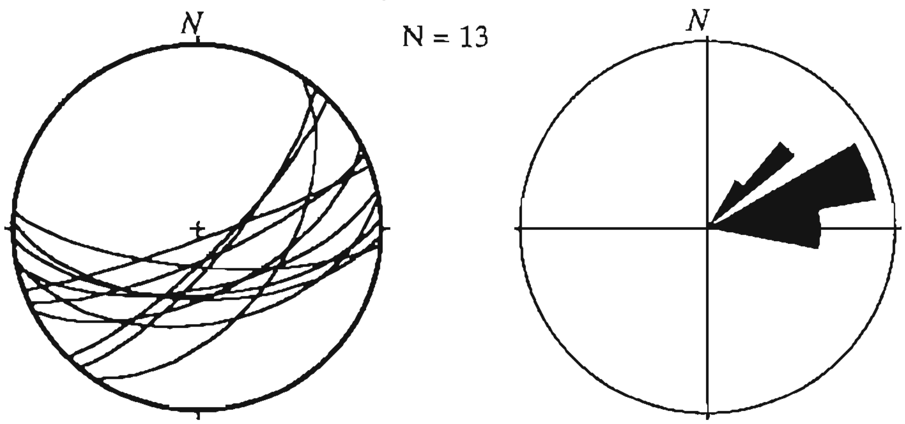


Figure 8. Photograph of bedding surface in the Wahoo Limestone. North is towards the top of the photo. Note the early throughgoing, dominant and spaced NNW-striking fractures. In contrast, the younger ENE-trending fractures are not as evenly spaced or as throughgoing, and often terminate against the older fracture set.

EW fractures in Wahoo Limestone in the hangingwall



EW fractures in Alapah Limestone in the footwall



EW fractures from both the hangingwall and footwall

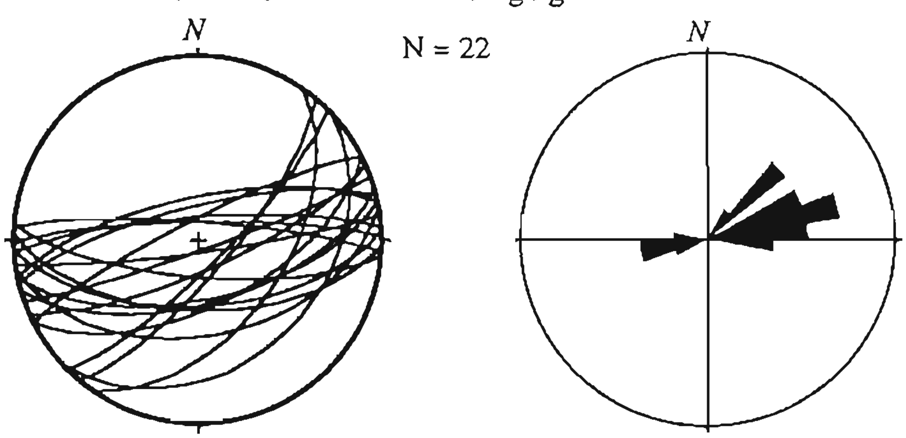


Figure 9. Lower hemisphere, equal area stereographic projects of the later, ENE- trending fractures in both the Wahoo Limestone in the hanging wall and the Alapah Limestone in the footwall. Data is also shown as rose diagrams of the strike of the fractures, with the outer circle equaling 25%.

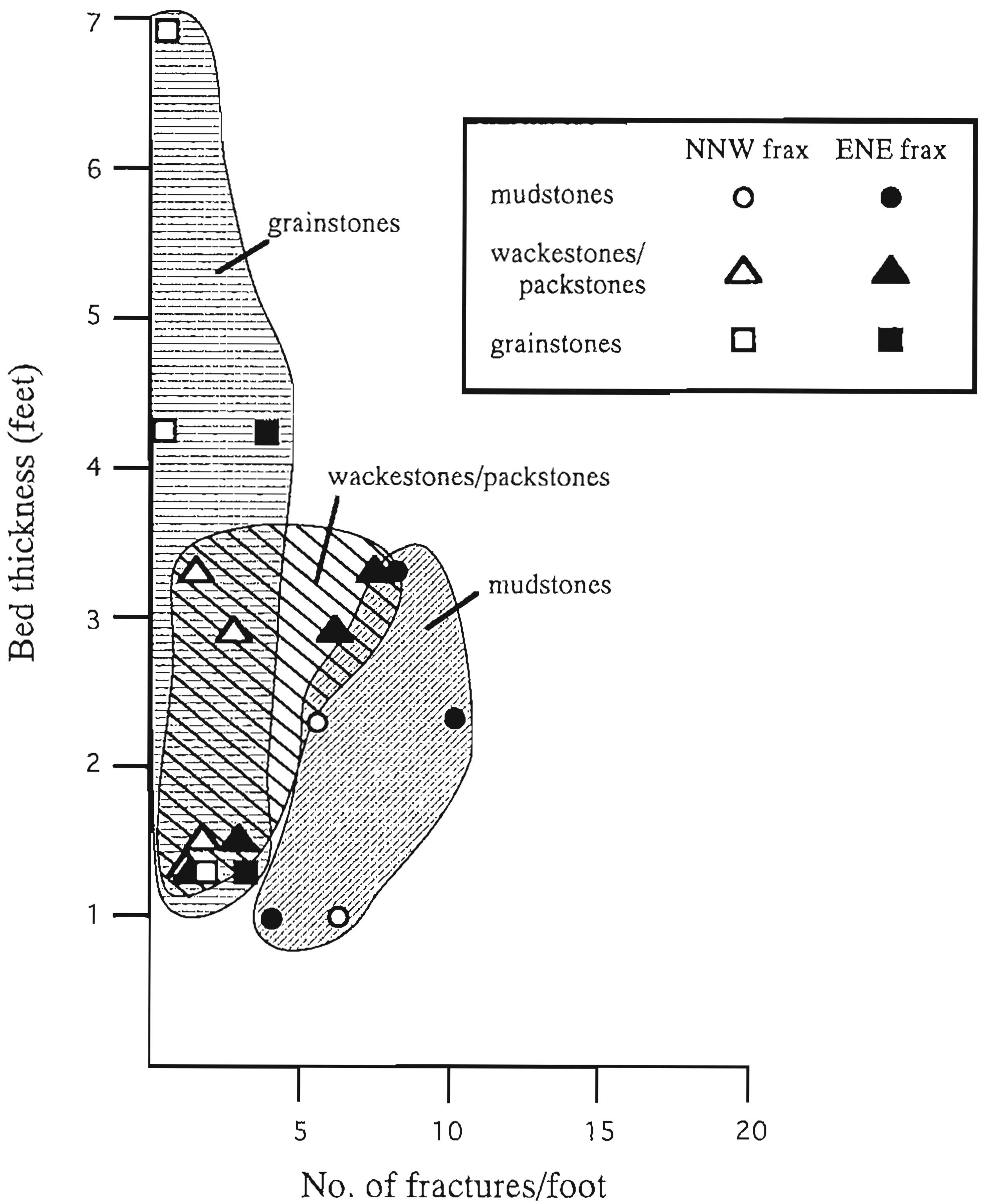


Figure 10. Graph of bed thickness vs fracture density. Data from Table 1.

Figure 11. Photograph looking southeast at dolomitized mudstone bed in the upper Wahoo Limestone. Note the dramatic increase in the density of fracturing within the mudstone bed in contrast to the fracture density in the overlying and underlying coarser-grained beds. Most of the fractures within the dolomitized mudstone terminate at the bed boundary.

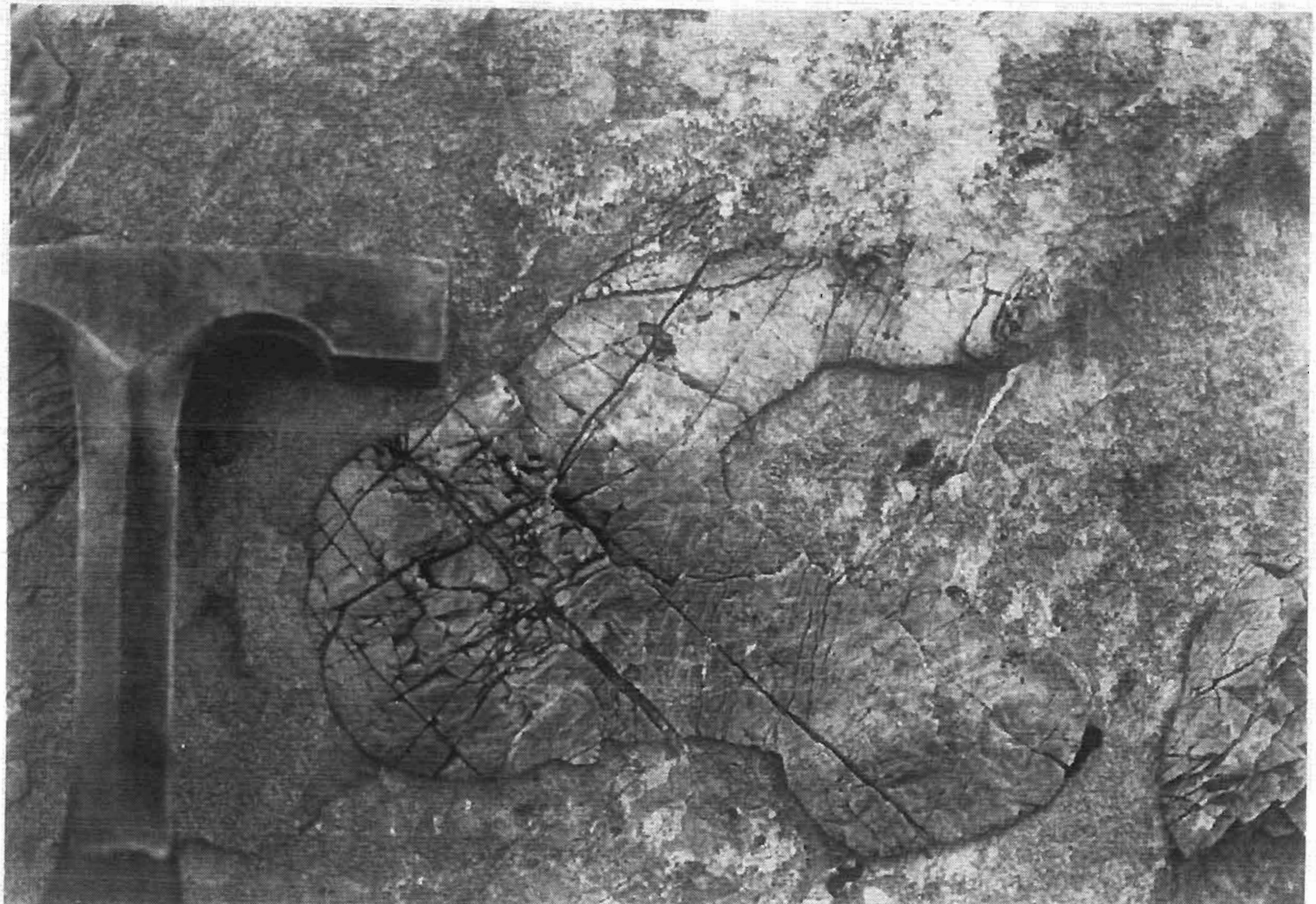


Figure 12. *Photograph* of bedding surface in the Wahoo Limestone showing large irregular secondary chert nodule. Note that the fractures within the chert nodule do not extend into the surrounding carbonate rock.

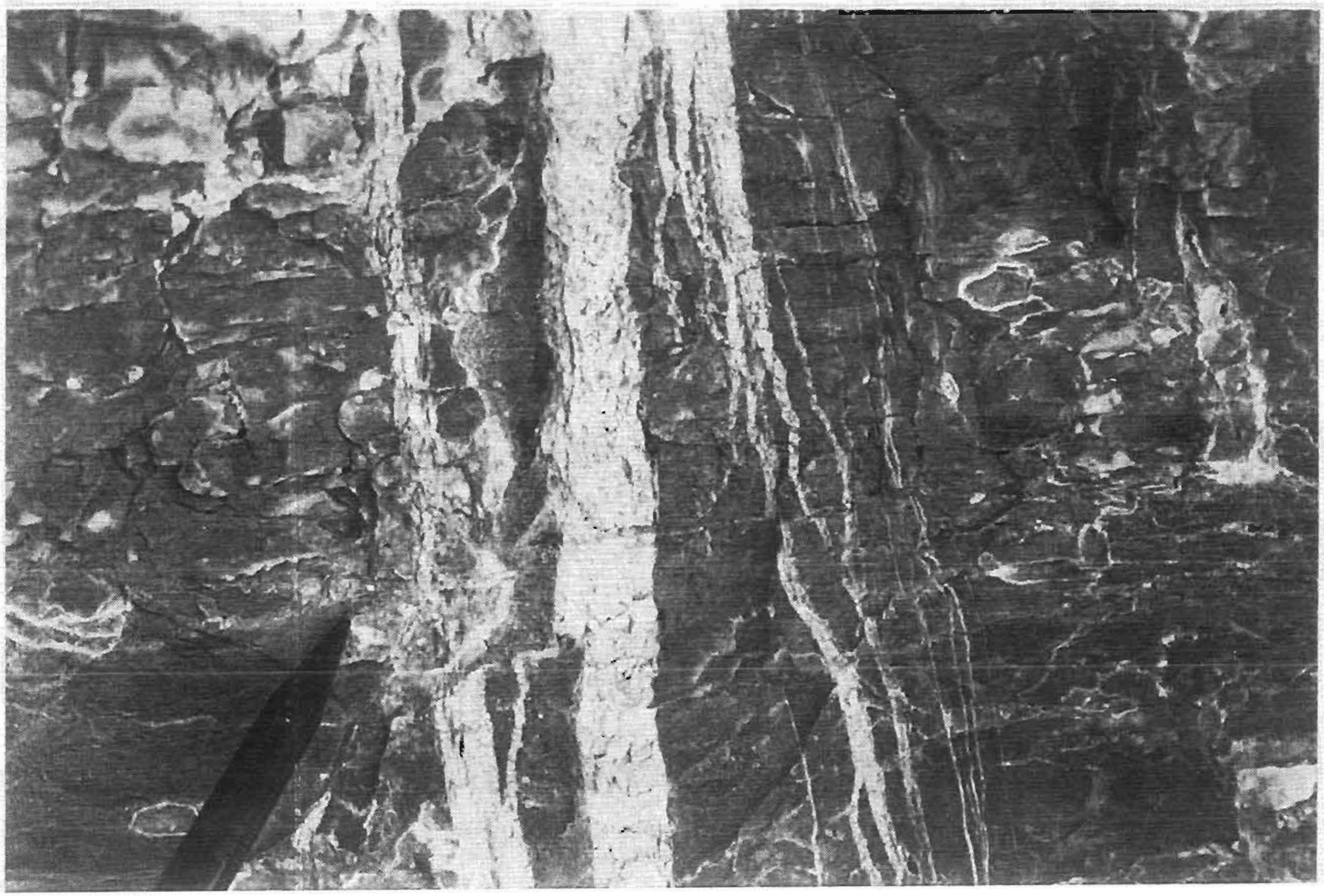


Figure 13. Photograph of ENE-striking filled multistranded fractures exposed on a NNW-striking fracture surface in a lime mudstone within the lower Alapah Limestone.

Alapah Limestone
(footwall)

Lithology	Bed thickness	NNW fractures number/ft	NNW fractures comments	ENE fractures number/ft	ENE fractures comments
grainstone/ packstone	3 + feet			1	•31% fractures > 10' in length, .1-.2' wide; extend across bedding planes; calcite filled; occasional offset •25% fractures 2-10' in length, <.05' wide, occ. filled, may or may not cross bed boundaries. •44% fractures <2' in height, narrow and unfilled, restricted to bed and/or internal chert layers. In lower beds, sets of large, calcite-filled, en echelon tension fractures of this orientation are common.
cryptalgal laminated lime mudstone	3" to 1.5'	3.5	frax evenly spaced ~2"-4" apart; some filled with calcite; evidence of multiphase microfracturing	3.1	•2% of frax are large (>0.2' wide, >15' in height), filled with cc, ± shear. •25% of frax are smaller (<.1' wide, <10' in height), commonly multistranded with narrow individual anastamosing calcite-filled frax. •72% of frax are small (<.05' in width, <2 ft in height), do not cross bedding planes, unfilled.

Table 1. Summary of fracture density and character from different lithologies within the Alapah and Wahoo Limestones exposed at the 'Sunset Pass' section. Fracture density normalized to number of fractures/foot.

Wahoo Limestone
(hangingwall)

Lithology	Bed thickness	NNW fractures number/ft	NNW fractures comments	ENE fractures number/ft	ENE fractures comments
bryozoan packstone	1-2'	1.7	2"-2' apart, most cut across bedding planes; unfilled.	3	2"-4" apart, not throughgoing, generally terminate on an E/W fracture
wackestone (98.5)	2.9'	2.8	throughgoing across bedding planes; 2-14 inches apart	6.2	do not necessarily cross bedding
dolomitic mudstone (99)	12"	6.2	some cross bedding	4	highly irregular, do not cross bedding planes; low-angle frax accomodate some bedding-parallel shear.
grainstone (100)		1		3.4	
packstone (108)	1.3'	1.2		1.2	
mudstone (108.5)	2.3'	5.5		11.1	
grainstone (121.5)	1.3'	1.8	66% throughgoing (across entire bed)	3.1	80% cut through entire bed

Table 1. (continued)

grainstone (120)	4.25'	<1	66% cut across entire bed	4	31% cut through entire bed; remainder terminate internally against stylolites.
oolitic grainstone (superficial) (147)	8.2'	2.5 ft	75% cut through bed 25% terminate internally	2.1 ft	
mudstone grading up into wackestone (149.5)	3.3'	in mudstone: 22.5	some, but not all, are throughgoing, filled with calcite and/or are multistrand microfractures	8.3	Most throughgoing, but many terminate against N/S frax.
		in wackestone: 1.4	86% throughgoing	7.5	50% throughgoing
grainstone (149)	8.2'	.28	75% cut across bedding planes		
packstone to oolitic grainstone (179)	16.5'	1.4	65% terminate against mudst. 53% terminate against small stylolite 95% terminate against large stylolite	3	only 14% extend through entire bed; others terminate internally against stylolites or thin mud layers.

Table 1. (continued)