SEDIMENTOLOGY AND TECTONIC SIGNIFICANCE OF THE NUTZOTIN MOUNTAINS SEQUENCE, ALASKA

A thesis presented to the Faculty
of the State University of New York
at Albany
In partial fulfillment of the requirements
for the degree of
Master of Science

College of Science and Mathematics
Department of Geological Sciences

Jane Kozinski
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ABSTRACT

The Nutzotin Mountains Sequence, a Mesozoic flysch sequence in the eastern Alaska Range, was studied along the southern border and in the central portions of the outcrop belt.

Three lithologic associations are recognized in the Bonanza Creek section (southern margin) that together indicate a coarsening-upward trend, suggestive of a prograding fan system. These associations are (from bottom to top): 1) debris flow conglomerates overlain by 500 m of intercalated mudstone and base-missing turbiditic siltstone, and mass movement features such as slump folds and slump horizons, 2) 195 m of thicker, coarser turbidites intercalated with mudstones; turbidites are graded but lack one or more of the Bouma C-E divisions, and, 3) 1075 m of massive mudstones alternating with thinly bedded sandstone, overlain by silty turbidites; mollusc fossil fragments are common in both sandstone and mudstone beds. Facies associations 1 and 2 are interpreted to represent deposition on the mid-fan portion of a submarine fan system. Facies association 3 represents either inner fan over-bank and channel margin deposition, or deposition in the slope environment. Paleocurrent indicators from the Bonanza Creek section indicate an overall northward-directed current.

The Sheep Creek section (middle of outcrop belt) consists of very thinly bedded silty turbidites and mudstones. Flaser and lenticular bedding suggests reworking of the sediment by bottom currents. The rocks are similar to channel over-bank deposits reported in other turbidite studies. Thick, massive coarse sandstone beds are also found in the Sheep Creek section; these may represent channel-fill deposits. The thinly bedded turbidites and the massive sandstones were most

likely deposited in channel and over-bank environments, either in the inner- or mid-fan portions of the fan system. Paleocurrent data from this section also demonstrate a northward-directed current.

Sandstones from the Bonanza Creek and Sheep Creek sections plot on or slightly above the feldspar-lithic fragment join of the QFL diagram. Mafic/intermediate volcanic clasts are the most abundant framework grain variety, and zoned, euhedral plagioclase is the most common feldspar. Grains of euhedral monocrystalline quartz with resorption cavities are present in some of the Bonanza Creek suite sandstones. The sandstones lack continentally-derived detritus. The composition of the sandstones indicates an active volcanic arc as the main sediment source, and the Wrangellia Terrane as a minor source.

The composition of the sandstones and the facies associations and paleocurrent directions observed in the Nutzotin Mountains Sequence are compatible with or similar to those features of the Dezadeash Group in the Yukon. This work supports the notion that the two flysch sequences were once a continuous belt, disrupted by 300-400 km of dextral strike-slip on the Denali Fault.

The Nutzotin Mountains Sequence was most likely deposited in a backarc or intra-arc basin. Blocks of Triassic(?) limestone (Wrangellian basement) within the flysch may be evidence of normal, reverse, or strike-slip faulting contemporaneous with deposition. This may suggest that the depositional basin was in part extensional.

ACKNOWLEDGEMENTS

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State University of New York at Albany

College of Science and Mathematics

Department of Geological Sciences

The thesis for the master's degree submitted by

Jane Kozinski

under the title

Sedimentology and Tectonic Significance of the

Nutzotin Mountains Sequence, Alaska

has been read by the undersigned. It is hereby recommended for acceptance by the Faculty with credit to the amount of six semester hours.

(Signed) [illegible]

(Date) 29th April 1985

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(Date) April 29, 1985

Recommendation accepted by the Dean of Graduate Studies for the Graduate Academic Council.

(Signed) ____________________

(Date) ____________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

The Nutzotin Mountains Sequence is a belt of late Jurassic-early Cretaceous flysch located in the eastern Alaska Range of Alaska. Overall, the Nutzotin Mountains Sequence separates the Paleozoic metamorphic rocks of the Tanana Upland from the late Paleozoic island arc and Mesozoic rocks of the Wrangellia Terrane. On an even larger scale, the Nutzotin Mountains Sequence is one of many late Mesozoic flysch sequences in Alaska.

Most of southern Alaska is interpreted to be a collage of allochthonous, or "suspect" terranes that have been emplaced on the North America craton during the Mesozoic. The nature, timing, and sequence of accretion events have become topics of considerable interest since the concept of accretionary tectonics has evolved (see, for example, Coney et al, 1980; Stone et al, 1982). The flysch basins of Alaska are mostly fault bounded and all of them lie between distinct tectonostratigraphic terranes. Such characteristics have led regional workers to believe that these ancient basins mark the suture zones of terrane-terrane or terrane-continent collisions (Csejtey et al, 1982; Nokleberg et al, 1984). Nokleberg et al (1984), Panuska (1984), Richter (1976), and Csejtey et al (1982) have either inferred or proposed such an origin for the Nutzotin Mountains Sequence. No direct evidence from the flysch supporting this interpretation has yet been produced. Thus, an understanding of the nature of the Nutzotin Mountains Sequence and its depositional history is crucial to an accurate synthesis of the tectonic history of the eastern Alaska Range.

In studying the Dezadeash Group, a Jurassic-Cretaceous flysch sequence in the Yukon, Eisbacher (1976) hypothesized that the Nutzotin Mountains Sequence and the Dezadeash were originally one flysch sequence, and that the basin was offset by 300 km of post Cretaceous strike-slip on the Denali Fault. Eisbacher concluded that the Dezadeash Group represents the distal sediments of a submarine fan, and speculated that the Nutzotin Mountains Sequence is the proximal portion of the same fan system. Until this study, Eisbacher's hypothesis has never been tested in the Nutzotin Mountains Sequence.

This project has the following complementary objectives: 1) to gain insight into the depositional history of the Nutzotin Mountains Sequence and 2) to test the validity of the Nutzotin Mountains Sequence/Dezadeash link. Three techniques of basin analysis were employed: turbidite facies sedimentology, point-count analysis of sandstones to establish provenance, and paleocurrent analysis. Logistical, financial, physical, and schedule limitations did not permit a large-scale survey of the flysch belt. Rather, two sections of the Nutzotin Mountains Sequence were examined in detail.

CHAPTER 1

REGIONAL GEOLOGY AND PREVIOUS WORK

INTRODUCTION

The main geologic elements to consider in evaluating the tectonic significance of the Nutzotin Mountains Sequence are the Wrangellia and Yukon-Tanana Terranes, the Denali Fault, and the Nutzotin Mountains Sequence itself.

WRANGELLIA TERRANE

The Wrangellia Terrane is defined by a distinct Paleozoic stratigraphy and its structural or stratigraphic contacts with surrounding terranes. The Denali and Totschunda Fault system mark the leading edge of the northern half of Wrangellia (Plate I). Both are right-lateral strike-slip faults. The Totschunda Fault is currently active; 9.6 km of displacement since the Late Wisconsin have been documented from offset drainage systems (Plafker et al, 1977). The amount and age of motion on the Denali Fault are unresolved. Complicating the problem is that the amount of displacement varies along the length of the fault (Table 1). The McKinley Strand is believed to have had anywhere from several tens to hundreds of kilometers of displacement since the Cretaceous (compare Csejtey et al, 1982 with Forbes et al, 1974). Displacement on the main segment of the Denali Fault is estimated to be 300 to 400 kilometers (Turner, 1974; Forbes et al, 1974; Forbes and Smith, 1973; and Eisbacher, 1976). Displacement estimates are based on three main offset markers: the correlation of the Nutzotin Mountains Sequence and the Dezadeash Group, the MacLaren Subterrane and the Kluane Schist, and the Ruby Range and

TABLE I: DISPLACEMENT ESTIMATES FOR THE DENALI FAULT

No.	Offset marker, location	Offset marker location	Lithologies	Amount (km) and strand	Time of motion	Reference
1	Ruby Range Batholith, Yukon	East Susitna Batholith, central AK	meta-igneous	400, Denali	since Early Cretaceous	Turner et al (1974)
2	" "	" "	" "	" "	" "	Forbes et al (1974)
3	Maclaren Meta. Belt, central AK	Kluane Schist and Ruby Range Batholith, YT	schists, phyllites	400, Denali	" " " "	Forbes et al (1973)
4	Nutzotin Mtns. Sequence, AK	Dezadeash Gr., Yukon	flysch	" "	Tertiary	Eisbacher (1976)
5	Foraker pluton Mt. Hayes Quad., Alaska	McGonall pluton Mt. Hayes Quad., Alaska	granites	38, McKinley	since Eocene	Reed and Lanphere (1974)
6	Maclaren Meta. Belt, north of Denali Fault	Maclaren Meta. Belt, south of Denali Fault	schists, phyllites	10-30, McKinley	since Late Cretaceous	Csejtey et al (1982)
7	plate reconstructions, central and eastern Alaska		NA	90, Denali	since Eocene	Stout & Chase (1980)

East Susitna Batholiths (Figure 1-1).

The proposed link between the Nutzotin Mountains Sequence and the Dezadeash Group in the Yukon is based on the following characteristics of the two flysch sequences (Eisbacher, 1976): 1) comparable fossil assemblages (mollusks ranging from Oxfordian to Valanginian in age), 2) debris flow conglomerates containing huge Triassic(?) limestone blocks within both flysch sequences, 3) dioritic plutons of like ages (115-120 m.y.) intruding the flysch belts, and 4) similar types of volcanic detritus in conglomerates. Eisbacher (1976) also established that the paleocurrent direction across the Dezadeash flysch belt is consistently toward the north/northeast, but observed that the flysch lacks a proximal facies. Hypothesizing that the Nutzotin Mountains Sequence also has a north/northeast paleocurrent direction (or one compatible with that in the Dezadeash) and contains a proximal facies, Eisbacher linked the two sequences and considered their apparent offset an estimate of displacement along the Denali Fault (Figure 1-2).

The western margin of Wrangellia is defined by the Broxson Gulch Thrust, a 200 km long, north-dipping thrust fault that places metamorphic rocks of the Maclaren metamorphic belt over Triassic and Paleozoic rocks of Wrangellia (Figure 1-1). The Broxson Gulch thrust zone is believed to mark the boundary between the block that contains Wrangellia and that which contains the Peninsula Terrane (Stout and Chase, 1980). Stout and Chase (1980) hypothesized that Cenozoic motion on the Denali Fault was taken up on the Broxson Gulch Thrust, thereby eliminating the need for great amounts of displacement on the McKinley Strand.

Finally, the southern and eastern margins of Wrangellia are bounded

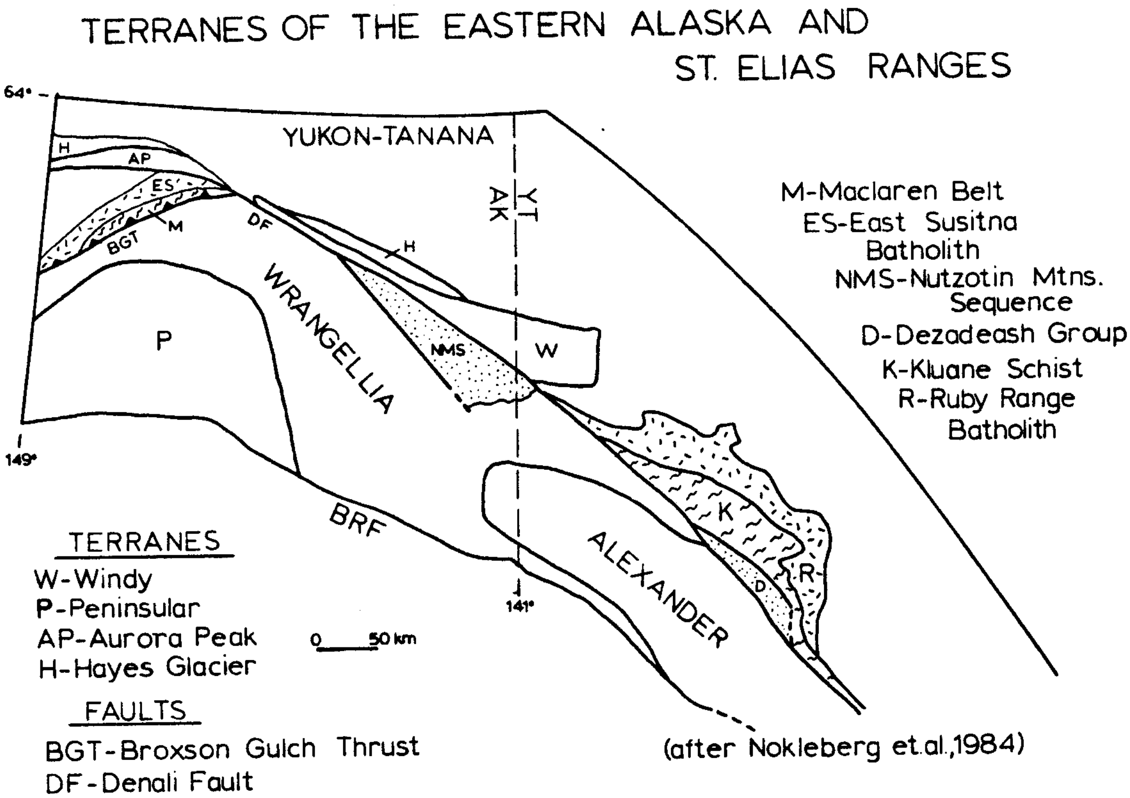

Figure 1-1: Cartoon map of the Eastern Alaska and St. Elias Ranges showing the Mesozoic flysch belts, the major terranes, faults, and offset markers along the Denali Fault.

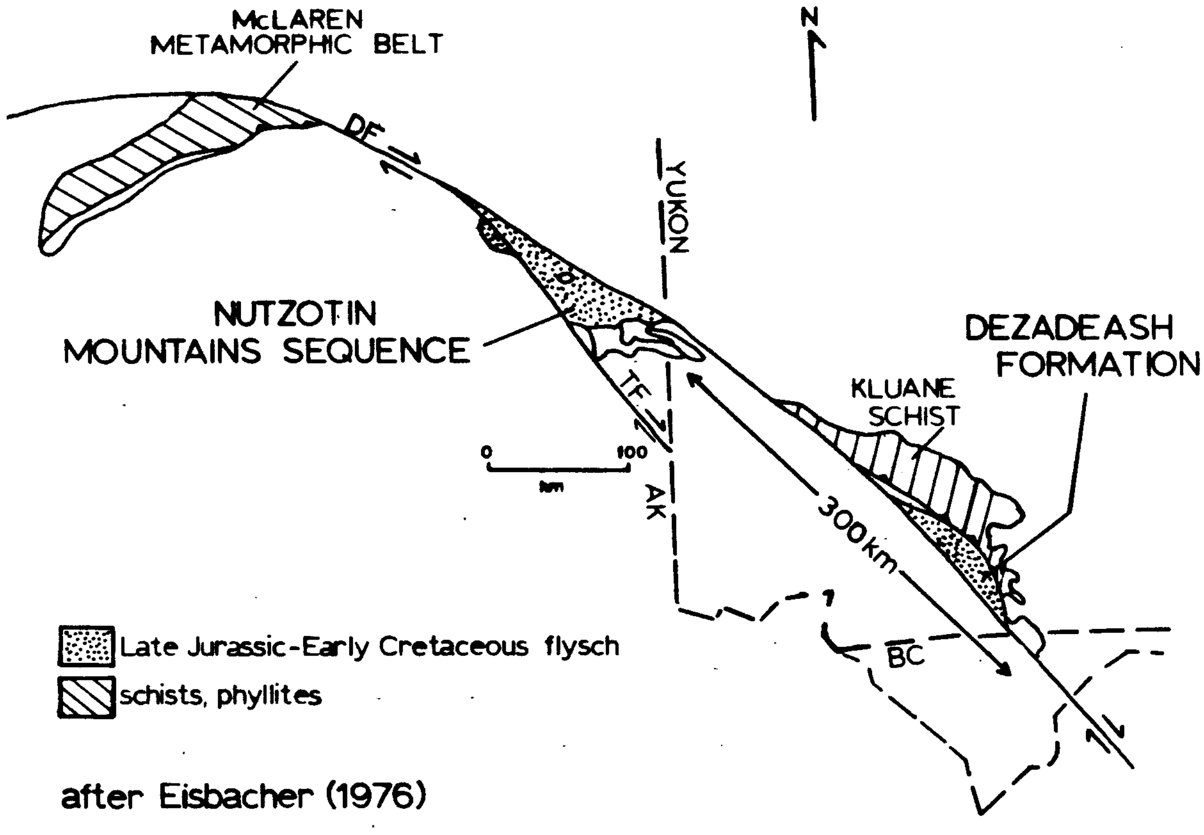

Figure 1-2: Sketch map of Eisbacher's (1976) displacement estimate for the Denali Fault.

by the Border Ranges Fault and an unnamed major thrust system respectively (Plate I). The Border Ranges Fault is a thrust fault and has been interpreted by Pavlis (1982) to mark the site of a Valanginian to Albian age subduction zone. The age of thrusting on the eastern margin of Wrangellia is poorly constrained. Panuska (1984) correlates the deposition of the Late Jurassic Root Glacier Formation, a fault-related conglomerate in the central Wrangell Mountains, to thrust faulting on the "Wrangellia-Alexander thrust".

Wrangellia is defined by its stratigraphy as well as by its structural boundaries (Figure 1-3). Briefly, Wrangellia consists of a Paleozoic sequence interpreted as a volcanic arc product, unconformably overlain by Triassic tholeiitic basalt (the Nikolai Greenstone), a Triassic-Jurassic transgressive carbonate sequence, Jurassic marine and nonmarine clastics, and Cretaceous marine clastics. The Paleozoic arc sequence, named the Skolai Group (Smith and MacKevett, 1970), consists of, at the base, schists, phyllites, and amphibolites and, overlying that, basaltic and andesitic flows and volcaniclastics metamorphosed to the prehnite-pumpellyite facies (MacKevett, 1978). Shelf limestones of the Lower Permian Hasen Creek Formation conformably overlie the Station Creek Formation. Lower Permian deep marine argillites, sandstones, cherts, and shales of the Hasen Creek Formation are conformable with the underlying limestones.

The Nikolai Greenstone is a 3000 m thick sequence of both submarine and subaerial tholeiitic basalt of late Middle and early Late Triassic age (MacKevett, 1978), in which porphyritic and amygdaloidal textures are common. The tectonic significance of the Nikolai Greenstone is unclear. A continental rift origin for the Nikolai has been suggested by Decker (unpub. data). The overlying

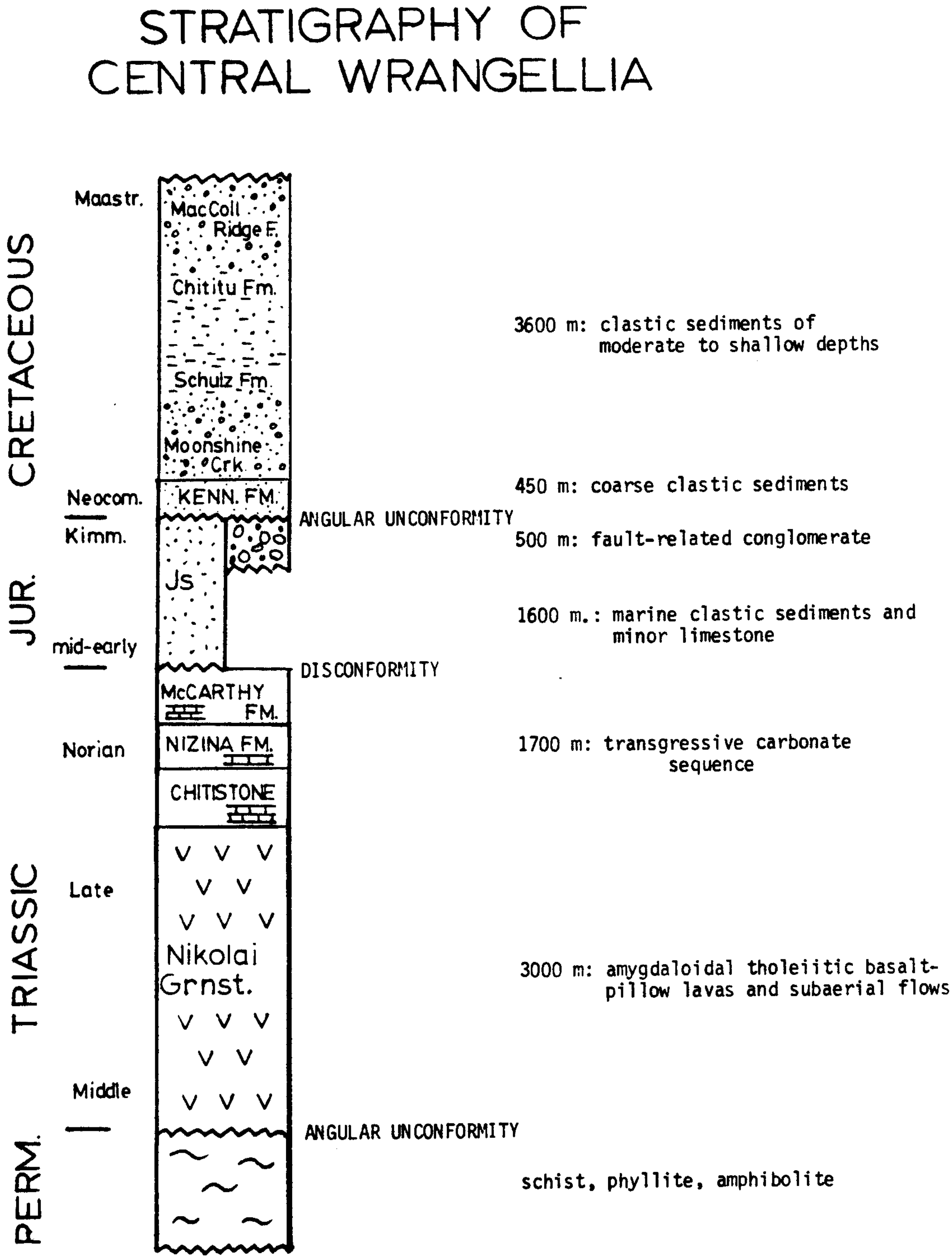

Figure 1-3: General Mesozoic stratigraphy of the Wrangellia Terrane. Compiled from MacKevett (1978), MacKevett (1967), and Jones and MacKevett (1969).

sabkha carbonate sequence (the Chitistone and Nizina Limestones) represents an encroaching sea and suggests that sedimentation (and rifting?) took place at low latitudes.

Regional workers hypothesize that the Jurassic clastics were deposited in shallow marine or littoral environments (MacKevett, 1978; Panuska, pers. comm., 1984). These clastics are nonturbiditic. In a cursory petrographic examination of sandstone samples from the Root Glacier Formation (provided by Bruce Panuska), I have noted the fine grained sandstones to consist of mostly monocrystalline quartz, unzoned plagioclase, some potassium feldspar, biotite, and muscovite, some fine grained metamorphic clasts and sedimentary clasts. Volcanic clasts are present in one coarse grained sample. The absence of zoned plagioclase and beta-quartz plus the nominal amount of volcanic rock fragments together suggest that a volcanic terrane was not the prime contributor of sediment.

MacKevett (1978) suggested that the Cretaceous clastics were deposited in local basins of a marginal sea, but did not speculate on the nature of this sea (forearc? backarc?). The Cretaceous section represents a deepening-upward sequence followed by coarse clastic sedimentation in the Maastrichtian. The Kennicott Formation is reported to possess a volcanic signature (Panuska, pers. comm., 1984); point-count data are not available.

YUKON-TANANA TERRANE

The Yukon-Tanana Terrane (also known as the Crystalline Upland) is a region of Proterozoic and Paleozoic metamorphic rocks. The stratigraphy of this terrane is quite complicated (see Templeman-Kluit, 1976, for a summary). Within five to ten kilometers of the Nutzotin Mountains Sequence, the Yukon-Tanana Terrane consists of two main lithologic units, both Devonian in age and both metamorphosed to lower greenschist facies: a phyllite, limestone, and greenstone unit and a section of predominantly marine metasedimentary rocks (Richter, 1976). The former includes such lithologies as metaconglomerate, recrystallized limestone, quartzite, phyllite, and quartz-mica schist. Lithologies commonly found in the latter unit are phyllite, calcareous quartzite, marble, and calcareous quartz-mica schist.

ALEXANDER TERRANE

The Alexander Terrane is discussed by Csejtey et al (1982) and Panuska (1984) as a part of the Talkeetna (or Southern Alaska) Superterrane, a composite terrane that also includes the Wrangellia and Peninsula Terranes. Simply on the basis of the observed distribution of the Alexander Terrane, it is less likely to have been a sediment source for the Nutzotin Mountains Sequence than the Wrangellia Terrane; however, the Alexander Terrane indirectly bears on the flysch in terms of the sequence and timing of the Wrangellia-North America collision. This terrane consists of Paleozoic volcanics, clastics, and limestones all overlain by a well-defined Mesozoic sequence of silicic and mafic volcanics, clastics, and limestones.

THE NUTZOTIN MOUNTAINS SEQUENCE

The discovery of gold and copper placer deposits near Chisana, Alaska in the early 1900's led to the first geological survey of the Nutzotin Mountains. Capps (1916) identified the flysch as a sequence of Jurassic-Cretaceous clastics of unknown but considerable thickness.

Full-scale mapping of the Nutzotin Mountains Sequence was first performed by Moffit (1954). Moffit concluded that the Jurassic-Cretaceous flysch was a "great synclinorium" of shallow-water, seasonal, varved clastics. This work resulted in a more complete eastern Alaska Range stratigraphy; the recognition of the Totschunda and Denali lineaments; the discovery of the disconformity between the Triassic limestones and the Jurassic-Cretaceous clastics; and to the differentiation of Cretaceous (now "Ks") and Jurassic-Cretaceous ("KJs") clastics on the basis of fossil and stratigraphic evidence (Moffit, 1954).

Berg et al (1972) gave the Nutzotin Mountains Sequence its name. Moreover, they first recognized the sequence as flysch and included it in the Gravina-Nutzotin belt, a somewhat continuous belt of late Mesozoic marine clastics and andesitic volcanics (discussed later). "Flysch" is used here in a lithologic sense and is defined as monotonously interbedded, alternating and laterally persistent layers of marine sands and shales showing turbidite characteristics that form a thick sequence (definition altered from Friedman and Sanders, 1978).

Richter's mapping in the Nabesna Quadrangle during the early 1970's led to the recognition of an informal stratigraphy for the Nutzotin Mountains Sequence (Figure 1-4) (Richter, 1976; Richter, 1971; Richter, 1971b; Richter and Jones, 1973; Richter and Schmoll, 1973). The lowermost unit is composed largely of late Jurassic argillite, graywacke, mudstone, and conglomeratic debris deposits (Richter, 1976). Conglomerate, graded turbiditic graywacke, and argillite of Late Jurassic to earliest Cretaceous age comprise the middle unit (KJg) (Richter, 1976). Finally, the third division of the informal

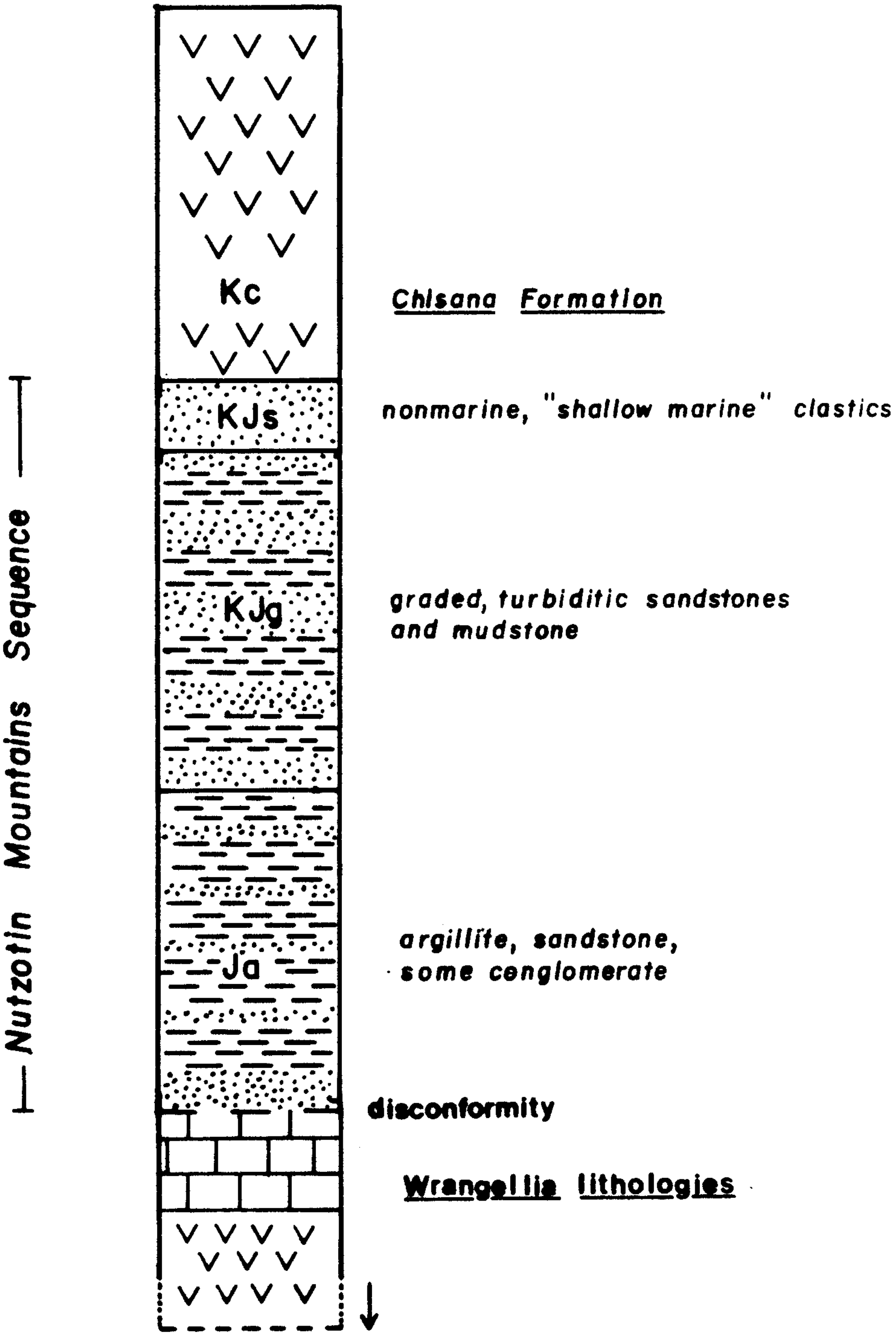

Figure 1-4: Present stratigraphy of the Nutzotin Mountains Sequence (Richter, 1976).

stratigraphy consists of marine to nonmarine clastics. A continuous section of this stratigraphy is mapped in the Nabesna C-5 quadrangle. Richter and Schmoll (1975) have also recognized subdivisions of the stratigraphy: 1) late Jurassic massive graywacke underlying the lower division of their stratigraphy, and 2) thick (up to 100 feet) lenses(?) of coarse graywacke and "extraformational pebble conglomerate" of Jurassic-Cretaceous age. This latter subdivision has not been mapped in other quadrangles.

The whole sequence is 3000 m thick and is conformably overlain by Chisana Formation andesitic volcanics and volcaniclastics. The Chisana Formation ourcrops most extensively at the southeast corner of the flysch belt (Plate I). The contact with the underlying Triassic limestone is conformable and depositional. It is unclear, however, whether the flysch was ever in sedimentary contact with the rocks of the Yukon-Tanana Terrane, or whether it has been tectonically juxtaposed with this terrane by strike-slip on the Denali Fault. My work supports this latter hypothesis.

Until this study, provenance studies have been restricted to outcrop observations of conglomerate clast compositions. Common lithologies reported in conglomerates along the southern margin of the basin include Triassic(?) limestone blocks, volcanic and volcaniclastic rock, limestone, and chert (Berg et al, 1972; Richter and Schmoll, 1973; Richter, 1976). Moffit (1954) observed clasts of "deeply weathered granitoid" in conglomerates on the far eastern margin of the flysch. Clasts of quartzite and metamorphic rock in conglomerates located near Nabesna are described by Berg et al (1972), Richter (1976) and Moffit (1954), but these lithologies are not abundant. In terms of probable source areas, the Wrangellia Terrane has been proposed to account for the volcanic and sedimentary clasts, and the Yukon-Tanana Terrane for the metamorphic lithologies (Richter, 1976). Berg et al (1972) also cited imbrication of the quartzite clasts as evidence for southward sediment transport.

Much of the fossil evidence, as well as the stratigraphic compilation above, comes from the Nabesna A-2 and C-5 quadrangles. The mollusks Buchia rugosa and Buchia concentrica found in sandstone and shale beds along Bonanza Creek and elsewhere in the basin suggest a late Oxfordian to Valanginian age for the flysch (Richter, 1976). A further constraint on the age of the flysch is provided by the Antler Creek pluton, which intrudes the flysch in the center of the basin. The pluton has yielded a K/Ar age of 111$\pm$6 m.y., presumed by Richter et al (1975) to be the age of intrusion.

Numerous dikes and sills intrude the flysch (see, for example, the C-5 and A-2 quadrangles). Along the Bonanza Creek section, these intrusives are andesitic (?) porphyries with large plagioclase phenocrysts; they are similar in the C-5 quadrangle (Richter and Schmoll, 1975).

The Nutzotin Mountains Sequence is characterized by open to isoclinal folds. The northwest trending fold axes are parallel to subparallel with the Denali and Totschunda Faults (Plate I). The Antler Creek pluton, with its long axis trending northeast/southwest, appears to cross-cut the northwest-trending set of folds. Another set of folds is oriented normal to the northwest-trending folds (and parallel to the long axis of the pluton). Two thrust faults are known to be present in the flysch belt; the age of faulting is not known. Normal and reverse faults are common about the edges of the present outcrop of the flysch.

CHAPTER II

FIELD OBSERVATIONS AND INTERPRETATIONS

INTRODUCTION

The Nutzotin Mountains Sequence was studied along and around the Bonanza Creek and Sheep Creek areas of the Nabesna A-2 Quadrangle (Figure 2-1). The emphasis of the field study was on noting changes in the outcrop-scale sedimentary features (e.g., coarse/fine bed ratios, occurrences of primary structures, and bedding thickness) in a near-vertical column; these observations were recorded on measured sections. Map-scale stratigraphic boundaries are impossible to map owing to the absence of conspicuous marker beds or contrasting units. The lithologic associations that I define from work on Bonanza Creek are laterally continuous for a minimum of 0.5 to 1.5 kilometers.

TURBIDITE FACIES

My interpretation of the facies associations on Bonanza and Sheep Creeks is based on the turbidite and flysch facies models of Walker (1978), Walker and Mutti (1973) and Mutti and Ricchi-Lucchi (1972). In their landmark paper, Mutti and Ricci-Lucchi (1972) concluded that the lithologies of the Apennine flysch occur in distinct lithologic associations. Moreover, these particular lithologic associations were correlated to specific environments of deposition on a hypothetical submarine fan. The fan model is, as Walker (1978) noted, a useful aid in interpreting flysch sequences of moderate size. Normark et al (1979) successfully correlated facies and structures of the active Navy Fan in the southern California Borderland with those predicted by the fan model.

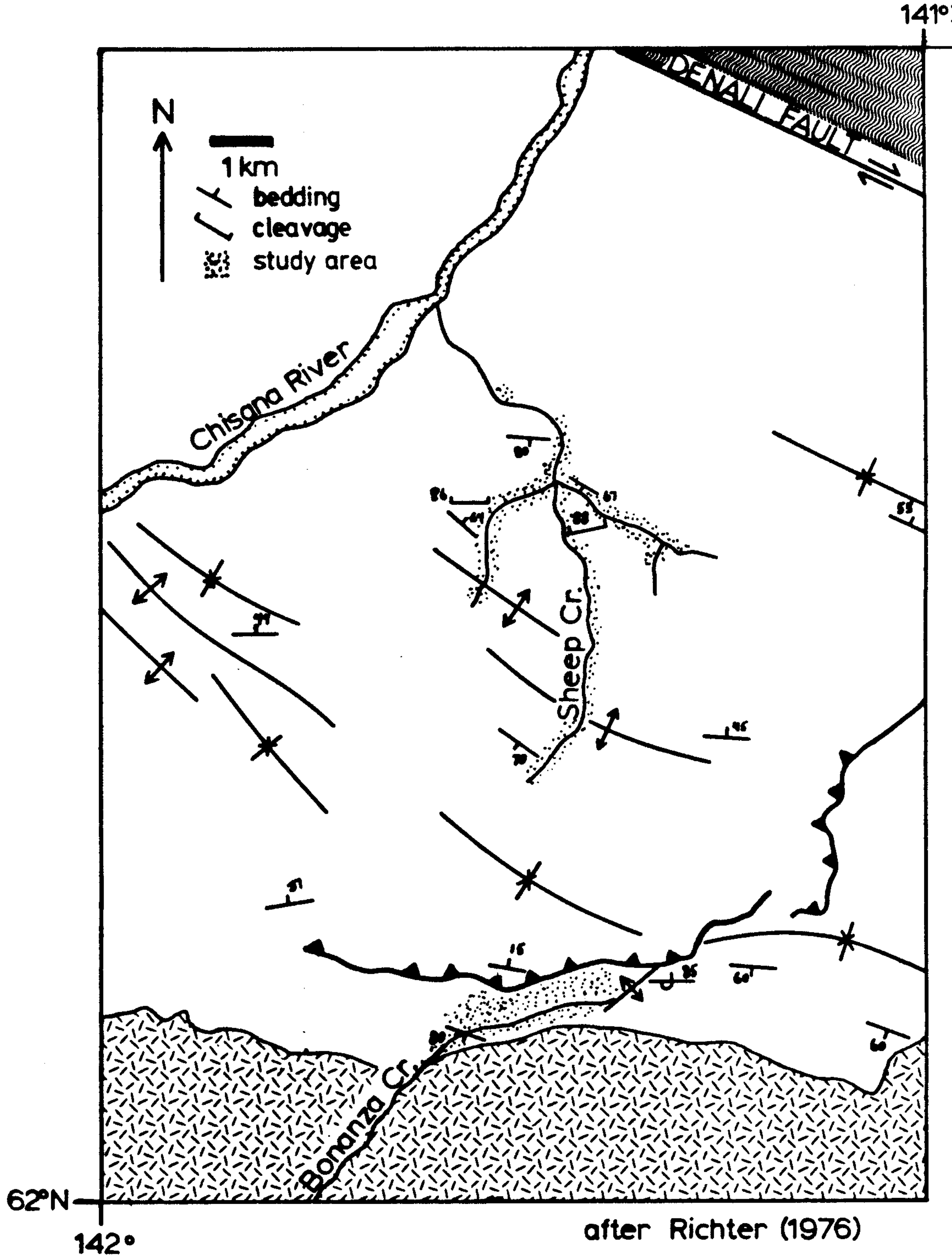

Figure 2-1: Sketch map of the Bonanza Creek and Sheep Creek study areas. Hatchered area is the Wrangellia Terrane and the wavy lines above the Denali Fault denote the Yukon-Tanana Terrane.

Table II provides an outline of the turbidite facies first introduced by Mutti and Ricci-Lucchi (1972) and later altered by Walker and Mutti (1973). Briefly, facies A consists of thick sandstones (10 meters or greater) and pebbly conglomerates that are generally not describable by the Bouma Sequence and that tend to occur as lenticular bodies (Walker and Mutti, 1973). Ingersoll (1978) associates this facies with channel-fill deposits. Facies B is characterized by medium- to coarse-grained sandstones that contain dish structure or are massive; this facies occurs in more planar and laterally continuous beds and is associated with thin pelitic interlayers (Mutti and Ricci-Lucchi, 1972). Mutti and Ricci-Lucchi (1972) suggested that Facies B is deposited by grain flow processes. Facies C, considered to be "classical proximal turbidites" (Walker and Mutti, 1973; Ingersoll, 1978), consists of coarse- to fine-grained sandstones intercalated with mudstones. The turbidites generally begin with the A division of the Bouma Sequence, and the sandstone to shale ratio is commonly greater than 1. Facies D consists of "classical distal turbidites" (Ingersoll, 1978; Walker and Mutti, 1973) alternating with mudstones. The turbidites in Facies D generally begin with the B or C divisions of the Bouma Sequence, and the sandstone to shale ratio of this facies is 1 or less. Facies E contains alternations of thinly bedded fine sandstone to siltstone and mudstone. Discontinuous, lenticular and flaser bedding as well as sandstone to shale ratios of 1 or more characterize this facies (Walker and Mutti, 1973). Facies E is believed to be the product of overbank flow (Mutti and Ricci-Lucchi, 1972). Facies F is characterized by all deposits that originate by mass movement (e.g., slumps, debris flows). Facies G consists of

TABLE II

TURBIDITE FACIES AND OTHER FLYSCH FACIES
after Walker and Mutti (1973)

FACIES A	coarse grained sandstones, conglomerates: includes organized and disorganized conglomerates, organized and disorganized pebbly sandstones
FACIES B	medium-fine to coarse grained sandstones: massive sandstones with or without dish structure
FACIES C	medium to fine grained sandstones: turbidites beginning with the graded (A) division of the Bouma Sequence
FACIES D	fine to very fine sandstones and siltstones: turbidites beginning with the B or C division of the Bouma Sequence
FACIES E	fine to very fine sandstones and siltstones: thinly interbedded sandstones and shales; flaser and lenticular bedding common.
FACIES F	mass movement deposits: slumps, slides, debris flows
FACIES G	pelagic and hemipelagic mudstones

pelagic and hemipelagic mudstones. Thin interlayered siltstones may also be present in this facies (Ingersoll, 1978).

As stated earlier, my stratigraphic work in the Bonanza Creek area is, by nature of the outcrop, restricted to a nearly vertical section. Field data on the lateral relationships of the facies associations that I have defined are limited. The fan model, however, requires lateral control. Because of insufficient field information, I am only using the fan model as a guide to my interpretation.

BONANZA CREEK

The Bonanza Creek section of the Nutzotin Mountains Sequence was chosen for study because of its exposure, accessibility, and age control. Approximately 1700 m of section were examined in varying degrees of detail. The Nutzotin Mountains Sequence along Bonanza Creek is truly a thick section of monotonously interbedded sandstones and shales. The thickness of a given bed is uniform, with the exception of scours and small channels. The sandstones are poorly sorted and vary texturally from matrix-supported pebbly conglomerate to very fine silty graywacke. Bouma Sequences are recognizable in outcrop, but the completeness of them varies considerably throughout the section. Graded-bedding and truncated cross-laminae provide abundant evidence of younging direction.

Other outcrop features worth noting in the Bonanza Creek section include: 1) the relatively uniform southwest dip of bedding, 2) the lack of slaty cleavage, 3) the presence of numerous andesitic dikes, characterized by large plagioclase phenocrysts, and 4) the presence of marine mollusk and crinoid fossils throughout much of the section.

Two faults were observed along Bonanza Creek. One fault runs through the very edge of the study area. The sense of motion on this fault is not known, but it is a steeply-dipping fault. A small fold occurs adjacent to the fault zone and appears truncated by the fault (Figure 2-2); the fold hinge has a plunge of 17° and a trend of 262°. Bedding on either side of the 1 meter wide fault zone is undisturbed. It is unclear whether the other fault, at outcrop BNZ35, is tectonic or related to soft-sediment deformation (Figure 2-3).

Three lithologic associations are recognized along Bonanza Creek (Figure 2-4). The criteria for subdividing the section include: coarse to fine bed thickness ratios, occurrences of the Bouma Sequence (particularly which division appears at the base) the degree of monotony of the outcrop-scale characteristics, and bedding thickness changes (see Table III for a summary of these observations).

Lower Division - conglomerates

The Lower Division of the Bonanza Creek section consists of two main lithologic units: a 75 m thick matrix-supported boulder to pebble conglomerate (Facies F) overlain by turbiditic sandstone and siltstone with intercalations of mudstone (primarily Facies C and D).

The composition of the conglomerate was determined by three separate clast counts, each performed on a roughly 5 m^2 area of outcrop. In Figure 2-5, sample MD represents the lowest part of the conglomerate section, MB_1 the middle, and MB the highest part. The categories in Figure 2-5 are from my field classification scheme. Silicic volcanic clasts were distinguished from intermediate/mafic clasts by lighter color index and by higher feldspar content as seen with the hand lens. Volcanic clasts containing garnets were grouped

Figure 2-2: Small fold adjacent to fault zone, Bonanza Creek.

Figure 2-3: Fault at low angle to bedding, Middle Division, Bonanza Creek.

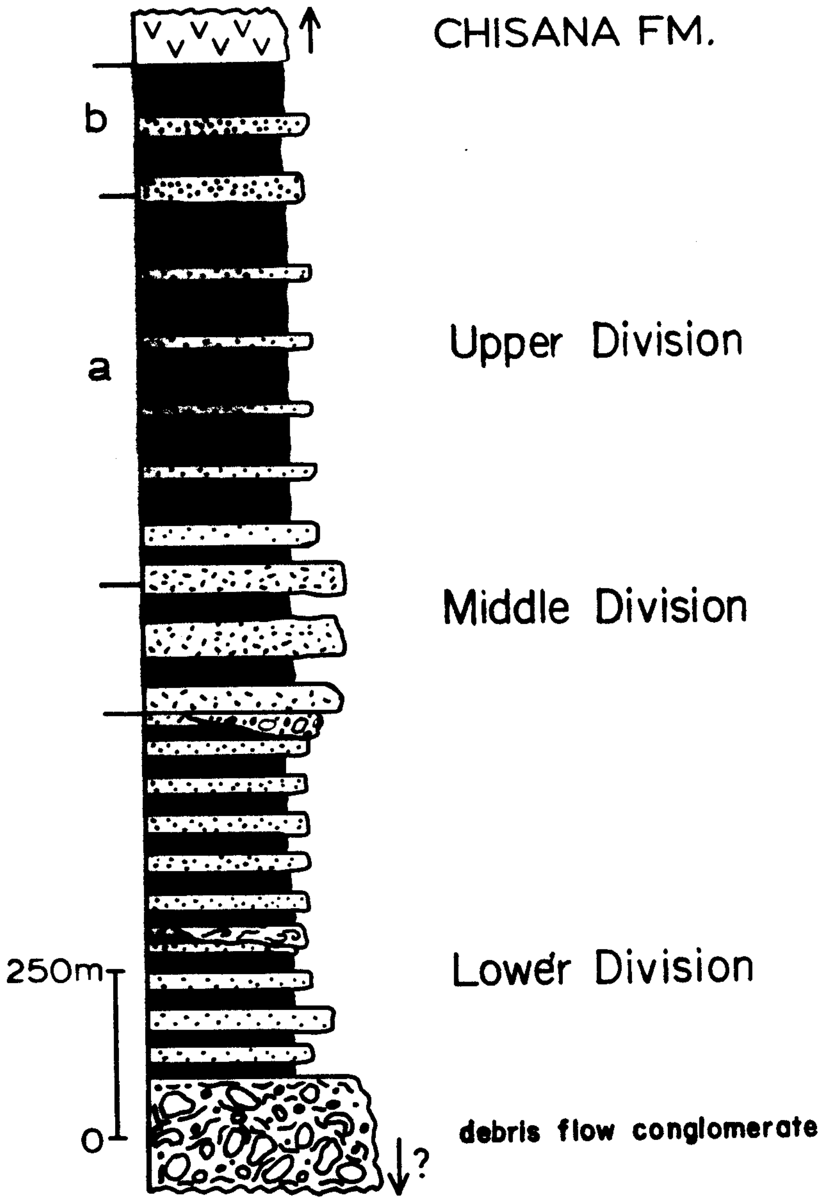

Figure 2-4: Proposed stratigraphy for the Bonanza Creek section of the Nutzotin Mountains Sequence.

Table III: Characteristics of turbidites, Nutzotin Mountains Sequence

SECTION	MEAN BEDDING THICKNESS(cm)	COARSE/FINE (BEDDING)	MEAN SAND SIZE	BOUMA DIVISIONS
Bonanza Creek				
Upper B.	7	1:4	med.-fine sand	(A), B, C
Upper A.	4	1:9-1:12	med.-fine sand	(B)?
Middle	13	1:1-1:2	coarse sand	A, B, (C)
Lower	3-5	1:1	fine sand-silt	(A), B, C, E
Sheep Creek	4	1:1	silt	A, B, C, (D), E

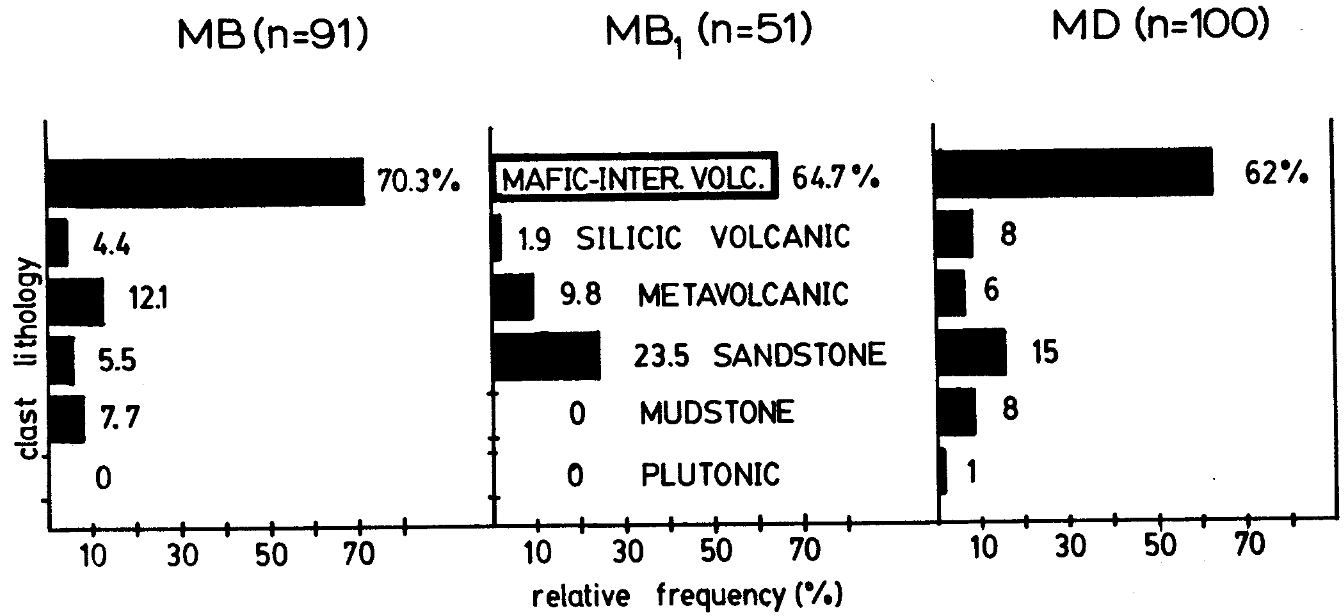

Figure 2-5: Histograms for clast counts on conglomerates from the Lower Division, Bonanza Creek.

as metavolcanics; these are primarily mafic/intermediate.

The conglomerate consists of rounded to subrounded clasts of volcanic and metavolcanic rock, sandstone, siltstone, and mudstone. Metamorphic rock types (e.g., quartzite, schists, and phyllite) and limestone are notably absent. Plutonic clasts are rare. Most of the intermediate/mafic volcanic clasts are aphanitic to fine-grained; some exhibit plagioclase and hornblende phenocrysts. Amygdaloidal basaltic clasts are also present. Calcareous sandstone occurs as pebbles and as boulders of disrupted, parallel-laminated beds. No fossils were found in the conglomerate. Meter-size blocks of thin-bedded turbiditic siltstone and mudstone (often folded) are also included within the conglomerate (Figure 2-6). These blocks usually occur where the conglomerate is observed to be in contact with sections of normally bedded turbidites.

Comparison of the three clast counts reveals near consistency in the composition of the conglomerate. Clearly, the main source was volcanic. The sedimentary rocks are most likely intraformational.

Texturally, the conglomerate is disorganized (Figure 2-7). Grading is present only on a gross scale; clasts are not imbricated; the amount of matrix varies from 50 to 75 percent; and sorting is poor. These characteristics suggest a debris-flow origin.

In outcrop, the conglomerate is in contact with turbiditic siltstone and mudstone of the Lower Division (described below). Room-size and meter-size slump blocks and slump folds are found within the sections of normal turbidites (Figure 2-8).

The conglomerate was most likely deposited in an active canyon or channel of a submarine fan. Volcanic and sedimentary detritus was incorporated into a fluidized mudflow. The flow was of high enough

Figure 2-6: Folded package of turbidites within the conglomerate of the Lower Division, Bonanza Creek.

Figure 2-7: Muddy matrix conglomerate, Lower Division, Bonanza Creek.

Figure 2-8: Small block of siltstone and mudstone within turbidites adjacent to the conglomerate of the Lower Division, Bonanza Creek.

velocity to pluck rafts of material from the channel wall (i.e., the blocks of turbidite). Periods of debris flow deposition alternated and occurred simultaneously with normal turbidite sedimentation. The presence of slump blocks and folds within the turbidites indicates that mass movement was also associated with the periods of turbidite deposition.

<u>Lower</u> <u>Division</u> - turbidites

Overlying the conglomerate is a 500 m thick section of silty to sandy turbidites and mudstones (Figure 2-9). Two thick and laterally discontinuous turbidite beds occur at the base of this section (Figure 2-10). These beds contain the A-C divisions of the Bouma Sequence; the A division begins with a cobble conglomerate and C consists of convolute laminae. These sandstone beds are also the bases of two vaguely-defined thinning- and fining-upward sequences. Mutti and Ricci-Lucchi (1972) interpret thinning- and fining-upward megasequences as indicative of channel filling. The pinching-out nature of these two sandstone beds also suggests a channel environment of deposition. Farther up-section, bedding attains a more monotonous and continuous character (Figure 2-11). Turbidite beds are largely of the T_{AC} variety where the C division of the Bouma Sequence occurs as convolute and wavy laminae (Figure 2-12). Coarse to fine bed ratios average 1:2. Approximately 200 m into this turbidite section, the character of the flysch changes slightly: the sandstone beds are only 4-5 cm in thickness, mean grain size is very fine sand to silt, and the coarse to fine ratio increases to 1:1. The turbidite beds are usually base-missing, beginning with the fine parallel-laminae of the B division. As shown in the measured

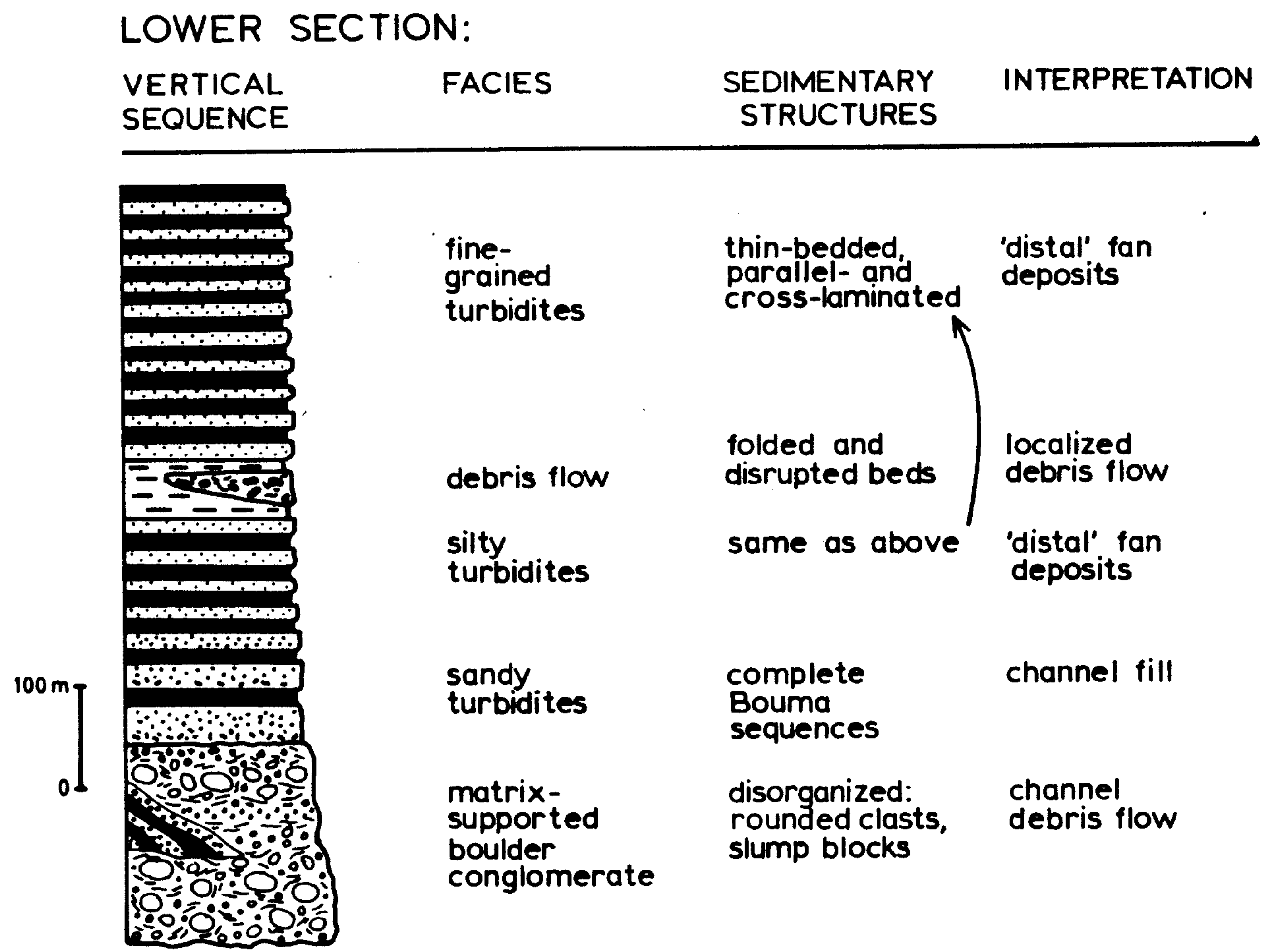

Figure 2-9: Outline of the Lower Division, Bonanza Creek.

Figure 2-10: Thick sandy turbidite beds, Lower Division, Bonanza Creek.

Figure 2-11: Typical appearance of the Lower Division turbidites, Bonanza Creek.

Figure 2-12: Convolute laminae in turbidite bed, Lower Division, Bonanza Creek.

section of outcrop B47 (Figure 2-13) some beds begin with the C-division of the Bouma Sequence. Fine-scale cross-laminae of the C division occur more frequently than do convolute laminae. Contacts between mudstone and sandstone beds can be smooth, slightly scoured, or, rarely, marked by minute load structures. Siltstone beds commonly contain mud rip-up clasts. Fossils make their first appearance, but are sparse.

Evidence of episodic mass movement is present throughout this turbidite section of the Lower Division. An isolated, 30 cm thick horizon of disturbed bedding was observed at outcrop BNZ48A (Figure 2-14). The convoluted and detached bedding is similar to that descibed by Morris (1971) from the Jackfork flysch of Arkansas. He attributed this style of deformation to shear along bedding due to downslope failure. A thicker zone of severely deformed, chaotic bedding of Facies F occurs at BNZ47. Within this lens-shaped zone, thin turbidite beds are disrupted and folded in random styles and orientations (Figure 2-15). The beds are included in a muddy matrix. Both slump zones occur between undisturbed bedding. Lenses of up to 25 m thick of muddy matrix debris-flow conglomerate (Facies F) similar to that described earlier are found within the upper 200 m of this section. I interpret the debris-flow conglomerate to be related to instability up-slope while the slump horizons are due to instability within the sedimentary pile.

Another manifestation of episodic slope instability during deposition of the Lower Division turbidites is the presence of slump folds. Unlike slump folds described in other flysch sequences (see Helwig, 1970; Rupke, 1976), the folds in this section are not isolated to one large slump horizon. The folds do, however, fit some of

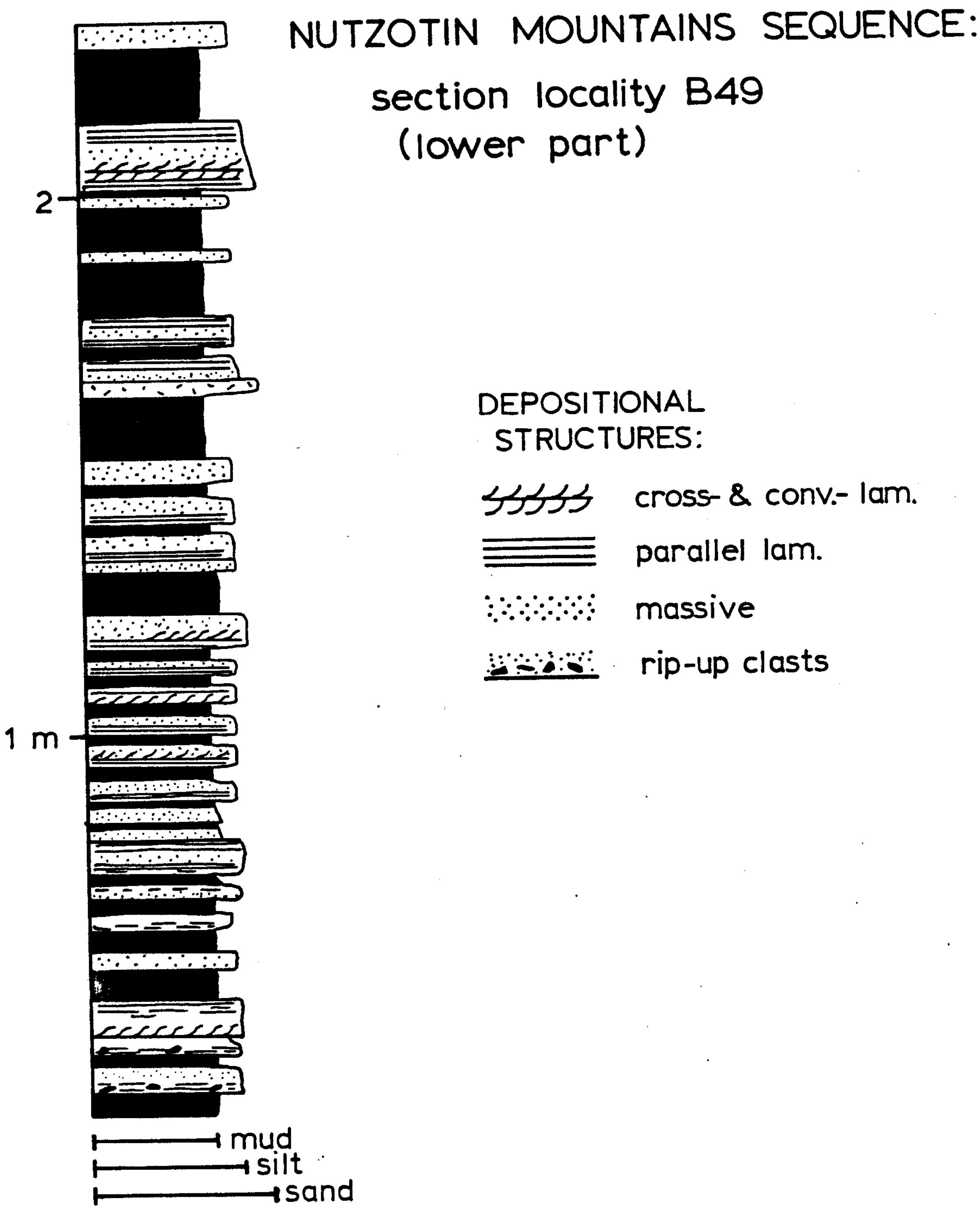

Figure 2-13: Measured section from the Lower Division, Bonanza Creek.

Figure 2-14: Layer of slumped bedding, Lower Division, Bonanza Creek.

Figure 2-15: Disrupted, folded beds in muddy matrix, Lower Division, Bonanza Creek.

Helwig's (1970) criterea for a slump origin: 1) they lie between undisturbed bedding, 2) they have welded (sedimentary) contacts with the overlying bedding, and 3) they usually occur as isolated, outcrop-scale "fold blobs". Of the seven slump folds observed in this section, the one at outcrop BV-F illustrates these slump characteristics most clearly (Figure 2-16).

Lower Division - paleocurrent data

Paleocurrent information from the Lower Division was obtained from cross-laminae. Other paleocurrent indicators such as grooves, flutes, and parting lineations are rare to absent. A total of 129 cross-laminae were measured over a stratigraphic thickness of 500 m. Bedding was rotated back to the horizontal; no plunge was assumed as all fold axes in the Nutzotin Mountains Sequence are horizontal. The vector mean varies up-section from 316° at the bottom to 030° toward the top (Figure 2-17). As noted earlier, convolute laminae are more abundant in the lower part of the section than are cross-laminae; thus, few data were obtained from the bottom part of the section. Those measured, however, strongly indicate a NW directed paleocurrent direction. Measurements from the middle of the section (BNZ49 and BNZ47,47A, and 48A) did not yield a well-defined current direction.

Scatter in the current direction may or may not be significant. The scatter produced in BNZ49, for example, may be attributable to the nature of the cross-laminae. Considering the prevalance of wavy and convolute laminae in this outcrop, it is possible that, despite careful inspection, some measurments were taken on inappropriate laminae. What appeared to be cross-laminae at one location were seen to be wavy or convolute where the quality of outcrop permitted the laminae to be

Figure 2-16: Slump fold, Lower Division, Bonanza Creek.

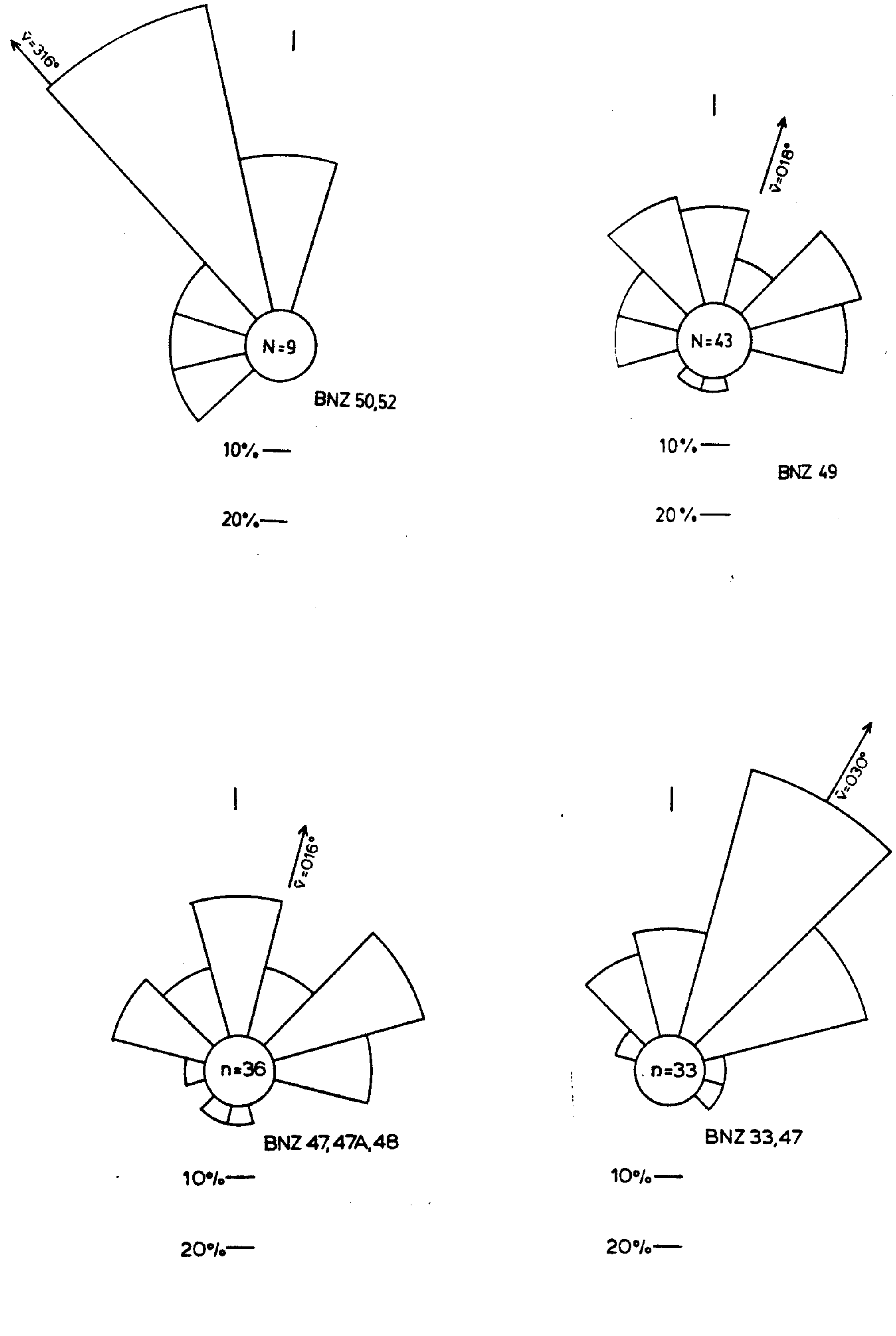

Figure 2-17: Paleocurrent data from the Lower Division, Bonanza Creek (a-d, up-section).

traced along bedding. Both BNZ49 and BNZ47,47A,48A contain two mean directions at approximately right angles to each other. The mean directions of BNZ33,46 and BNZ50,52 are also at near right angles. This relationship may represent two current directions from two overlapping depositional lobes. A younger, prograding lobe with a mean current direction of 030 degrees smothered an older lobe with a mean current direction of 316 degrees. In this scenario, the scatter represents the transition of primary deposition from the older lobe to the younger. I should note that this relationship may alternatively represent two overlapping fans. In all, this latter hypothesis takes into account the general change in paleocurrent direction, and for this reason it is favored over the former.

Aside from these relatively minor shifts in paleocurrent direction, the sediment was transported northward. This finding is consistent with Eisbacher's (1976) prediction.

Lower Division - interpretation of facies

The conglomerate and slump features of the Lower Division correspond to Facies F of Walker and Mutti (1973) (Table II). The overlying turbidites are similar to their Facies C and possibly D. I interpret the rocks of the Lower Division to represent slump and debris flow deposition in an active mid or upper fan channel followed by deposition of silty to sandy turbidites. Walker and Mutti (1973) restricted their interpretation of Facies F to the slope or main channel of the upper fan. However, with significant tectonic activity within the basin, slope instability leading to mass movement may occur anywhere on the fan. Following the "proximality index" of Walker

(1967), the base-missing nature of the turbidites suggests that these are somewhat distal turbidites. Also suggestive of a mid fan depositional environment for these rocks is the change in paleocurrent direction; that is, this type of change would only occur where one channel and its lobe die out and the new system overlaps. Normark et al, (1979) demonstrated that the upper fan portion of Navy Fan is composed of only one main channel and that this channel does not meander or braid. The preservation of fragile bryozoan fossils in the Lower Division of the Bonanza Creek section, however, would suggest a more proximal environment of deposition.

Middle Division

The contact between the Middle and Lower Divisions is sharp to gradational depending on the presence or absence of a 5 m thick lens of muddy matrix conglomerate at the top of the Lower Division. The Middle Division of the proposed stratigraphy for Bonanza Creek also consists of alternations of sandstone and mudstone. In this section, however, the mean sand size is coarse sand, compared to fine sand and silt in the Lower Division. Fossil content also increases, with some sandstone beds consisting of 30-50% fossil fragments. Most of the sandy turbidite beds begin with the graded division of the Bouma Sequence, and lack one or more of the B-E divisions (Figure 2-18). Cross-laminae are rare, and where observed, could not be measured for paleocurrent analysis because of poor exposure of the laminae. Sandstone beds average 13 cm in thickness and the bedding contacts are planar or wavy. The thicker sandstone beds actually consist of individual graded turbidite beds lacking the shaly interlayers. A bed of shale-chip conglomerate forms the base of a vaguely-defined thinning- and fining-

Figure 2-18: Typical graded and parallel-laminated sandstone bed from the Middle Division, Bonanza Creek.

Figure 2-19: Massive mudstone beds alternating with much thinner sandstone beds, Upper Division A, Bonanza Creek. Cross-cutting feature is an andesite dike.

upward sequence. Mudstone beds are generally massive but may contain 1-2 cm thick lenses of sandstone that are continuous for only 50-75 cm. The Middle Division is 195 m thick.

Middle Division - interpretation of facies

The sandstones of the Middle Division compare most closely with those of Facies C, and the mudstones to Facies G of Walker and Mutti (op.cit). These sandstones possess a higher "proximality index" than those in the Lower Division. Increased grain size and bedding thickness indicate a transition from the lower energy environment of the Lower Division to one of higher energy. This section, then, represents a more active and perhaps a more proximal site of deposition on the fan system. Additional field evidence would be required for a more specific conclusion.

Upper Division

The contact of the Middle Division with the Upper Division is gradational. The Upper Division is composed of 1075 m of massive mudstones alternating with much thinner sandstones (Figure 2-19). Coarse to fine ratios as low as 1:12 are typical of this section, but this ratio tends to increase toward the top. Where present in the sandstone beds, Buchia fossils are typically broken, indicating transport. In mudstone beds, the fossils are both intact and broken, and can be up to 5 cm in their longest dimension. Fossil content within a single mudstone bed may vary from 80 percent at the base to less than 5 percent in the middle and upper parts of the bed. Mollusks are the predominant phylum (see Richter (1976) for details of the fossil population). Millimeter to centimeter thick lenses and layers of siltstone appear within the thick mudstone beds. Some of these layers possess a pulled apart appearance and others are convoluted (Figure 2-20). These sedimentary structures tend to be more common toward the top of this section. Elongate carbonate concretions parallel to bedding occur throughout this section. The sandstone beds cannot readily be described by the Bouma Sequence. The beds are usually structureless, but some of the thicker beds contain parallel-laminae and are graded. Sorting is fair, but notably better than in the sandstones of the underlying sections. Mud rip-up clasts tend to occur only in the thinner, unfossiliferous sandstone beds. Sandstone/mudstone contacts are generally planar, but may also be wavy (on a meter-scale) or scoured (on a centimeter-scale).

Within the top 275 m of the Upper Section, the sandstone beds are slightly thicker than those below (average 6 cm thick compared to 4.5 cm). The coarse to fine ratio increases to 1:4 (Figure 2-21). More importantly, these sandstones are turbiditic. Bouma Sequences of the T_{A-C} and T_{A-E} variety are present. Mud rip-up clasts and scours are common at sand/mud interfaces. A set of symmetrical sole marks at outcrop BNZ1 yields a current direction of 304-134 degrees. Poor quality of outcrop or inaccessibility did not permit further measurement of paleocurrent indicators in these turbidites.

At the very top of the Upper Division, mudstones alternate with beds or thin, discontinuous layers of highly fossiliferous mudstone. These fossiliferous layers consist of 50 percent or more of mollusk fossils.

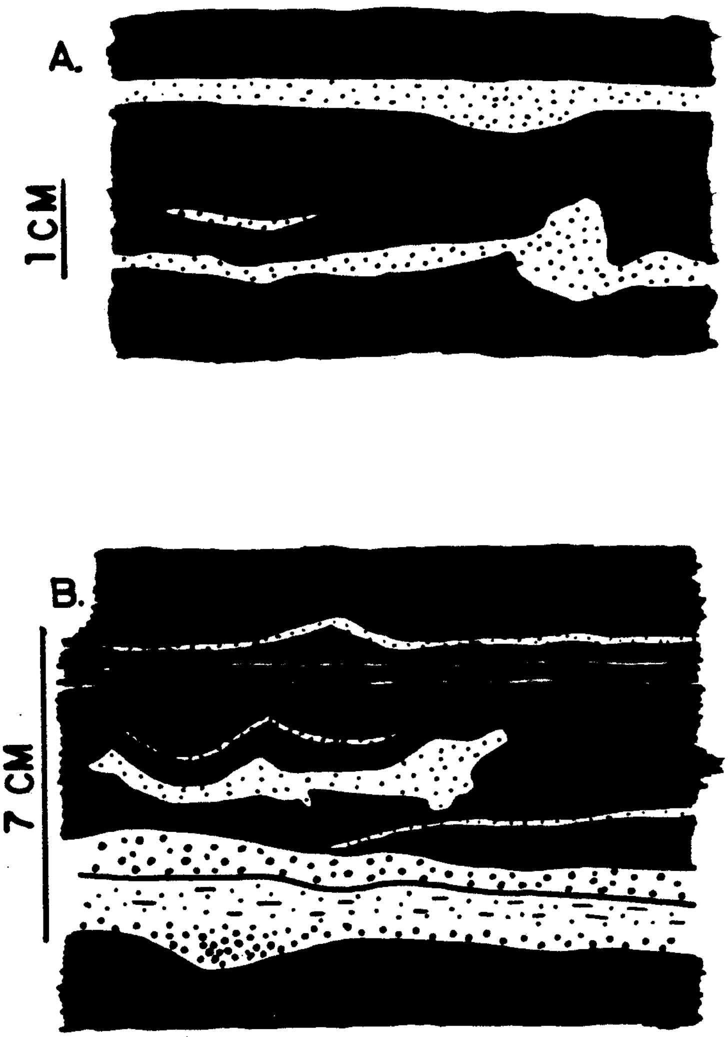

Figure 2-20: Outcrop sketches of fine convoluted and wavy silty laminae within mudstone beds. Stippled pattern is siltstone, black is mudstone. Upper Division A, Bonanza Creek.

Figure 2-21: Upper Division B, Bonanza Creek.

Upper Division - interpretation of facies

The Upper Division consists primarily of Facies G mudstones and, toward the top, Facies C or D turbidites. In considering the environment of deposition for this thick section of primarily mudstone, deposition in the slope facies must be considered. Mutti and Ricci-Lucchi (1972) interpret thick beds of mudstone alternating with thin, relatively nondescript sandstone in the Apennine flysch to be slope deposits in origin. In work on the Upper Cretaceous Great Valley Sequence in California, Ingersoll (1978) recognized a lithofacies of mudstone alternating with thin sandstones and also interpreted them to be the products of slope deposition. Other sedimentary features diagnostic of the slope facies include: 1) slumps, 2) slumping and contortion of bedding, 3) intercalated lenticular sandstone wedges (Mutti and Ricci-Lucchi, 1972). None of these features were observed in the Upper Division along Bonanza Creek.

The alternate hypothesis for the rocks of the Upper Division is that they are inner-fan overbank deposits in origin. The high fossil content in this section may be an indication of greater proximity to the shelf. Interpretation of this as a shallowing-upward trend, however, is inconsistent with the deep-water turbidite beds overlying the mudstone section. It is unlikely that the depositional environment fluctuated from deep marine (represented by the Middle Division) to relatively shallow (the Upper Division mudstones) to deep marine (Upper Division turbidites) and back to shallow (the most upper fossiliferous mudstones). A simpler and more reasonable explanation is that deposition took place at a consistent depth but in different environments on the upper fan.

More specifically, the rocks of the Upper Division may be the products of overbank flow from the main channel. Normark et al (1979) reported thick mudstones on the fringes of the main channel levees. They suggested that for a turbidity current too thick for its channel, the fine portion of the current will overflow the banks. This hypothesis is applicable to the Upper Division mudstones. Overbank flow would result in large volumes of mud in a turbid current that is able to transport shells. As an individual current slowed, most of the shells settled out of the current while some remained incorporated in the flow. This scenario accounts for the presence of large fossils within very fine grained to muddy material. The nature of the sandstone beds is unclear, but these may also be related to overbank flow deposition. For an exceptionally thick turbidity current, the overbank flow could contain a coarse sand fraction. The sharp sandstone/mudstone bedding contacts may, then, be due to the erosion of an originally thick turbidite bed by current action at the sea floor. The turbidites overlying the mudstone were perhaps deposited closer to the channel. These turbidites are very similar to those of the channel-margin facies in the Hecho Group in Spain (Mutti, 1977).

The Upper Division can be explained by both slope and inner-fan overbank environments of deposition. The available data do not permit a more concrete conslusion. Knowing lateral stratigraphic relationships might help constrain the interpretation of the Upper Division. For example, some of the diagnostic characteristics of the slope facies may be found if the Upper Division could be traced out further than was possible.

CHISANA FORMATION

Chisana Formation volcanics and volcaniclastics overlie the Nutzotin Mountains Sequence. On Bonanza Creek, the contact is gradational. Ash beds and submarine lava flows are intercalated with the deep marine sandstones and mudstones of the Nutzotin Mountains Sequence.

SHEEP CREEK SECTION

Work in the Sheep Creek area was restricted to Upper Sheep Creek (about half-way from the southern margin of the belt of flysch) and to Two-By-Four and Camp Creeks (about 3-5 km south of the Denali Fault) (Figure 2-22). Exposure at creek level along Sheep Creek itself is poor. This portion of the Nutzotin Mountains Sequence has been assigned a Late Jurassic age on the basis of lithologic similarities with rocks underlying the late Jurassic-early Cretaceous section along Bonanza Creek (Richter and Jones, 1973).

Slaty cleavage is well-developed in the rocks along Two-By-Four and Camp Creeks (hereafter, Lower Sheep Creek). The cleavage strikes between 270°and 260° and is near vertical. Bedding-cleavage relationships vary from high- to low-angle depending on the location of the outcrop with respect to the fold axis mapped by Richter (1973) (Figure 2-1).

A probable thrust fault was observed on Two-By-Four Creek (Figure 2-23). Farther up the creek at location TBF7, the deformation becomes more severe. Within a 300-500 meter wide zone, the cleavage has variable and random orientations. Some slickensided cleavage surfaces were observed. In places, phacoidal cleavage is present; its orientation is generally 265, 70°S. Bedding is obscured by the chaotic

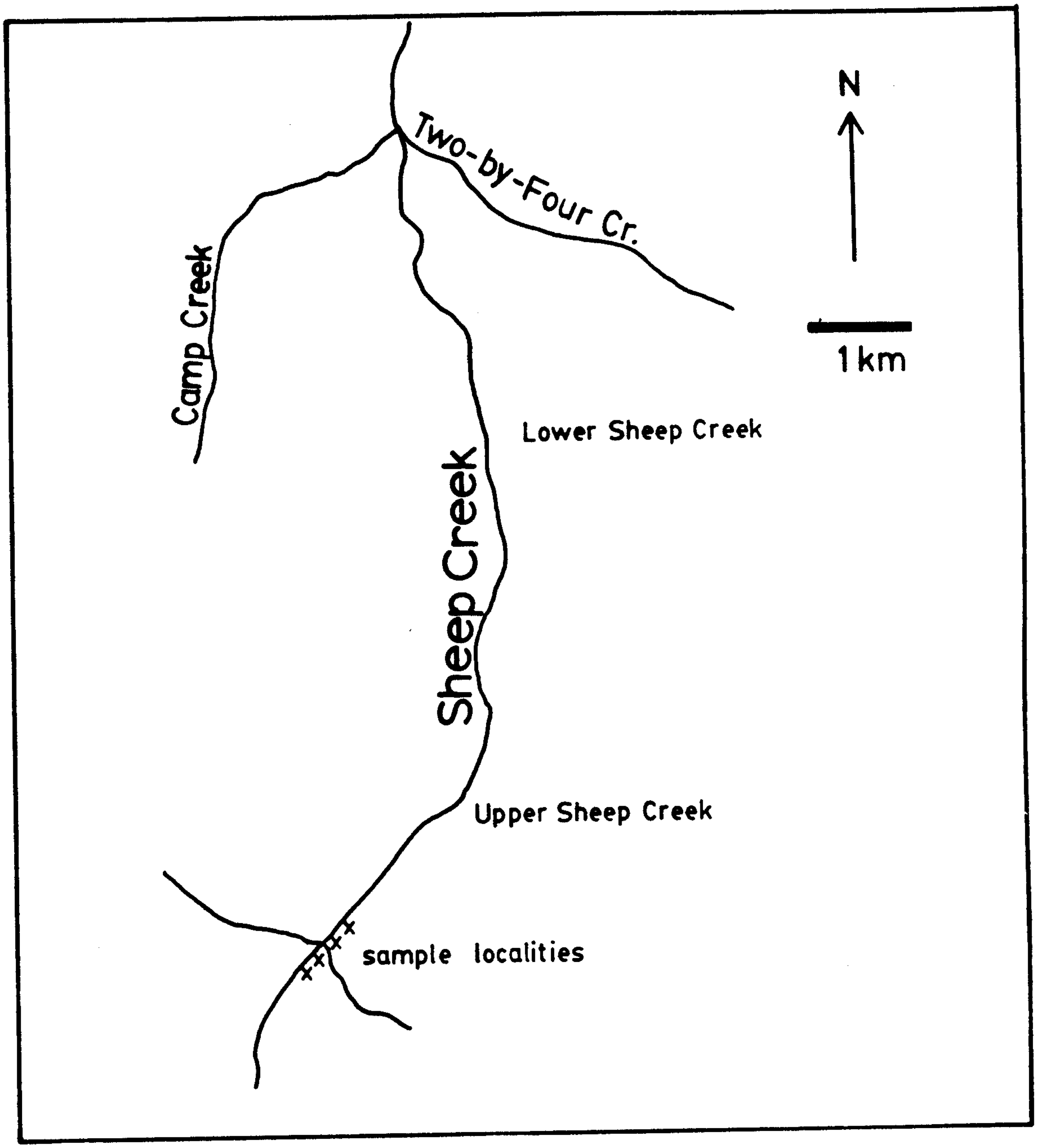

Figure 2-22: Location map of Sheep Creek study area.

Figure 2-23: Thrust fault (?), Two-by-Four Creek. (Note person for scale).

structure. Bosworth and Vollmer (1980) link phacoidal cleavage to thrust fault-related melange zones. The association of this deformed zone with the proposed thrust fault supports the notion that this zone is thrust-related melange. Clearly, more field mapping would be required to test this hypothesis.

The nature of the flysch is much different along Sheep Creek. The major difference is in grain size. In the rocks from the Two-By-Four and Camp Creeks exposures (hereafter, Lower Sheep Creek), very fine silt to fine silt is the average grain size of the coarse beds. Consequently, collecting sandstone samples suitable for provenance study is, in general, not possible. Coarse grained sandstones were found at outcrop SHP1 and several coarse sandstone beds are located at the exposure along Upper Sheep Creek (Figure 2-22).

The lithologies of Lower Sheep Creek are turbiditic siltstone with alternations of mudstone. One turbidite bed is 45 cm thick. The average bedding thickness, however, is only 4 cm. Coarse to fine ratios are typically 1:1 or less.

A variety of primary and secondary depositional structures are present in the sandstones. T_{AB}, T_{AE}, T_{A-C}, and T_{BE} turbidite beds are present. Parallel-lamination is the most common structure in the turbidites. The C-division of the Bouma Sequence consists of minute cross-laminae. Sole structures are absent. The bases of the turbidite beds are characterized by asymmetric soft-sediment deformation structures (Figure 2-24).

Flaser and lenticular beding occurs throughout the rocks of Lower Sheep Creek (Figure 2-25). These beds are very thin (less than 1 cm), discontinuous, and have sharp contacts with the underlying and overlying mudstones. Reworking of the silt by bottom currents may have

Figure 2-24: Soft-sediment deformation features (at tip of hammer), Camp Creek, Lower Sheep Creek.

Figure 2-25: Flaser and lenticular bedding, Two-by-Four Creek.

produced this type of bedding.

Upper Sheep Creek is also characterized by mudstone alternating with sandstone. Mudstone beds are much thicker, averaging 18 cm compared to only 4-5 cm on Lower Sheep Creek. The mudstones contain 1-2 cm thick layers of siltstone, and in places, horizons of parallel- and cross-laminated siltsone (Figure 2-26). These latter structures are similar to the lenticular and flaser bedding noted in the Lower Sheep Creek exposure. Both massive and thoroughly parallel-laminated sandstone beds (Figure 2-27) are found in this section. The parallel-laminated sandstones are atypical; they are coarse grained, well-sorted and contain no other primary sedimentary structures. These sandstones represent short-lived changes in the depositional environment. Whether the sandstones are the result of reworking by bottom currents, storm deposition, or restricted provenance is unclear.

Where the flysch consists of regularly interbedded siltstone and mudstone, the siltstones are T_{BE} turbidites. The C-division of the Bouma Sequence is absent or occurs as convolute laminae. Sole marks are absent as well. Outcrop UC3 consists of massive sandstone. None of the Upper Sheep Creek outcrops contain fossils.

Sheep Creek Section - paleocurrent data

Cross-laminae from the turbidites on Two-By-Four and Camp Creeks provided all paleocurrent information for this field area. A total of 91 cross-laminae were measured. Again, no plunge was assumed in correcting the data for tilt. No measurements were taken within 25 m of the faulted and melange zones described earlier. Few outcrops contained more than ten measureable cross-laminae. Where possible, laminae

Figure 2-26: Parallel- and cross-laminated siltstone within mudstone bed, Upper Sheep Creek.

Figure 2-27: Thick, parallel-laminated sandstone bed, Upper Sheep Creek.

measurements were taken from more than one bed. The results from Camp Creek and Two-By-Four Creek are shown in Figure 2-28. Vector means of 14.3 degrees and 337.9 degrees demonstrate a northward flowing current.

Sheep Creek Section - interpretation of facies

The mudstones and siltsones of the Sheep Creek section compare most closely to Facies E of Mutti and Ricci-Lucchi (1972). The thick, massive sandstones found along the Upper Sheep Creek exposure correspond to Facies B sandstones. Thick, structureless sandstones such as these may represent channel fill. The association of these thick, possible channel-fill sandstone beds with probable overbank deposits suggest deposition on either the channelized portion of the midfan or deposition associated with the main channel of the inner fan. The absence of other proximal facies argues in favor of the midfan interpretation for these rocks.

CONCLUSIONS

The section of the Nutzotin Mountains Sequence exposed along Bonanza Creek was deposited in both high- and low-energy environments on a submarine fan. The Lower Division was deposited on the mid-fan portion of the fan. Increased grain size and "proximality index" in the turbidites of the Middle Division suggest that these were deposited on the mid- to upper-fan. The mudstones and turbidites of the Upper Division are possible overbank and channel-margin deposits or slope deposits. The overall coarsening-upward trend in the section suggests progradation of the fan system. Paleocurrent directions demonstrate that sediment was transported into the basin from the south. The change in paleocurrent direction from northwest to northeast may be the result

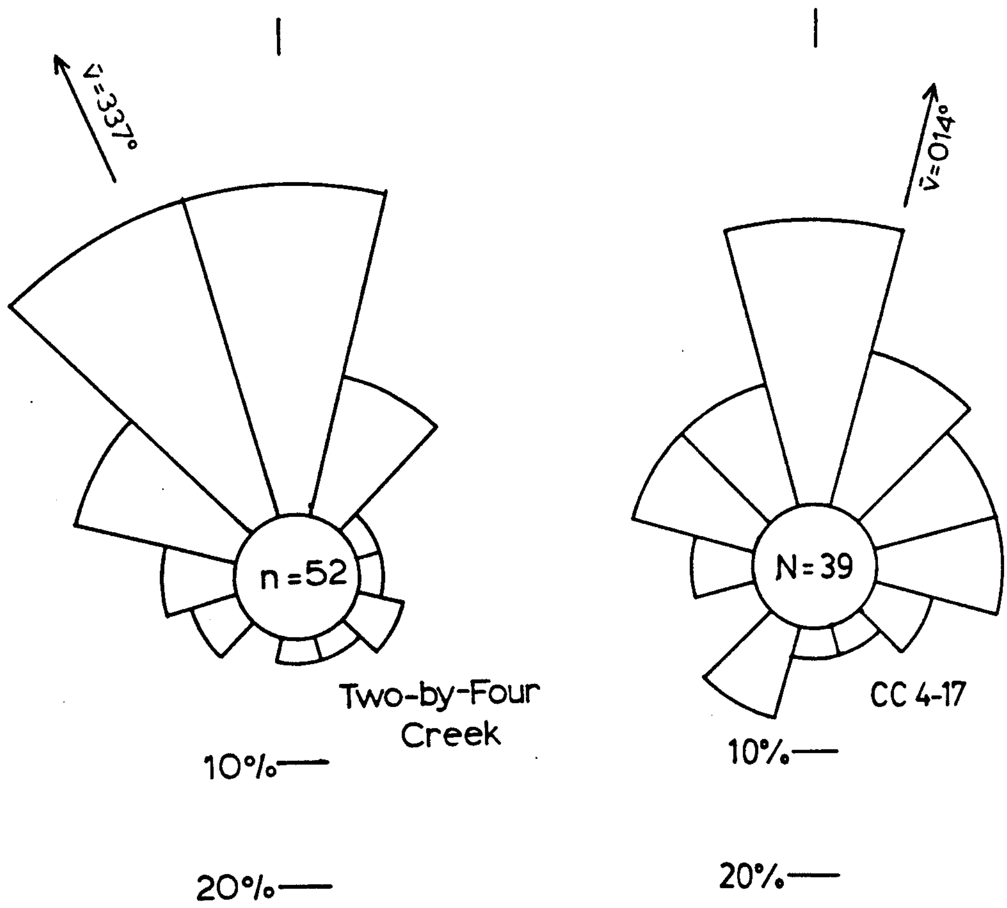

Figure 2-28: Paleocurrent data from the Sheep Creek study area.

of overlapping lobes. The section along Sheep Creek probably represents channel in-filling and channel overbank deposition on the mid-fan.

Because the stratigraphic relationship between the Bonanza Creek section and the Sheep Creek section is unclear, it is difficult to infer progradation of a fan system or regression. In the simplest model, in which there is no appreciable difference in age between the rocks of the Bonanza Creek section and those of the Sheep Creek section, the distal and proximal members of a fan system are represented by the rocks of Sheep Creek and Bonanza Creek respectively. If the Sheep Creek section is indeed Late Jurassic as Richter and Jones (1973) indicate, then a more complex model must be invoked or, if my interpretation is correct, structural complications must be introduced.

CHAPTER III

COMPOSITION AND PROVENANCE OF NUTZOTIN MOUNTAINS SEQUENCE SANDSTONES

INTRODUCTION

The provenance portion of this study is based largely on petrographic point-count data from 38 sandstone samples from the Bonanza Creek section and seven samples from the Sheep Creek section. The two goals of this portion of the study are to identify the major source(s) of the flysch and to determine if volcanism was coeval with sedimentation.

METHOD

To determine the composition of the rocks, 400 to 600 points were counted per thin section using a .6mm grid spacing. My technique is based on the assumption that the percent area that a grain occupies on a randomly oriented slide is an accurate assessment of the volume that a grain occupies in the actual rock (Chayes, 1956). In this study, therefore, I have determined the percent area of a given slide that is occupied by volcanic clasts, matrix, and so on and not the number of grains per category. The slides were examined under 100X magnification. Samples B10A, B10B, B33, 19-BP-81, 20-BP-81, 21-BP-81, 23-BP-81, and UC3D were counted on a .3 mm grid.

Since the composition of sandstones is a function of grain size (see Blatt, 1967; Ingersoll et al, 1984), then the composition of the flysch would be accurately determined with a suite of samples that consists of a range of grain sizes. Modal analysis reveals that for rocks collected from the same outcrop (within 10-15 m of of each other in stratigraphic section), the finer grained rocks are slightly more quartzose than the coarser grained rocks (Figure 3-1). No firm conclusion on size dependency of composition can be drawn from this limited sampling of fine-grained rocks, but it does show it to be a very small effect.

Ingersoll et al (1984) and Dickinson (1970) would argue that fine grained samples are compositionally more mature and thus more representative of the stable composition of a suite of sandstones than are coarse grained rocks. Had the coarser grained sandstones of the Bonanza Creek suite undergone the same amount of transportation and mechanical breakdown, their composition would be similar to that of their finer grained counter-parts; that is, lithic fragments would break down into their mineral components. These authors further claim that the way to obtain the "mature" composition from an "immature" sandstone is to count all sand size particles, including those within lithic fragments. This method of point-counting was used on sample B30 and the results compared to those from my standard point-counting method (Figure 3-2). The increase in total feldspar reflects the number of feldspar phenocrysts of sand size within volcanic fragments. Had all of the sandstone samples been counted by the new method, they would plot farther toward the feldspar corner of the QFL. The alternate method of point-counting is, in essence, concerned with the composition of a hypothetical rock. The purpose of this study is to examine the nature of the detrital components.

The above discussion emphasizes the desirability of studying the coarser grained sandstones from a turbidite sequence. The coarser sandstones will yield first-hand information about the source lithologies while the fine sandstones yield second-hand information.

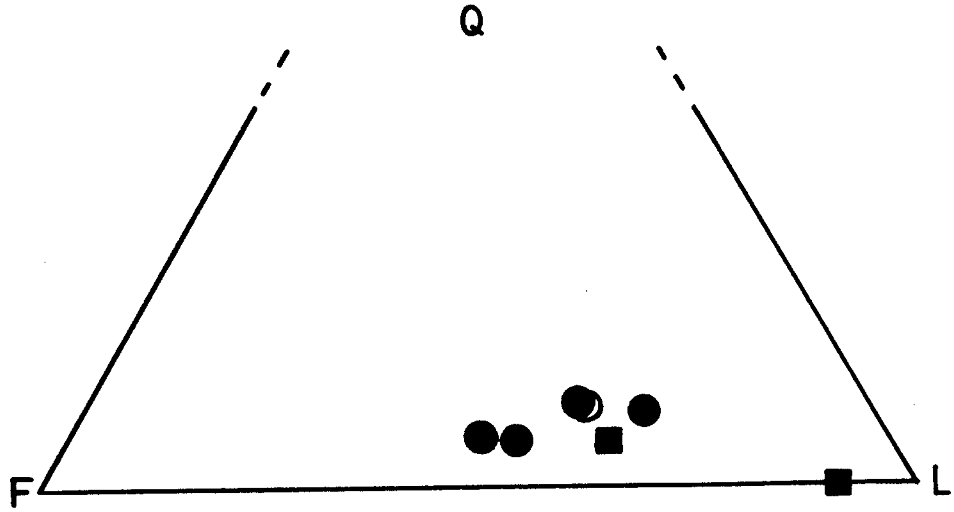

Figure 3-1: QFL plot of fine grained (circles) and coarser grained (squares) sandstones from the same outcrop.

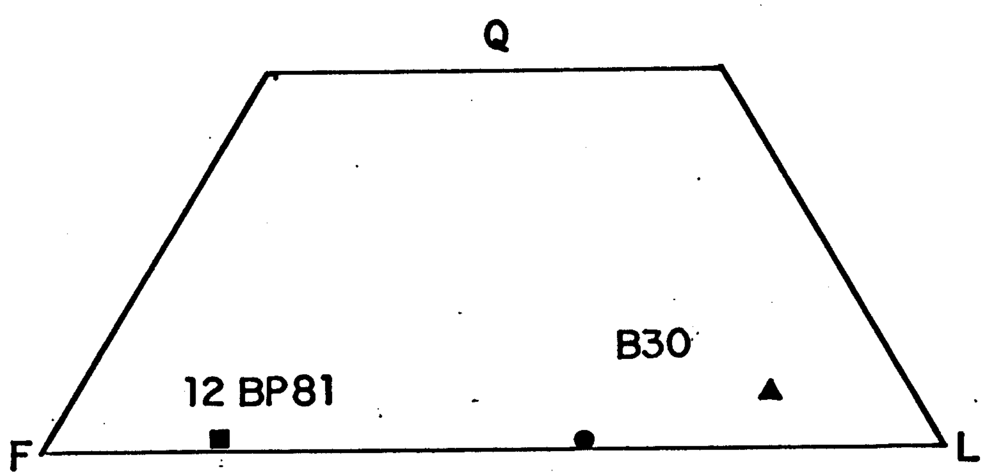

Figure 3-2: Comparison of point-count results on sample B30 using the Gazzi-Dickinson method (circle) and the method of this study (triangle). (Square is sample 12-BP-81)

The Gazzi-Dickinson method of point-counting (Ingersoll et al, 1984) may have the desired effect of "standardizing" compositions between coarse and fine sandstones, but in counting phenocrysts within volcanic clasts as distinct detrital components, the method also has the effect of obtaining second-hand source information from what are otherwise very informative rocks.

Thirteen categories of framework grains were counted in the point-count analysis and are outlined in Table IV.

GENERAL DESCRIPTION

The sandstones of Bonanza Creek and Sheep Creek are volcanic lithic wackes and volcaniclastic sandstones according to the classification scheme of Pettijohn, Potter, and Seiver (1973). The amount of matrix was tallied during counting and is found to constitute an average of 20.6% of the rocks for the Bonanza Creek sandstones and 18% for those from Sheep Creek. The grains are angular to subrounded, and the sandstones are poorly sorted (Figure 3-3).

Silicic material is readily distinguishable from mafic/intermediate by its relative lack of alteration and mafic minerals. The distinction between silicic volcanic clasts and polyscrystalline quartz (chert), however, is not as obvious and is clearly subjective. Silicic clasts containing larger crystals of quartz or feldspar are interpreted to be porphyritic silicic volcanic clasts. Those not containing larger quartz crystals are grouped into the polycrystalline quartz class. Overlap between these two classes is very likely. Combined, however, both categories constitute only between 5% and 15% of the points counted.

Matrix in my classification scheme is simply dark brown to green

Table IV: Parameters for Modal Analyses

Framework Grains

Q:	Q_M	monocrystalline quartz
	Q_P	polycrystalline quartz: includes foliated, chert, and recrystallized grains
F:	Plag	plagioclase feldspar
	Kspar	potassium feldspar
L:	L_T	total lithic fragments (L_V + L_S)
	L_V	volcanic lithic fragments: V_M: mafic/intermediate volcanics-volcanic clasts with greater than 10% mafic minerals V_{Si}: volcanic clasts with less than 10% mafic minerals, and quartz phenocrysts
	L_S	sedimentary clasts

Mafic and accessory minerals

mica: biotite, muscovite
opaque: undifferentiated
other: hornblende, clinopyroxene, zircon, apatite, fossil fragments
matrix: clay minerals

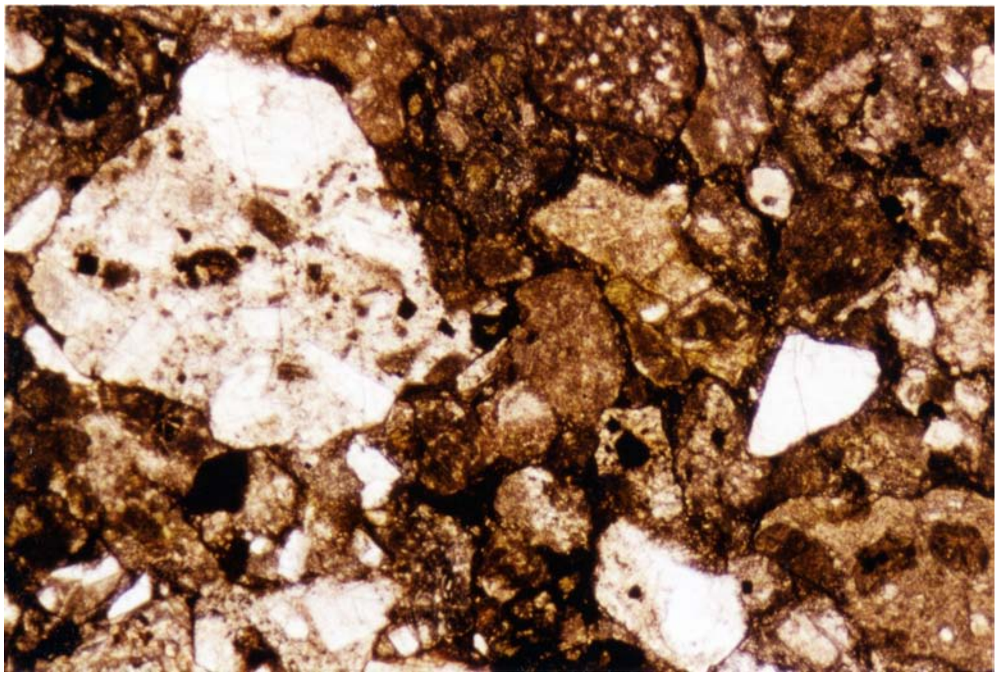

Figure 3-3: Typical sandstone from the Bonanza Creek suite. Note poor sorting and angularity. (25x, Plane light).

interstitial material that is murky in appearance. The "matrix problem" has been discussed by Cummins (1962) and Dickinson (1970). Briefly, the matrix in graywackes has two possible origins: it may be detrital (true matrix), or the product of recrystallization along the boundaries of unstable grains. The amount of alteration in some of the sandstones is substantial. It follows that the amount of detrital matrix in these slides has been overestimated (on the order of about 15%) and that the amount of volcanic clasts and mafic minerals has been underestimated. The point-count data must be viewed with these inherent errors in mind. Because the lithologies of the lithic fragments are identifiable, the provenance work on these sandstones is still valuable despite the "matrix problem".

Slaty cleavage in the fine grained sandstones collected from Lower Sheep Creek has enhanced the "matrix problem". Distinguishing between grains and matrix is impossible in some samples. Because of the large uncertainties in identifying the constituents of the rocks from Lower Sheep Creek, these samples were not included in the provenance study.

Only rarely did the amount of alteration in the sandstones present a problem in identifying detrital grains. In cases of heavy alteration, the grains could often be identified by relict textures. Several samples could not be analyzed due to severe replacement by calcium carbonate. Sandstones from the Upper Section of Bonanza Creek, for example, are so carbonate-rich (fossil fragments and replacement by calcium carbonate) that the original detrital textures are obscured. These samples were point-counted nonetheless simply to establish the proportions of the recognizable framework grains.

METAMORPHISM

The presence of pumpellyite in the sandstones from the Bonanza Creek section and prehnite (Figure 3-4) in those from the Sheep Creek section indicate that the rocks have undergone prehnite-pumpellyite grade metamorphism. In the sandstones collected along the Sheep Creek section, feldspar grains are also replaced by epidote.

SANDSTONES FROM THE BONANZA CREEK SECTION

Quartz

Of the framework grains, quartz is by far the least abundant, averaging only 5.4%. The ratio of polycrystalline quartz to total quartz ranges from 1.0 to 0.0 and averages .68. Several varieties of polycrystalline quartz are present in the sandstones: 1)single euhedral grains that are recrystallized (Figure 3-5) 2) irregularly-shaped masses of strained quartz, 3) faintly foliated quartzite grains (Figure 3-6) and 4) chert. Subgrains in the coarser polycrystalline quartz clasts exhibit undulose extinction.

The foliated polycrystalline quartz grains (type 3) are metamorphic in origin. The provenance of the other varieties of strained quartz is ambiguous. Considering the folding and faulting that has taken place in the Nutzotin Mountains Sequence, it is possible that the strain exhibited in these composite quartz grains (types 1 and 2) was acquired during deformation of the flysch sequence. The recrystallized euhedral quartz grain mentioned above argues in favor of this interpretation. No fossils were observed in the chert grains. The origin of the chert grains is difficult to assess; they may be sedimentary cherts or cherts produced by the alteration of silicic volcanic material.

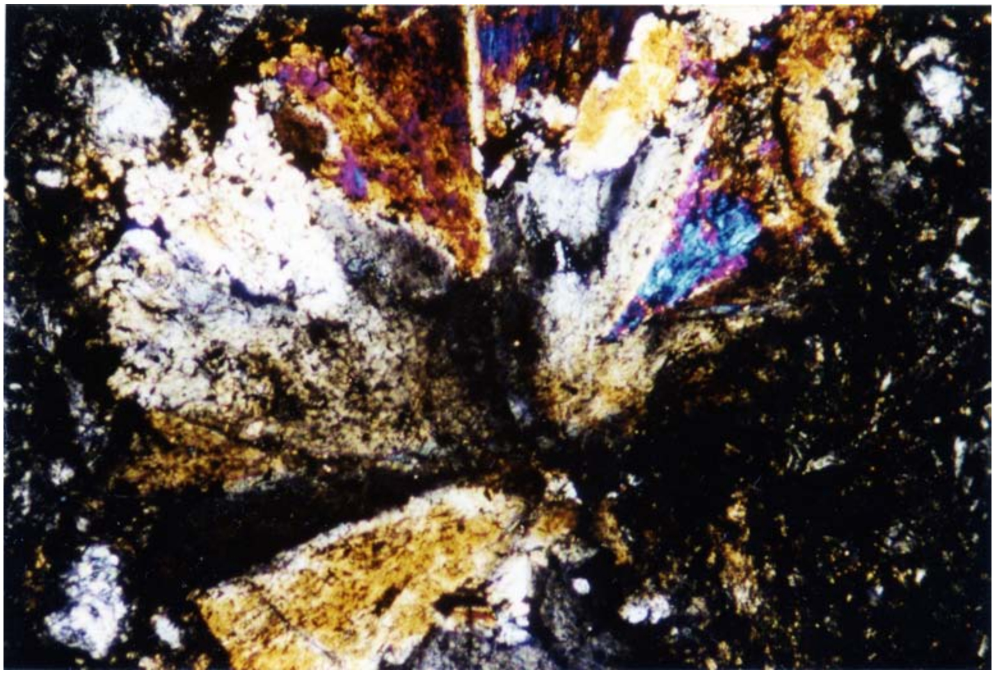

Figure 3-4: Prehnite in sandstone sample, Upper Sheep Creek (40x).

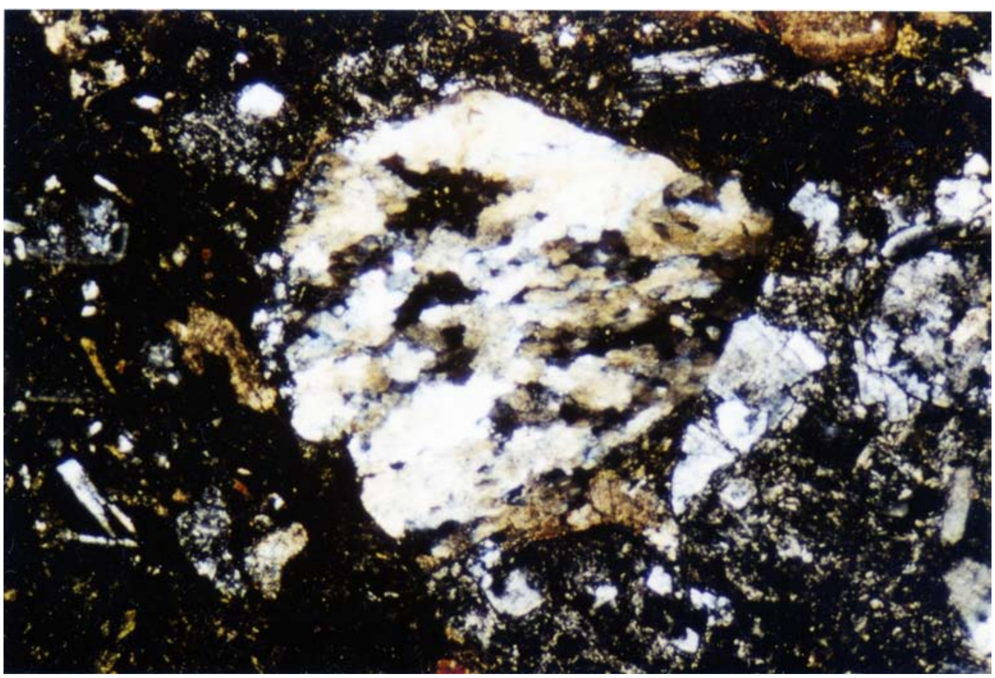

Figure 3-5: Recrystallized, faintly foliated quartz grain, Bonanza Creek suite. (25x).

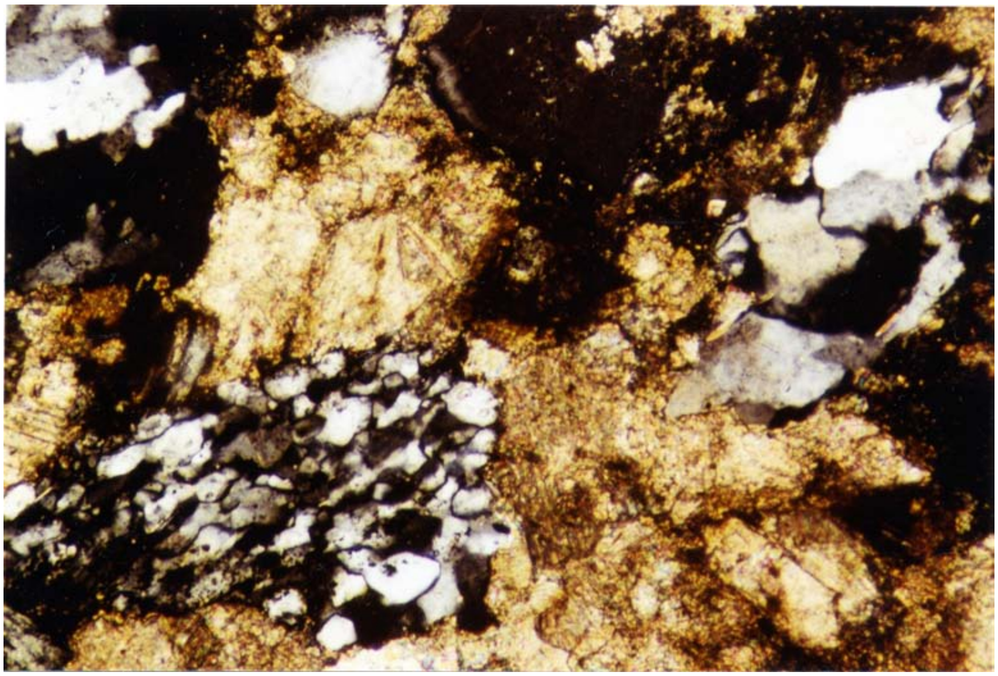

Figure 3-6: Polycrystalline quartz clasts, Bonanza Creek suite. (100x).

Monocrystalline quartz is rare in the Nutzotin Mountains Sequence along Bonanza Creek. The average monocrystalline quartz to total quartz ratio (.32) is quite low. These quartz grains are typically angular to subangular, medium-grained, and show uniform or wavy extinction Rocks with the highest percentage of monocrystalline quartz are those in the Lower Division (outcrop BNZ49). It is also within these samples that grains of beta-quartz are found. These grains possess at least one crystal face or are perfectly euhedral. The presence of resorption cavities within the quartz grains confirms that these are volcanic in origin (Figure 3-7).

Feldspar

The sandstones from the Bonanza Creek suite are rich in feldspar. Feldspars typically comprise 29% of the framework grains, but range from 8.5% to 45%. Plagioclase feldspar is ubiquitous while potassium feldspar is rare. The plagioclase grains have not been albitized (i.e., they are "clean" in appearance). The majority of the plagioclase grains are progressively zoned. The composition of the plagioclase, determined by extinction angles on twins, ranges from that of oligoclase to that of andesine. Where crystal faces are not obscured by alteration, the plagioclase grains are euhedral (Figure 3-8). Grain size is highly variable. No resorption cavities were observed in the plagioclases.

Pitman (1963) has noted that some zoned plagioclase grains in sedimentary rocks may be metamorphic in origin, but the abundance of plagioclase grains in the Nutzotin Mountians Sequence and their association with a plethora of volcanic detritus strongly indicate a

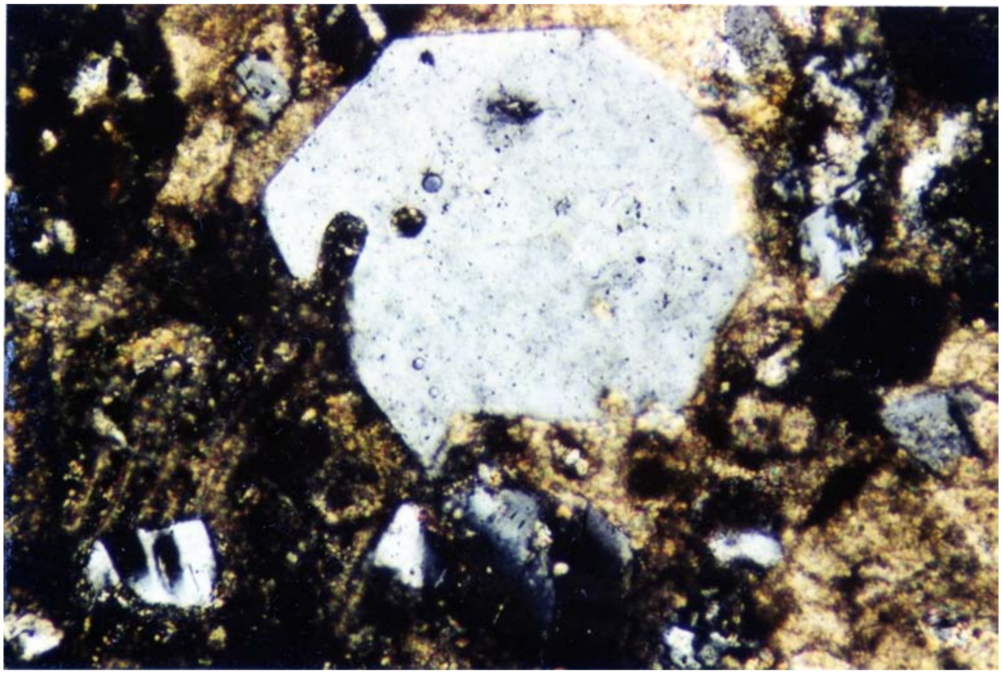

Figure 3-7: Euhedral monocrystalline quartz with resorption cavity, Bonanza Creek suite. (100x).

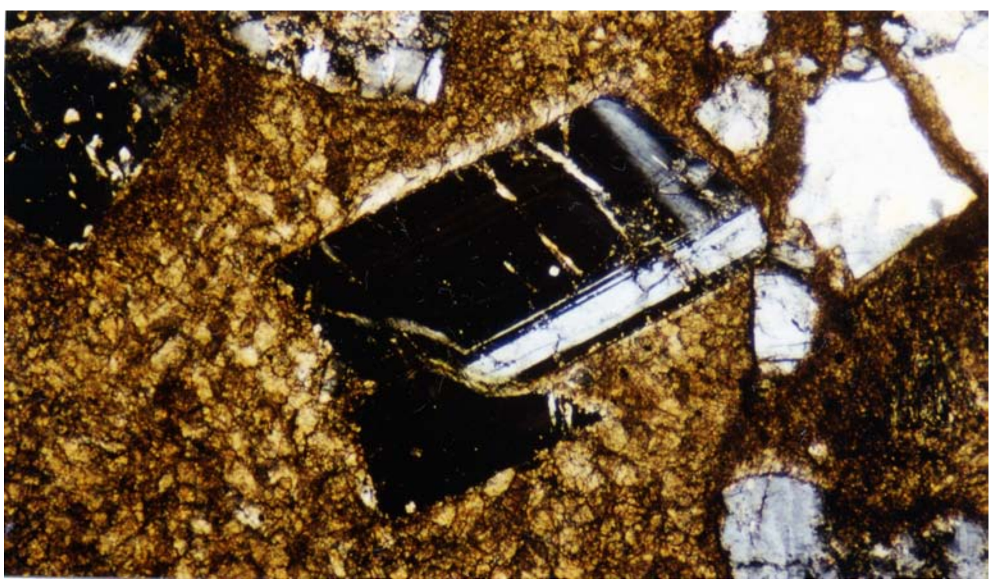

Figure 3-8: Euhedral, zoned plagioclase grain, Bonanza Creek suite. (100x).

volcanic source for the feldspars.

Potassium feldspar was identified by its general lack of twins, its fresh appearance under plane light, and its equant shape (plagioclase tends to be elongate). In some cases, an optic axis figure was obtained for a positive identification. Four slides from my collection were stained with sodium cobaltinitrate to highlight the potassium feldspar; all of the slides from Panuska's collection (i.e., 18-BP-81, etc.) were stained as well. There was no appreciable difference in the amount of potassium feldspar counted in the slides before and after staining. These feldspars are generally angular, fine- to medium-grained, and lack twins (Figure 3-9). Kspar to total feldspar ratios are very low; the average is .07 and the range is .02-.18. Potassium feldspar is chemically and mechanically more stable than plagioclase feldspar (Pettijohn, Potter, and Siever, 1972). Therefore, the great proportion of plagioclase to potassium feldspar in the Nutzotin Mountains Sequence must be a reflection of the source area.

Lithic Fragments

Lithic fragments constitute 50% to 95% of the framework grains. Three types of rock fragments were recognized in thin-section: 1) volcanic, 2) sedimentary (including shales/slates, chert, and volcaniclastic fragments), and 3) metamorphic. The amount of plutonic clasts observed in the sandstones is nominal, and even the classification of these clasts as plutonic is dubious (see below). The lithic fragments vary widely in grain size. With the exception of rounded silicic volcanic clasts, chert, and fine-grained sedimentary

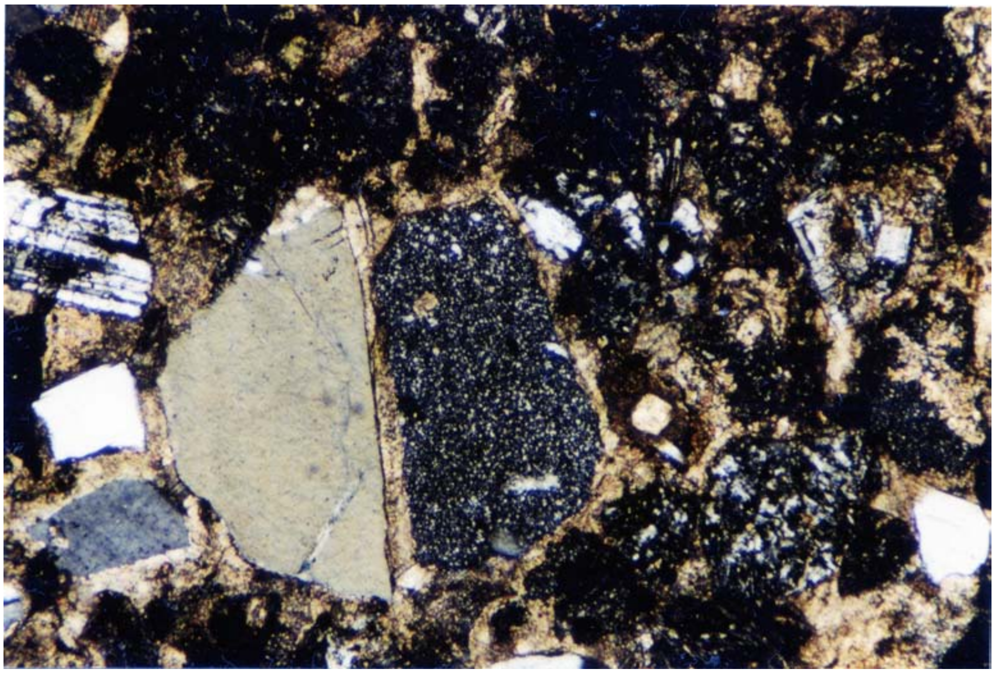

Figure 3-9: Alkali feldspar (left), Bonanza Creek suite. (40x).

clasts, the lithic fragments are angular to subangular. Where the rock fragments are exceptionally fine-grained (for example, a volcaniclastic grain), plane light aids in distinguishing between the grain and matrix.

Volcanic fragments are the main constituents of the sandstones. The ratio of mafic volcanic clasts to total volcanic clasts is high (.98) and varies little throughout the section. The rims of the volcanic clasts are altered; in some cases, alteration obscures the original grain boundaries. The calcium-rich cores of plagioclase phenocrysts in the porphyritic clasts are usually preferentially altered, the relatively sodium-rich rims being unaltered. Pyroxene and hornblende phenocrysts are often only recognizable by their relict textures. Biotite flakes occurring in one silicic volcanic (plutonic?) fragment are truncated at the grain's boundary. One volcanic clast contains a quartz vein which is also truncated by the clast's boundaries. On the other hand, some volcanic clasts are remarkably fresh (Figure 3-10), and the majority lack foliation, quartz veins, and evidence of recrystallization.

Lithic Fragments - mafic/intermediate volcanic clasts

A wide variety of mafic/intermediate volcanic textures are present in any given sample. Porphyritic texture is the most common (Figure 3-11). The phenocrysts are plagioclase, pyroxene, and hornblende. No olivine phenocrysts were observed. Other volcanic textures are also found in the sandstones from the Bonanza Creek suite. Trachytic texture (Figure 3-12) is defined by the subparallel alignment of plagioclase crystals. Volcanic clasts with diabasic texture are present but are relatively uncommon. Mafic/intermediate volcanic

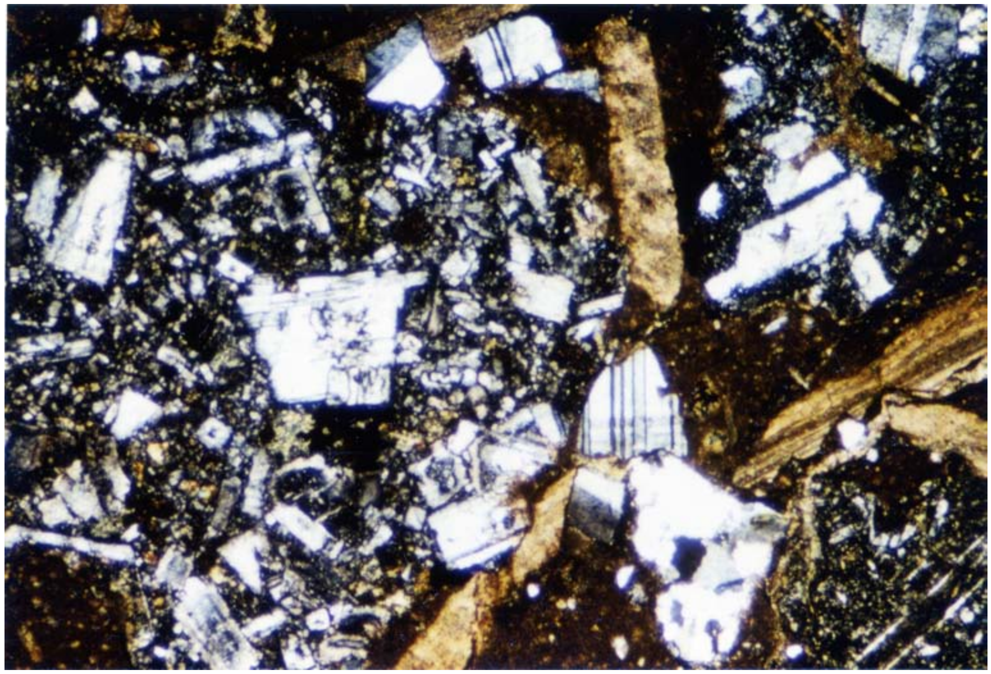

Figure 3-10: Typical appearance of volcanic clasts, Bonanza Creek suite. (40x).

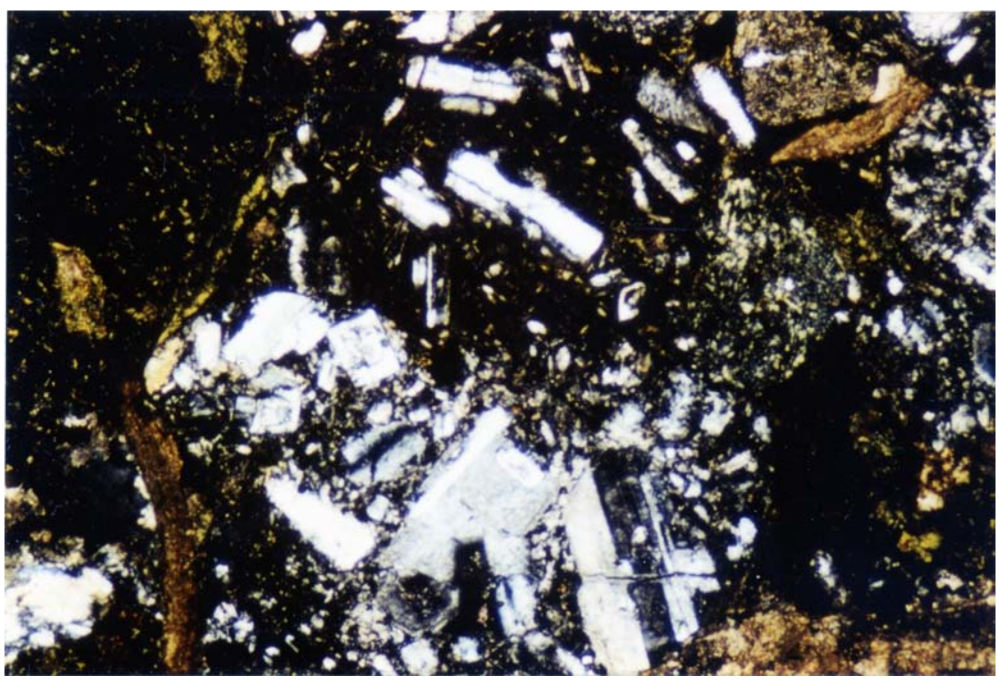

Figure 3-11: Mafic/intermediate volcanic clast with porphyritic texture, Bonanza Creek suite. (40x).

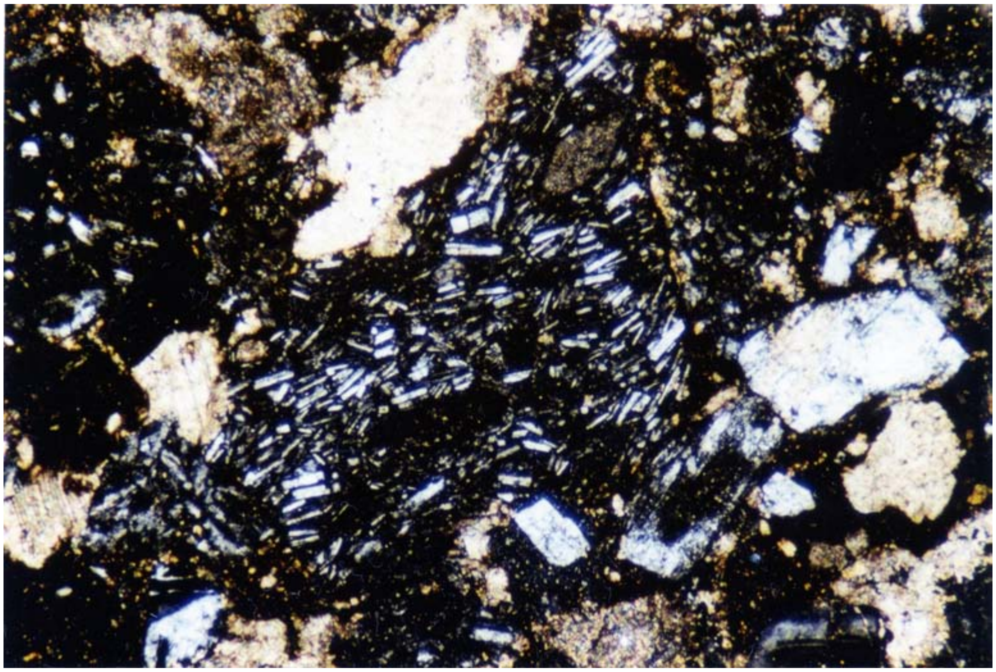

Figure 3-12: Mafic/intermediate volcanic clast with trachytic texture, Bonanza Creek suite. (40x).

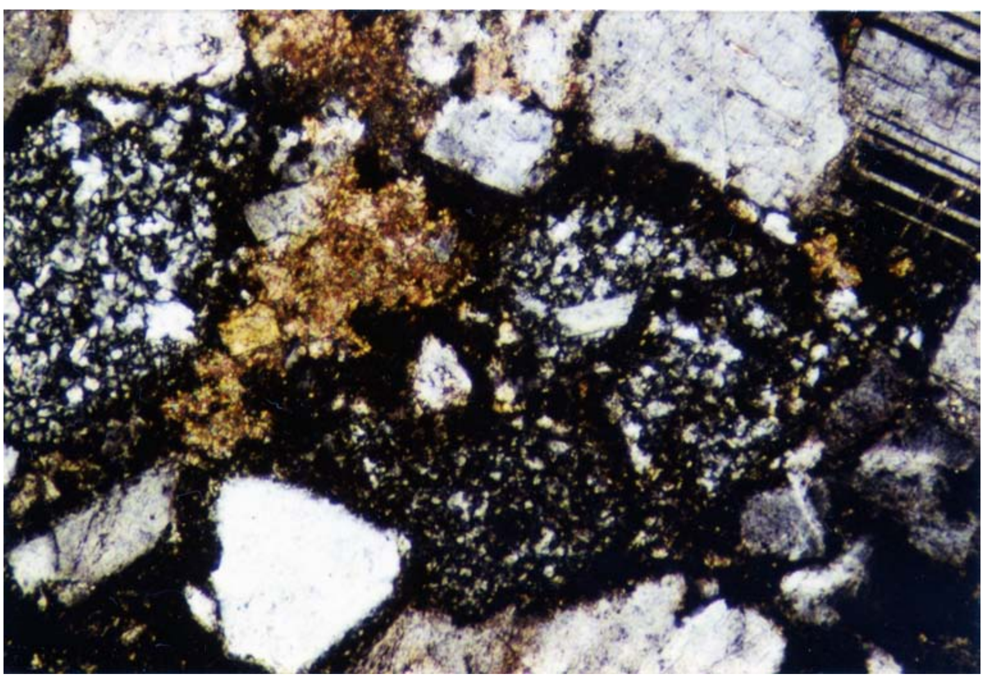

Figure 3-13: Silicic volcanic clast, Bonanza Creek suite. (40x).

clasts with calcite- or chalcedony-filled amygdules are also rare. Finally, aphanitic and seriate textures are present in small amounts. In all, these textures fall into the felsitic, microlitic, and lathwork grain categories that Dickinson (1970) has outlined.

Lithic Fragments - silicic volcanic fragments

Silicic volcanic clasts are usually composed of quartz or feldspar phenocrysts in a silicic aphanitic groundmass (Figure 3-13). Block-shaped phenocrysts are assumed to be alkali feldspar. Medium to coarse grained silicic igneous clasts are rare; their occurrence is greatest in the sandstones of the Lower Division. The coarse and equigranular texture of the silicic igneous clast shown in Figure 3-14 is suggestive of a plutonic or hypabyssal origin. Only two or three igneous clasts with granular texture were observed in the whole suite of sandstones. The ratio of silicic volcanic clasts to total volcanic clasts (V_{Si}/V_T) averages .04 and only rarely exceeds .10.

Lithic Fragments - sedimentary and metamorphic clasts

Sedimentary clasts are typically rare in the sandstones of Bonanza Creek; the ratio of sedimentary clasts to total lithic clasts averages only .14. Sedimentary clasts are of three varieties (listed in decreasing abundance): 1) poorly sorted volcaniclastics or graywackes, 2) mudstones, and 3) medium-grained, moderately well-sorted arenites. Limestone clasts are not present. The clasts of the first category are characterized by angular feldspar and mafic grains in a fine grained matrix (Figure 3-15). The argillaceous clasts are recognized by their faint foliation as well as by their lack of a coarse fraction (Figure

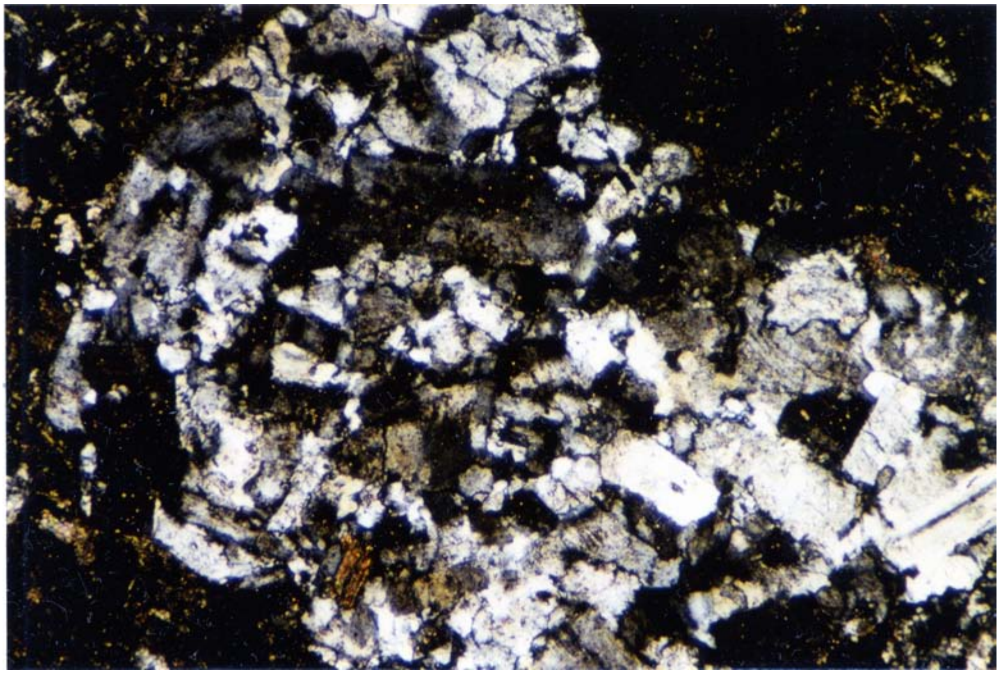

Figure 3-14: Coarse grained silicic igneous clast, Bonanza Creek suite. (40x).

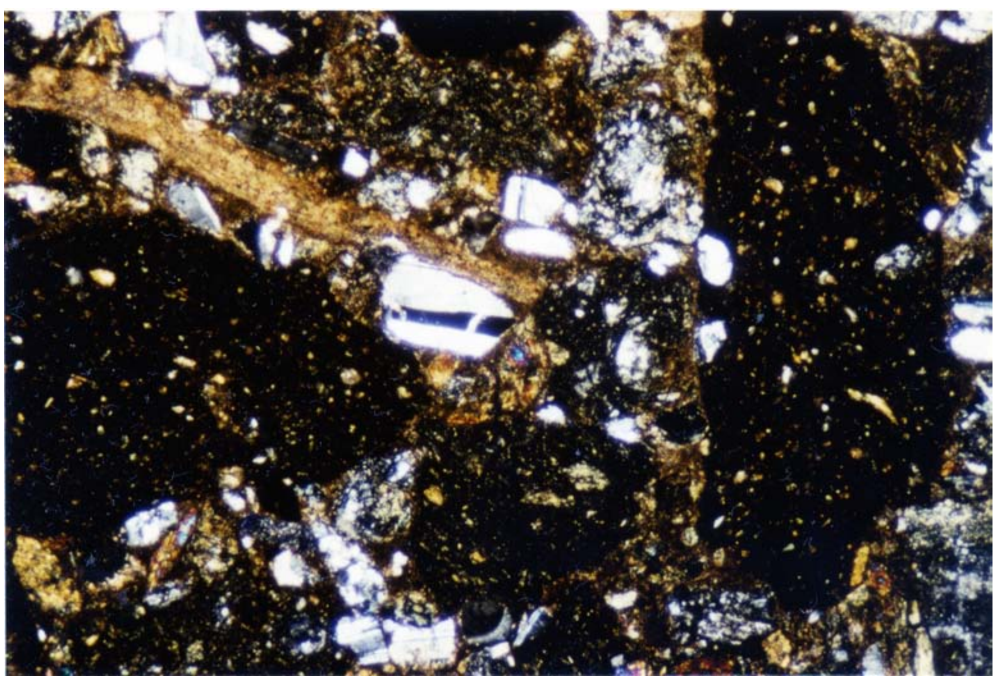

Figure 3-15: Sedimentary clasts, Bonanza Creek suite. (25x).

3-16). The clasts of the third category are similar in appearance to the finer grained wackes of the Bonanza Creek section. They are probably intraformational sandstone clasts.

The metamorphic clasts in the Bonanza Creek sandstones are so scarce that a separate category is not utilized. Rather, quartzites are classified as polycrystalline quartz, and quartzose schists, slates, and shales as sedimentary clasts. The clasts of schist are subangular grains consisting of alternating quartzose and graphitic and slightly micaceous layers (Figure 3-17). This clast is extremely fine grained, unlike what would be expected from rocks of the Yukon-Tanana Terrane.

Mafic and Accessory Minerals, and other clasts

Mafic minerals present in the sandstones are clinopyroxene, hornblende, biotite, and undifferentiated opaques. The pyroxene is most likely augite or titanaugite. Pyroxene grains are usually angular and broken, although euhedral grains were observed. Faint hour-glass zoning is present in some grains.

The hornblende present in the sandstones is brown and usually occurs as euhedral to subhedral crystals. Detrital biotite is difficult to recognize owing to alteration. Biotite grains are usually bent and distorted between larger clasts. The texture of the opaque minerals varies widely from euhedral crystals to anhedral or broken grains. Detrital epidote and apatite are also represented in the sandstones although in very minor amounts.

The high fossil content in some rocks from the Upper and Middle Divisions precluded meaningful point-counting. Mollusk and crinoid fossil fragments are abundant. The fossil fragments are typically very coarse grained.

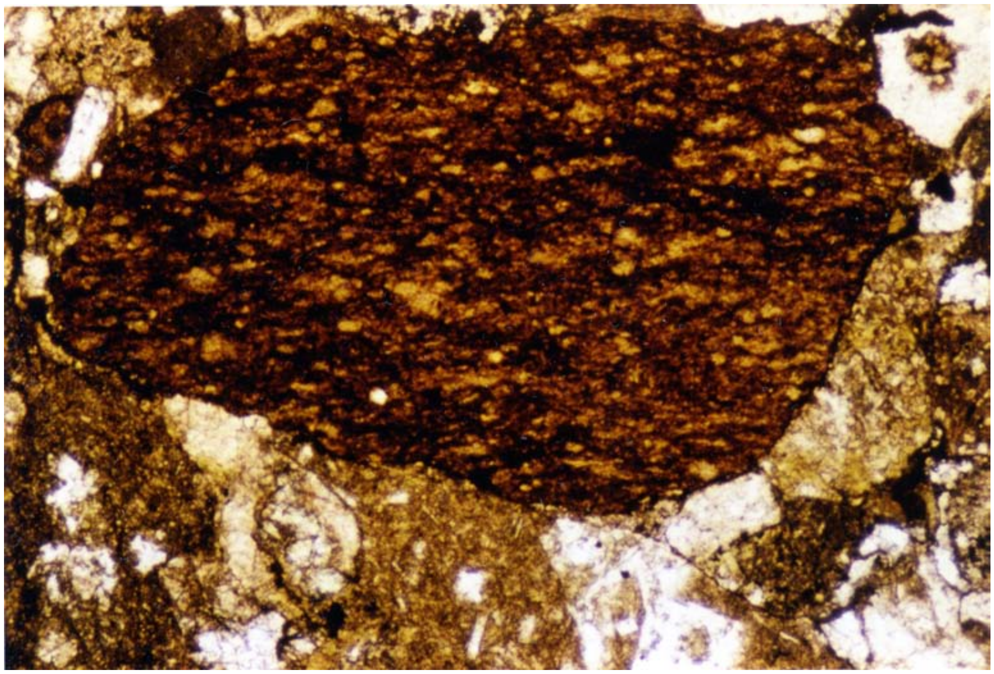

Figure 3-16: Sedimentary clast, Bonanza Creek Division. (25x).

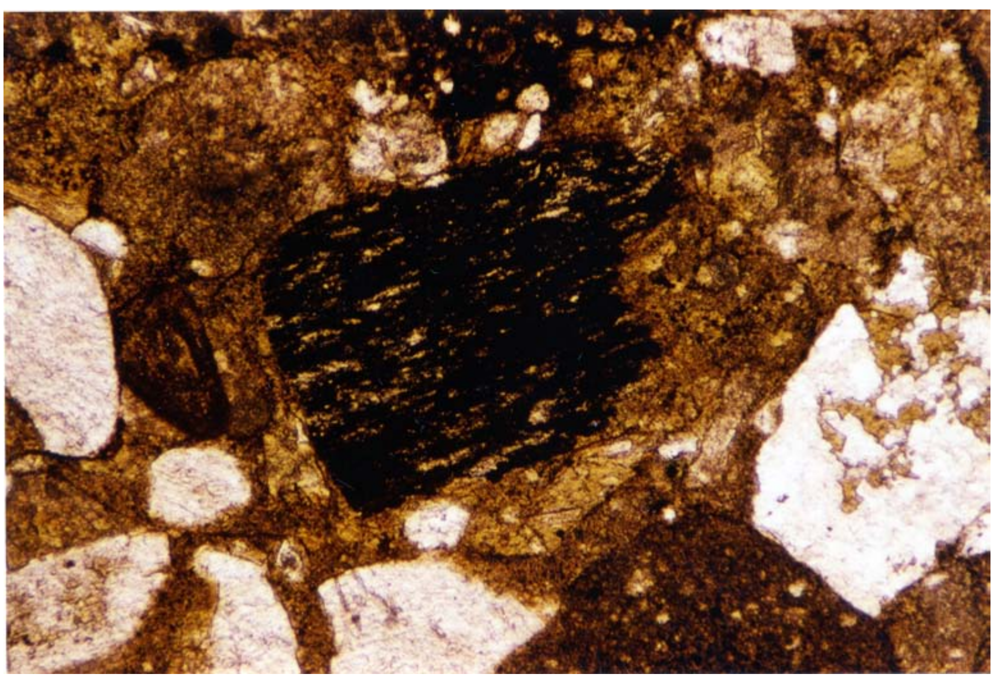

Figure 3-17: Foliated metamorphic clast, Bonanza Creek suite. (40x).

SANDSTONES FROM THE SHEEP CREEK SECTION

Samples from Upper Sheep Creek were the only rocks from Sheep Creek suitable for provenance study. A total of seven sandstones were analyzed using the same point-counting procedure as that on the Bonanza Creek samples. All of the thin-sections were stained for potassium feldspar with sodium cobaltinitrite.

The Sheep Creek sandstones are very similar both texturally and compositionally to those of the Bonanza Creek section. By visual inspection, the degree of sorting in the Sheep Creek sandstones is slightly higher than in those from Bonanza Creek, but the angularity of the grains is comparable. Of the points counted, an average of 76% are framework grains, 18% matrix, and 6% mafic minerals and opaques. These rocks are also volcanic lithic wackes.

Quartz

The amount of quartz in the Sheep Creek sandstones averages 10.1% of the framework grains, and varies from 14.4% (sample UC3D) to 7.3% (UC3A). The average ratio of polycrystalline quartz to total quartz is .56. Both chert and recrystallized vein-type varieties of polycrystalline quartz are present in these rocks. Foliated quartzite clasts and single, euhedral recrystallized grains such as those found in the suite of rocks from the Bonanza Creek section are not observed in these samples.

Monocrystalline quartz is slightly more common in the sandstones from along Sheep Creek than those from Bonanza Creek; the average ratio of monocrystalline quartz to total quartz is .43 compared to .32. The monocrystalline quartz grains of these sandstones are typically angular, possess no original cystal faces, and show slight undulose extinction. Euhedral quartz grains and quartz with resorption cavities are absent.

Feldspar

Feldspar constitutes 38.6% of the framework grains for the Sheep Creek samples compared to only 29% for the Bonanza Creek suite. Again, however, plagioclase is the main variety of feldspar; the ratio of plagioclase feldspar to total feldspar averages .71. Unlike the plagioclases in the sandstones from the Bonanza Creek section, the plagioclase grains in these sandstones are generally not zoned and are often broken into irregularly shaped grains. The plagioclase grains are not restricted to one grain size. One plagioclase grain with a resorption cavity was observed.

The Sheep Creek suite sandstones are much richer in potassium feldspar than those from Bonanza Creek; compare potassium feldspar to total feldspar ratios of .30 for the Sheep Creek suite and .02 for Bonanza Creek. These feldspars are typically untwinned and unzoned, and they occur as angular grains. The increase in the amount of potassium feldspar in these rocks over those from Bonanza Creek reflects either a change in the source or the breakdown of feldspar-bearing volcanic clasts during sediment transport. Both hypotheses are discussed more fully in a later section of this chapter.

Lithic Fragments - volcanic clasts

Mafic/intermediate volcanic clasts constitute 94% of the points counted for volcanic fragments. The most common volcanic textures are porphyritic and trachytic. Trachytic texture is generally more common in these sandstones than in those from the Bonanza Creek section.

Silicic Volcanic and Sedimentary Clasts, Mafic and Accessory Minerals

Both silicic and sedimentary clasts are similar to those found in the sandstones from the Bonanza Creek section. Clasts of coarse grained sedimentary rock are absent. Mudstone-type clasts with coarser grained feldspars floating in the matrix are the most common variety of sedimentary clasts. Faintly foliated argillaceous clasts are rare.

Pyroxene and biotite are the only mafic minerals present in these sandstones. Coarse and very fine biotite grains are present in the sandstones. The biotite grains are typically distorted about feldspars and volcanic clasts. Undifferentiated opaque minerals constitute only 3.2 % of the points counted per slide. These grains are typically very fine grained and angular. Negligible quantities of epidote and apatite are present in these sandstones. These sandstones are also devoid of fossil fragments.

DISCUSSION OF RESULTS

The results of point-counting are plotted on a QFL ternary diagram in which Q is the total quartz, F is the total feldspar, and L is the sum of the various lithic fragments (Figures 3-18 and 3-19). The sandstones occupy the quartz-poor, lithic fragment-rich region of the QFL plot.

Some of the Upper Division sandstones appear to tend more to the feldspar corner of the QFL diagram, but it is not clear whether this trend of increasing feldspar up-section is significant. These stray points are from samples 12-BP-81, B10A, B21, and B30A. The amount of alteration in specimen B21 may have led to the misidentification of

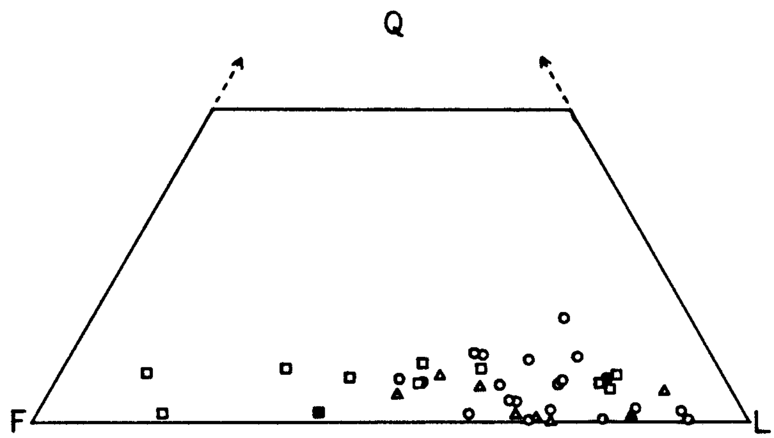

Figure 3-18: QFL plot of the Bonanza Creek suite of sandstones. Circles denote samples from the Lower Division, triangles the Middle Division, and squares the Upper Division. Solid figures denote samples that were heavily altered or contained a great amount of fossil fragments.

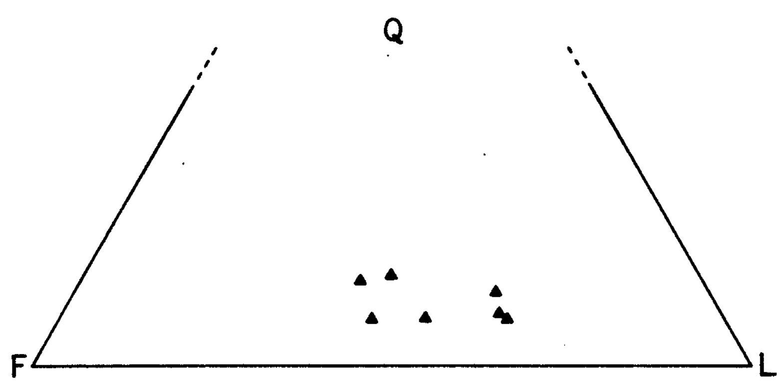

Figure 3-19: QFL plot of the Sheep Creek suite of sandstones.

volcanic clasts. Sample B30A, however, is relatively fresh and its determined modal composition ($Q_{12.3}F_{56.4}L_{31.2}$) is probably more accurate and reliable than that determined for B21. The composition of sample 12-BP-81 may be a reflection of smaller grain size.

The other sample with exceptionally high amounts of feldspar is B10A. This sandstone is a medium-grained, angular to subangular, moderately well-sorted feldspathic lithic arenite (Figure 3-20). Both plagioclase and potassium feldspar are present in the rock; the ratio of plagioclase to potassium feldspar being nearly 2:1. Zoning is either absent or faint in the plagioclase grains. Fine grained silicic volcanic clasts and monocrystalline quartz grains are common in this rock, and mafic minerals and opaques constitute only 3.7% of the counted grains. Because the difference in composition between this sample and the other sandstones is so extreme, I believe that the modal composition is a reflection of source and not of grain size. Also, a higher degree of rounding suggestive of a longer transport history is not seen in these feldspathic sandstones. The nature of this source is discussed later.

The sandstones from the Sheep Creek section are also low in quartz but tend to plot more toward the middle of the feldspar-lithic fragment leg of the QFL diagram. The feldspar data also demonstrate the marked increase in potassium feldspar in the Sheep Creek sandstones over those from Bonanza Creek: the potassium feldspar to total feldspar ratio increases from .07 to .30. The Quartz-Potassium feldspar-Plagioclase feldspar diagram (QKP) (Figure 3-21) highlights the difference in the amount of potassium feldspar between the two suites. A change in the nature of plagioclase feldspar is also observed. As noted in the

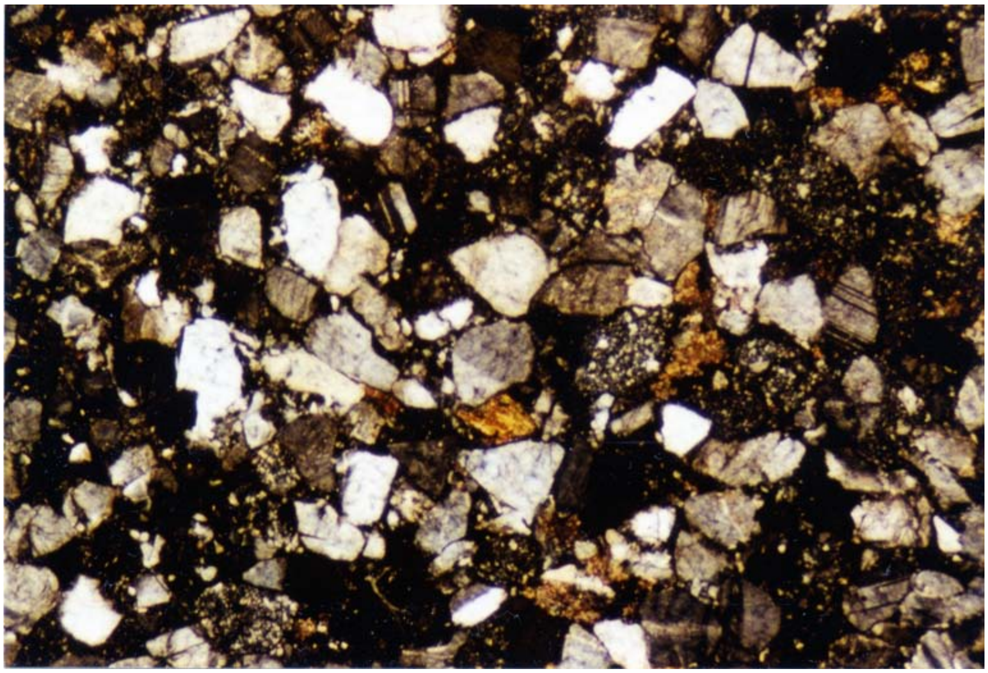

Figure 3-20: Feldspathic sandstone from Upper Division, Bonanza Creek. (25x).

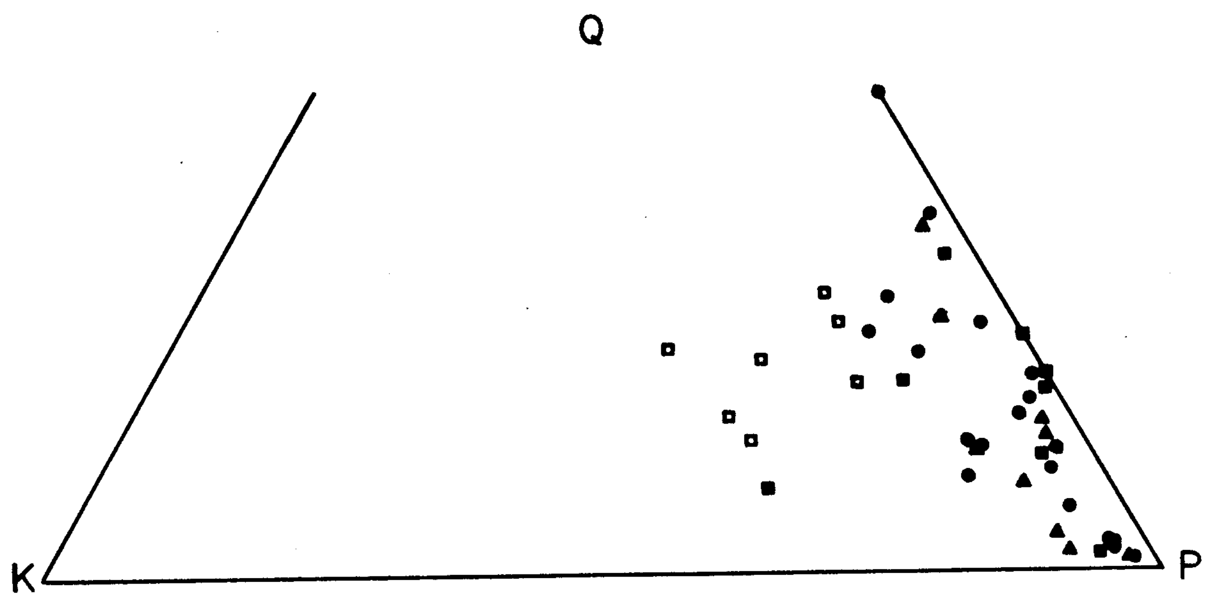

Figure 3-21: QKP plot of the sandstones from the Bonanza Creek and Sheep Creek sections of the Nutzotin Mountains Sequence. Open squares denote samples from the Sheep Creek suite; closed circles, triangles, and squares from the Lower, Middle, and Upper Divisions of the Bonanza Creek suite respectively.

preceding section, the detrital plagioclase grains in the Bonanza Creek sandstones are well-zoned and are euhedral crystals. In the Sheep Creek suite of sandstones, plagioclase grains are unzoned and are usually angular, broken grains. It is not clear whether the difference in the percent feldspar and the increase in the alkali feldspar to total feldspar ratios between the two suites of sandstones represent two sources (or a change in the source with time) or simply a composition difference related to smaller grain size.

The problem hampering the interpretation of this observation, and indeed of many observations of the flysch, is the poor age control on the rocks from this portion of the flysch belt. Fossils from the section along Bonanza Creek provide most of the age control on the entire belt of the flysch. The age (Late Jurassic) placed on the rocks along Sheep Creek is based on lithologic similarities between the Sheep Creek rocks and rocks stratigraphically underlying the Late Jurassic-Early Cretaceous Bonanza Creek section; that is, the fine grained graded turbidites and mudstones along Sheep Creek are considered to be the same age as similar turbidites and mudstones along Bonanza Creek. Moreover, similar rocks in adjacent quadrangles in the Nutzotin Mountains Sequence belt are assigned a Late Jurassic-Early Cretaceous age (Richter and Schmoll, 1973; Richter and Jones, 1973). The correlation of like lithologies and lithologic associations in the absence of fossils and stratigraphic contacts is tenuous. This is particularly so in dealing with the turbidites of a flysch sequence presumably deposited on a submarine fan system where sediments of the same age may be vastly different in outcrop appearance. The relative ages of the various sections of Richter's (1976) stratigraphy are ambiguous. Whether the rocks along Sheep Creek stratigraphically overlie, underlie or are correlative with the rocks of the Bonanza Creek section is left unknown.

Resolving this stratigraphic ambiguity is important in correctly interpreting the compositional differences (and similarities) between the Bonanza Creek and Sheep Creek suites of sandstones. The differences may reflect a change in the provenance with time, if they are of different age, or with different source areas, if they are of the same age range.

The increase in the amount of feldspar and decrease in lithic (volcanic) fragments from the Bonanza Creek suite to the Sheep Creek suite is not conclusive evidence for two sources or changing sources. However, the change in potassium feldspar/total feldspar ratios may be. Dickinson (1970) suggests that low plagioclase/total feldspar ratios (around .75) in volcanic sandstones are indicative of dacitic and rhyolitic provenances, and that plagioclase/total feldspar ratios approaching 1.0 are indicative of andesitic source terranes.

In studying the provenance of the Great Valley Sequence in California, Dickinson and Rich (1972) identified several "stratigraphically controlled petrofacies" within the sequence. A petrofacies is a set of composition characteristics (e.g., potassium feldspar/total feldspar and volcanic clasts/total lithic fragments ratios, and QFL percentages) of a sandstone that may indicate its provenance and distinguish it from other petrofacies in the same rock unit. "Petrologic intervals" are nearly synchronous petrofacies and are traceable on a basin-wide scale. In the light of the marked difference in the potassium feldspar to total feldspar ratios between the Bonanza and Sheep Creek suites of sandstones, it is reasonable to interpret these two suites as two petrofacies. The significance of this interpretation lies in the observation that the petrofacies defined in the Great Valley Sequence do not transgress time-stratigraphic boundaries (Dickinson and Rich, 1972). If the two sandstone suites examined in this study are indeed petrofacies, then the two sections are most likely not correlative in time.

The Sheep Creek suite of sandstones also possess a higher ratio of monocrystalline quartz to total quartz than do the Bonanza Creek sandstones (compare .43 to .32), possibly further suggesting a more silicic volcanic source for the Sheep Creek rocks. The ratio of silicic volcanic clasts to total volcanic clasts is, however, quite low in the Sheep Creek suite (.06) and is comparable to that in the Bonanza Creek suite (.04). These compositional differences simply cannot be explained on the available evidence. However, on the basis of the dramatic increase in the potassium feldspar/total feldspar ratio, I favor the notion that the compositional differences reflect a change in the source over time. Both a larger suite of sandstones from the Sheep Creek and adjacent areas and the stratigraphic position of these rocks relative to the Bonanza Creek section are needed to test this hypothesis.

Possible sources for the foliated metamorphic detritus found in these sandstones include the Yukon-Tanana Terrane to the northeast or a section of quartzo-feldspathic schist at the base of the Paleozoic island arc sequence of Wrangellia. Not only do paleocurrent indicators argue against a northern source for these rocks but so does the composition. The Yukon-Tanana Terrane is characterized by quartzo-feldspathic and quartz-mica schists; the metamorphic clasts observed in the sandstones are fine grained and composed largely of graphitic material and quartz. By the same reasoning, the schists of the Wrangellia Terrane may also be eliminated as the source of the foliated clasts. It is possible that these clasts were derived from rocks associated with local thrust faulting. For example, this clast may have originated as a quartz-rich mudrock that became incorporated in and was subsequently deformed in a thrust zone (Kidd, pers.comm., 1984).

Aside from a few scattered points, the sandstones of the Bonanza Creek and Sheep Creek sections fall in a region of 0-15% total quartz, 10-45% total feldspar, and 45-95% lithic fragments. On a plot of all composite grains ($Q_pL_VL_S$) the sandstones cluster tightly in the L_V corner (Figure 3-22). This diagram serves to highlight 1) the strong volcanic signature of the sandstones, and 2) the paucity of continentally-derived detritus. Petrographic observations indicate that the volcanic source was predominantly mafic/intermediate.

Based on studies of ancient sandstones, Dickinson and Suczek (1979) suggest that sandstones of this composition are derived from an "undissected" magmatic arc; that is, a volcanic arc not yet eroded down to underlying plutons. Valloni and Maynard (1981) classify sandstones of this composition as forearc to backarc in origin. Mack (1984) contends that sandstone classification schemes fail for sandstones derived from a region of transitional tectonic regimes (for example, convergent to strike-slip). It is possible that Wrangellia and the other terranes surrounding the Nutzotin Mountains Sequence had complex tectonic histories. I can conclude that these sandstones have a volcanic arc provenance but cannot draw inferences regarding the nature

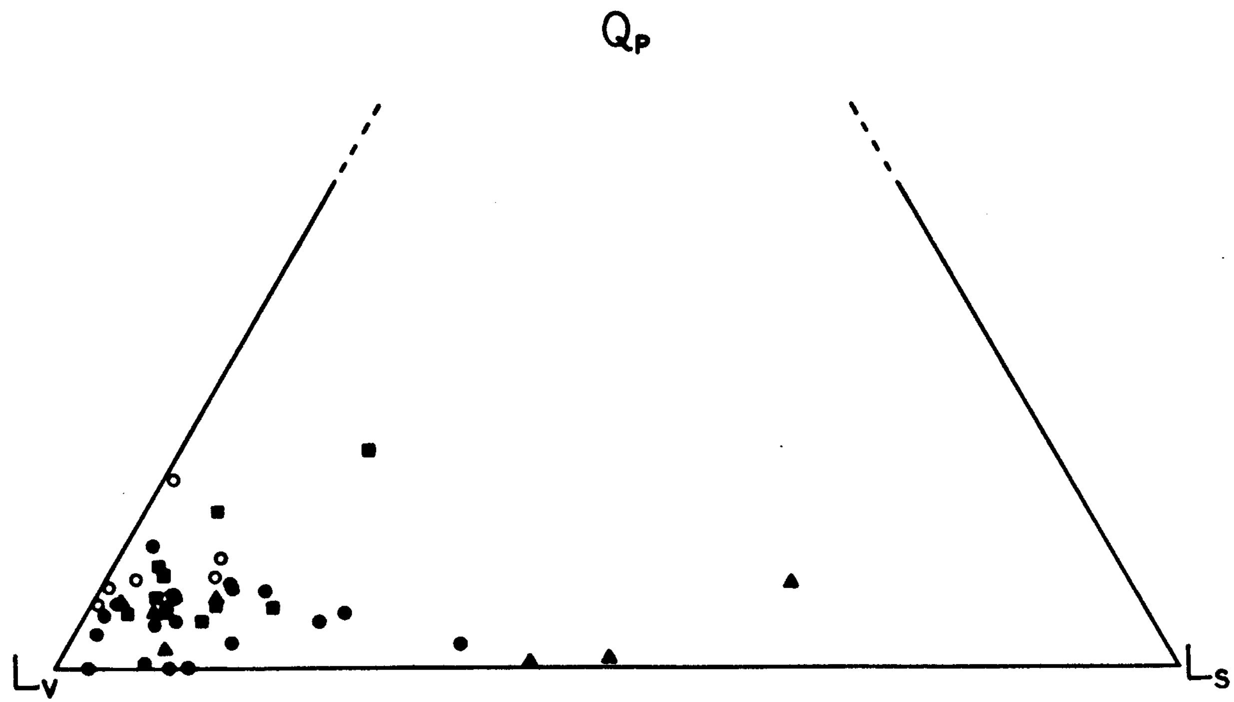

Figure 3-22: $Q_pL_vL_s$ plot of the sandstones from the Bonanza and Sheep Creek Divisions. Solid circles represent samples from the Lower Division of the Bonanza Creek suite, solid triangles the Middle Division, solid squares the Upper Division, and open circles the Sheep Creek samples.

of the depositional basin based solely on composition.

Having identified the main sediment source as a volcanic arc terrane, the next pertinent question is: were these sandstones derived from an active volcanic event or from an older volcanic pile? In terms of regional geology, is the volcanic detritus in the Nutzotin Mountains Sequence from a volcanic arc that was active during sedimentation or is it merely attributable to the erosion of Wrangellia? There are four possible known sources of the volcanic detritus in the flysch sandstones: Paleozoic island arc volcanic rocks from Wrangellia (Tetelna Formation), rift-type basalts from Wrangellia (the Nikolai Greenstone), Paleozoic andesites and basalts from the Yukon-Tanana Terrane, and a volcanic arc active during flysch deposition. Paleocurrent data indicating a northward transport direction argue strongly against a northern provenance and thereby eliminate the Yukon-Tanana as a likely source for the volcanic sandstones. The Nikolai Greenstone consists largely of subaerial amygdaloidal basalt flows and equivalent submarine flows, and the Tetelna Volcanics of porphyritic and amygdaloidal basalt and andesite flows (Richter, 1976). By their positions south of the flysch belt and their lithologies, both formations are possible candidates for the origin of the volcanic detritus in the flysch. Because the Nikolai Greenstone lacks any silicic volcanics (MacKevett, 1970) and the variety of volcanic textures observed in the flysch rocks, the Tetelna Formation, which possesses these characteristics, is the more likely sediment source of the two.

However, the overwhelming proportion of volcanic detritus to other framework grains and the near absence of other Wrangellian lithologies (limestone, chert, plutonic rock) together suggest that Wrangellian basement was not the main contributor of detritus. The presence of beta-quartz with well-preserved resorption cavities lends further support to the notion that the sediment was derived from an active volcanic source.

The feldspathic sandstones from the Upper Division along Bonanza Creek (samples B10A and B10B) may be explained in one of two ways: 1) they may be attributed to a short-lived change in the depositional system such that the sediment was derived from a local volcanic source within, but compositionally different from the main volcanic terrane, or 2) they may have been transported by the original depositional system but derived from a magmatic stage or event in the main volcanic source that is compositionally different than the bulk of the volcanic activity. In support of the first hypothesis, one might turn to recent volcanic arcs (such as the New Hebrides); there, andesitic and basaltic volcanic piles of the same age range are adjacent to each other and are most likely shedding significantly different types of detritus into the depositional system. Sample B8A, which is stratigraphically higher in the section than the two feldspathic sandstones in question, is compositionally similar to the rest of the sandstones. This implies that the source of the feldspathic sandstones (whatever that may have been) was a minor contributor of sediment on the scale of the whole flysch sequence. However, because these feldspathic sandstones are at the top of the Nutzotin Mountains Sequence, their unusual composition may be related to the onset of Chisana Formation volcanism (*sensu stricto*).

CONCLUSIONS

Based on the composition of the sandstones and on petrographic observations I propose that the flysch was derived from an active volcanic arc proximal to the depositional basin. Additionally, since the volcanic textures present in the sandstones are similar to those of the Chisana Formation volcanics overlying the Nutzotin Mountains Sequence (see Richter, 1976), these volcanic clasts are probably, in a very broad sense, Chisana Formation equivalents. (The regional significance of this is discussed in the next chapter.) The presence of beta quartz in the sandstones also indicates that the volcanism was, in part, silicic.

Establishing that volcanism was occurring at least during the Late Jurassic-Early Cretaceous places a lower age limit (albeit a loosely constrained one) on this period of volcanism. Based on the absence of tuffs in the older sections of the Nutzotin Mountains Sequence, Berg et al (1972) placed the main bulk of volcanic activity in post-Valanginian time. The oldest sandstones sampled from the Bonanza Creek section, however, are Late Kimmeridgian in age (Richter and Jones, 1973), and the volcanic detritus in these sandstones was derived from an active source. The "Chisana volcanic terrane" was therefore active from at least the latest Kimmeridgian to the middle Cretaceous. This volcanic terrane was not as "short-lived" as Nokleberg et al (1984) contend.

CHAPTER IV

DISCUSSION AND CONCLUSIONS

DEPOSITIONAL SYSTEM

Constructing a reasonable model for the geometry of the depositional system of the Nutzotin Mountains Sequence based on this work and previous reconnaissance mapping is tenuous. To confidently place the two sections examined in this study into a coherent facies model, the stratigraphic positions of the two sections in relation to each other must be known. In the absence of this stratigraphic (and structural) control, we may only entertain a variety of models (based on different assumptions) that are still geologically practical and that include the known information.

Assuming that the two sections of this study are of the same age range, two depositional geometries are possible: 1) a prograding fan system and 2) a regressing fan system. In both cases, the rocks of the Sheep Creek section would represent the distal equivalents of the Bonanza Creek section (Figure 4-1a-b). A deepening- and fining-upward sequence in the stratigraphic column is predicted by the regressing fan model. However, a coarsening- and perhaps shallowing-upward trend is observed in the Bonanza Creek section and this is more compatible with a prograding fan system. The Cretaceous shallow marine to littoral rocks reported by Berg _et al_ (1972) to be the top of the Nutzotin Mountains Sequence in the Nabesna area may also be a part of this shallowing- and coarsening-upward trend in the Nutzotin Mountains Sequence.

On the other hand, if the Sheep Creek section is Jurassic in age

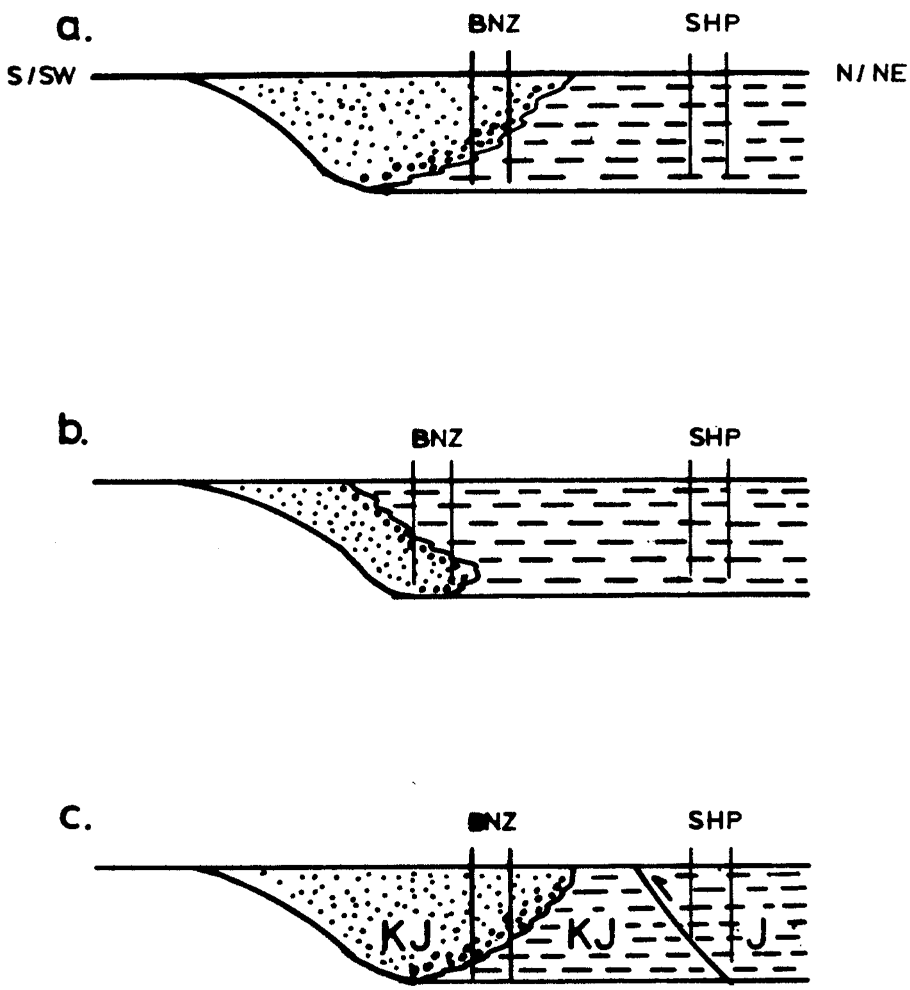

Figure 4-1: Profiles of a) a prograding fan system in which the Bonanza Creek and Sheep Creek sections are the same age, b) a regressing fan system in which the sections are the same age, and c) a Jurassic-Cretaceous prograding fan system with older basin plain sediments thrust over the younger.

as Richter and Jones (1973) suggest and older than the Bonanza Creek section (previously discussed), then post-depositional faulting must enter the model. For example, a thrust fault through the section may emplace the Jurassic(?) rocks of the Sheep Creek section over younger flysch rocks (Figure 4-1c). A thrust fault with a southward sense of motion has been mapped, in fact, in the Nabesna A-2 quadrangle (Richter, 1976). The fault is there believed to cut through rocks of the same age; namely, the Late Jurassic fine-grained graded turbidites that underlie the Jurassic-Cretaceous section along Bonanza Creek.

THE NUTZOTIN MOUNTAINS SEQUENCE/DEZADEASH LINK AND DISPLACEMENT ON THE DENALI FAULT

The facies associations, paleocurrent data and sandstone compositions found in the Nutzotin Mountains Sequence in this study are consistent with Eisbacher's (1976) speculations. The Nutzotin Mountains Sequence does contain a proximal flysch facies and it yields a paleocurrent direction towards the north +/- 30 degrees. Removing 300-400 kilometers of dextral strike-slip, the two flysch sequences combine to form one sequence with a reasonable succession of facies and a consistent paleocurrent direction. The two sequences are also of like ages.

Moreover, the sandstone compositions from both flysch belts compare very well (Figure 4-2). Eisbacher (1976) did not report whether feldspar phenocrysts were counted as "feldspar" (i.e., as in the Gazzi-Dickinson method of point-counting) or simply as volcanic clasts. If the feldspars phenocrysts were counted as volcanic clasts, then the Dezadeash sandstones are indeed very similar in composition to the Bonanza Creek suite of sandstones from the Nutzotin Mountains

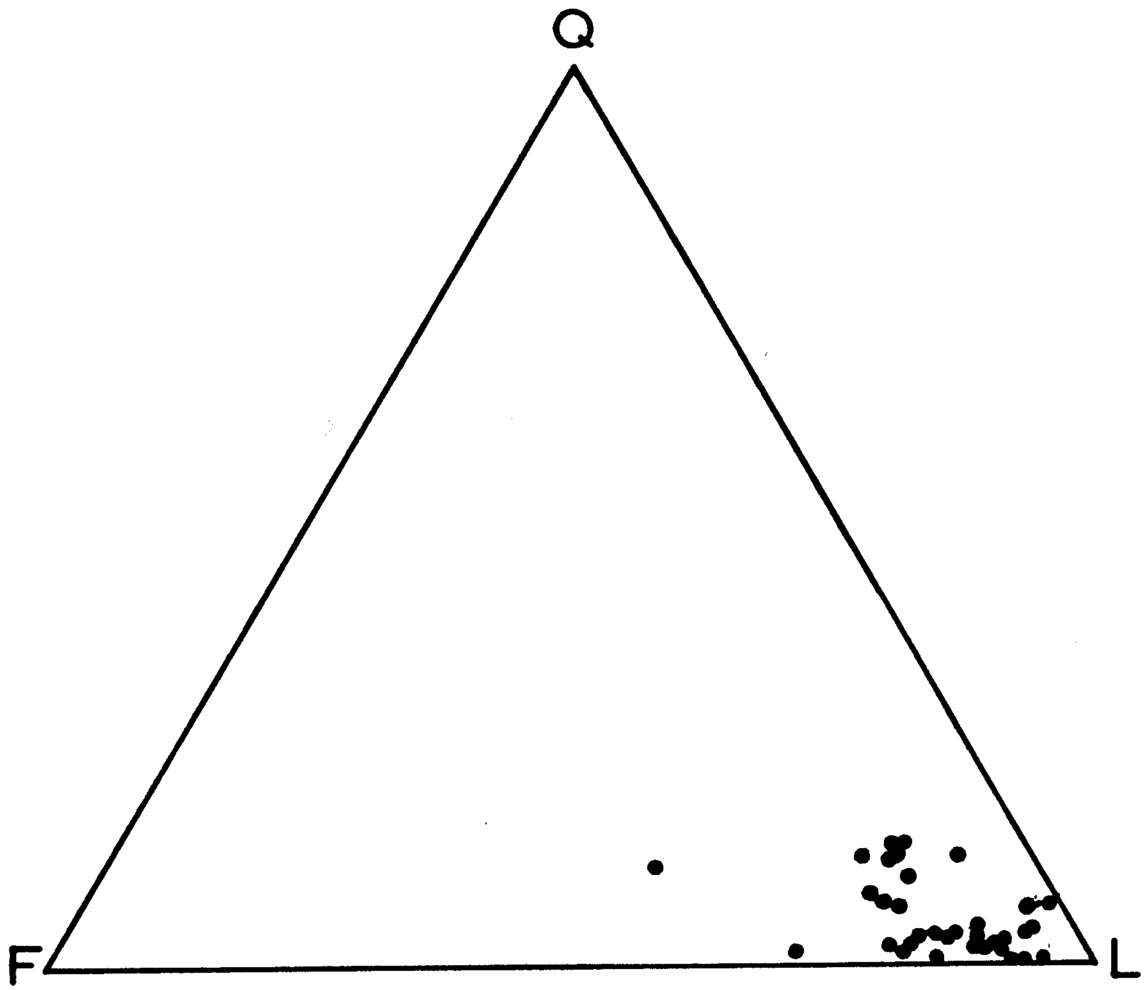

Figure 4-2: QFL plot of sandstones from the Dezadeash Group, Yukon. (Eisbacher, 1976)

Sequence. If the feldspars phenocrysts were counted as feldspars, then the Dezadeash sandstones may be poorer in feldspar-bearing volcanic clasts than are the Nutzotin Mountains Sequence sandstones. Both suites of sandstones are lithic wackes, but the Dezadeash contains a greater amount of sedimentary clasts (26%) than do the sandstones from the Nutzotin Mountains Sequence (5-10%). Because no description of the volcanic clasts in the Dezadeash sandstones is available, it is not clear whether these are Wrangellian basement in nature or attributable to active volcanism. Eisbacher (pers.comm., 1984) favors the former idea.

Mass flow conglomerates have been observed in the Dezadeash Group (Eisbacher, 1976). Unlike the conglomerates found along Bonanza Creek in the Nutzotin Mountains Sequence, these conglomerates consists of rounded to angular cobbles and boulders in a sandy matrix. Rounded clasts of chlorite schist, limestone, granitic rocks and angular clasts of mafic/intermediate volcanic rock were reported in these conglomerates. Eisbacher (1976) argues that the angular volcanic clasts are from contemporaneous Chisana Formation volcanism and that the rounded clasts represent well-transported basement lithologies. These conglomerates appear to be similar to conglomerates observed by this author in the Sheep Creek study area. The stream bed of Camp Creek (see Figure 2-1) is lined with meter size boulders of sandy matrix cobble conglomerate; unfortunately, the source of these loose boulders was never found but their occurrence was restricted to this one stream bed, suggesting that the outcrop was on a nearby peak. (A conglomerate body was not mapped in this area by Richter and Jones (1973).) Lithologies present in the conglomerate include fine-grained limestone, black phyllitic rock, green porphyritic andesite(?), and graywacke.

These conglomerates are very interesting because they indicate a provenance much different than that suggested by the sandstones. The granite clasts in the Dezadeash indicate either a continental type source such as the Alexander or Yukon-Tanana Terrane, and the metamorphic clasts (chlorite schists) strongly indicate the Yukon-Tanana Terrane, or perhaps Wrangellian basement. The absence of quartzo-feldspathic schists, lithologies more typical of the Yukon-Tanana Terrane, tends to suggests that these conglomerate clasts were not derived from this terrane. Chlorite schists have not been reported in Wrangellia, either; the only schistose rocks there are coarse grained quartzo-feldspathic schists. The granitic clasts have a variety of possible source terranes: 1) Paleozoic granitic plutons of the Alexander Terrane (see Plate I), 2) Paleozoic monzonites and granites from the far southeastern edge of Wrangellia (see MacKevett, 1978), and 3) Jurassic-Triassic diorites and granodiorites from the northwestern edge of Wrangellia (see Richter, 1976). The Tanana Upland can probably be eliminated as the source for the granitic detritus because it lacks pre-Jurassic-Cretaceous plutons (at least in this region of the terrane). The limestone detritus was most likely derived from the Triassic carbonate sequence of Wrangellia; limestones in the Yukon-Tanana have been totally recrystallized, probably in the earliest Jurassic (Cushing, pers.comm.). Granitic and metamorphic detritus may also have been derived from terranes that were originally adjacent to the flysch basin but have since been removed from proximity to Wrangellia and the Nutzotin Mountains Sequence by strike-slip motion. This would include, for example, the Taku Terrane (see Jones et al, 1983).

The only conglomerates that suggest the Yukon-Tanana as a source are those reported in reconnaissance work in the Nutzotin Mountains Sequence (Berg et al, 1972). These are the conglomerates containing quartzite and plutonic clasts (located along the Tetlin River, about 3-4 miles southwest of the Denali Fault (Richter, pers.comm., 1984)), the imbrication of which indicates a southward transport direction. This type of detritus suggests that the flysch was in contact with autochthonous North America at some point during sedimentation. Whether it was in contact with the Yukon-Tanana or with some other portion of North America prior to strike-slip displacement is not known.

Limestone blocks are present in both the Nutzotin Mountains Sequence and the Dezadeash Group. The blocks reported in the Dezadeash are slabs up to 5 m in their longest dimension and they occur in zones of slumped turbidite beds and conglomerate within the center of the Dezadeash belt (Eisbacher, 1976). The blocks in the Dezadeash lie within a late Jurassic-early Cretaceous section (Eisbacher, 1976). Triassic-Jurassic(?) limestone blocks within conglomerates of Late Jurassic age are found along the southern margin of the Nutzotin Mountains Sequence belt (Nabesna C-5 quadrangle) (Richter and Schmoll, 1973). No description of the conglomerates is available.

It is not clear whether the conglomerates bearing the limestone blocks are fault-related (for example, olistostromes brought up by thrust faulting or blocks eroded from a high-angle fault scarp) or simply the result of the incision into and the erosion of Wrangellian basement by muddy debris flows (a likely origin for those described in the Bonanza Creek section of this study). Fault-related conglomerates are absent in the Late Jurassic-Early Cretaceous rocks of the Nutzotin Mountains Sequence but are present in flysch of that age in the Dezadeash. If these blocks are indeed fault-related, and if the two flysch belts did indeed once form a single depositional basin, then it can be inferred that basin-margin or intrabasinal faulting occurred at times through a substantial portion of the history of flysch deposition.

Further support for the Nutzotin Mountains Sequence/Dezadeash link and the displacement estimate of 300-400 km comes from other regional offset markers. The Maclaren metamorphic belt and the East Sustina Batholith in the central Alaska Range are linked to the Kluane Schist and the Ruby Range Batholith of the Yukon (Figure 1-1). Nokleberg et al (1984) cite the following evidence from these units in support of their correlation: 1) both the East Susitna and Ruby Range batholiths consist of metamorphosed gabbro, granodiorite, and quartz diorite, 2) both possess foliations parallel to those in the Maclaren and Kluane Schist belts, 3) both the Maclaren Metamorphic Belt and the Kluane Schist are believed to be meta-flysch, 4) the Maclaren and Kluane belts have similar metamorphic cooling ages (28.5-67.9 my and 50-70 m.y. as determined by K/Ar on biotites), 5) both metamorphic belts grade from lower greenschist facies to amphibolite facies toward the adjacent batholiths. Finally, the East Susitna Batholith/Maclaren Metamorphic Belt complex is bounded on its southern margin by the Broxson Gulch Thrust, and the Ruby Range Batholith/Kluane Schist complex is bounded on its southern margin by what is assumed by Eisbacher (1976) and Nokleberg et al (1984) to be a thrust fault. These features and the flysch belts match-up reasonably well after removing 300-400 kilometers of displacement on the Denali Fault.

Several problems still surround the Nutzotin Mountains Sequence/Dezadeash link. Proximal facies for both the southern and northern margins of the composite flysch basin would be expected as would at least two opposing paleocurrent directions. Neither a northern proximal facies nor south/southeast directed paleocurrent directions are observed in the Dezadeash flysch. Eisbacher (1976) contends that the Kluane Schist is the metamorphosed equivalent of the Dezadeash and that these missing features lie within this metamorphosed terrane. This correlation was based on chemical similarities between the two units, on the uniqueness of the schist unit in the Yukon, and the simple nearness of the two belts (Eisbacher, 1976). The contact between the Dezadeash Group and the Kluane Schist is believed to be in part a steep metamorphic gradient or reverse fault and in part a continuation of the Denali Fault system (Eisbacher, pers.comm., 1984). (The contact is largely obscured by Quaternary glacial deposits.) It is just as likely that the contact is a strike-slip fault.

Because the Nutzotin Mountains Sequence is bounded by strike-slip faults (i.e., the Denali and Totschunda Faults) and the Dezadeash is also possibly bounded by strike-slip faults (the Denali Fault and the "Shakwak Lineament"), rotation of the flysch terranes since the late Mesozoic is possible. Rotation of blocks within the fault bounded region would reorient planar and linear features. More specifically, how could possible block rotation have affected the validity of the paleocurrent indicators collected in this study and is it reasonable to correlate these paleocurrent indicators with those from the Dezadeash?

Block rotations have been documented by utilizing paleomagnetism in strike-slip systems such as the Dead Sea (Ron _et al_, 1984). In this system, the mean paleomagnetic vectors for blocks between strike-slip faults differ from the expected field direction by +/- 22 to 35 degrees, indicating clockwise and counterclockwise rotations of these blocks (Ron et al, 1984). Wells and Coe (1980) have also demonstrated significant amounts of rotation of blocks bounded by strike-slip faults in southwestern Washington.

Because the Denali and Totschunda Faults are right-lateral strike-slip faults, an overall clockwise sense of rotation of the flysch belt would be expected. Blocks within the fault bounded region would also be expected to rotate in a clockwise sense. Cross-cutting, conjugate sets of strike-slip faults have not been mapped in the Nutzotin Mountains Sequence, and the amount of displacement on the Totschunda Fault is unknown. In the absence of structural and paleomagnetic data, it is impossible to judge how block rotation, if any, has affected the flysch belt. A theoretically simple test, however, would be to compare paleocurrent directions from a transect across the Nutzotin Mountains Sequence; significant and systematic variations in the mean directions not explicable in terms of the depositional system may reflect block rotations. It would also be valuable to compare paleocurrent data from the flysch bounded by the strike-slip faults to those from flysch that outcrops outside the strike-slip system, such as in the Nabesna C-5 quadrangle.

MODELS FOR THE ACCRETION OF WRANGELLIA

Because it is in sedimentary contact with the Wrangellia Terrane and because it contains detritus from this terrane, the origin of the Nutzotin Mountains Sequence is undoubtedly linked to the tectonic history of the Wrangellia Terrane. Some of the recent models for the accretion of Wrangellia to North America are based on structural, stratigraphic or metamorphic data (Table V). Much of the current thinking on this accretion problem though, is derived from interpretations of paleomagnetic data. None of the models (except the earliest by Berg et al, 1972) include geologic information from the Nutzotin Mountains Sequence to constrain plate reconstructions based on geophysical or other geologic data.

Two schools of thinking exist among the most recent reconstructions of Mesozoic terrane configurations. One school favors the idea that the "emplacement" of Wrangellia (and its possibly associated terranes) into its present position occured via thousands of kilometers of dextral strike-slip after its collision with North America. The other school will allow some amount of right lateral displacement of the terrane (about 400 km), but does not recognize a significant amount of post-collisional displacement; that is, they do not make a distinction between the collision of Wrangellia and North America and the terrane's "arrival" into its present position.

In an early model (Berg et al, 1972), the Nutzotin Mountains Sequence was interpreted to be a "basinal sea", adjacent to an island arc, both of which are related to northward subduction under Wrangellia (Figure 4-3a). The function of the Nutzotin Mountains Sequence as a sedimentary link between the Wrangellia and Yukon-Tanana Terranes was proposed on the basis of the sedimentary contact with Wrangellia and the inferred sedimentary contact with the Yukon-Tanana. These authors suggested that subsidence of the flysch basin was initiated by southward migration of a volcanic arc. Finally, volcanic detritus in the Nutzotin Mountains Sequence was interpreted to have been derived

Table V: Models for the accretion/collision of the Wrangellia Terrane

No.	Nature of collision	Age of collision/ age of arrival	Type of evidence	Reference
1	subduction of oceanic crust under Wrangellia	late Cretaceous	regional strat.: Eastern Alaska Range	Berg et al (1972)
2	subduction of Wrangellia under North America	middle Cretaceous	structural/metamorphic data: McKinley Strand, Denali Fault	Csejtey et al (1982)
3	Molucca Sea type	middle Cretaceous	struct., strat., meta. data: Alaska Range	Nokleberg et al (in prep.)
4	subduction of oceanic crust under Wrangellia	middle Cretaceous/ Tertiary	structural data: Border Ranges Fault	Pavlis (1982)
5	unknown	very late Cretaceous	Paleomagnetic data: Cantwell Fm. (Tertiary)	Hillhouse and Gromme (1982)
6	unknown	middle Cretaceous	Paleomagnetic data: Nikolai Greenstone (Triassic)	Hillhouse (1984)
7	"docking"	early Cretaceous/ Tertiary	K/Ar reset ages: Nikolai Greenstone	Silberman et al (1979)
8	unknown	late Cretaceous/ early Tertiary	Paleomagnetic data: southern, central, eastern AK and B.C.	Stone et al (1982)
9	unknown	late Cretaceous/ early Tertiary	Paleomagnetic data: MacColl Ridge Fm. (Maastrichtian)	Panuska (1983)
10	unknown	late Cretaceous/ early Tertiary	Paleomagnetic data: SW Alaska (late Cretaceous)	Globerman (1983)

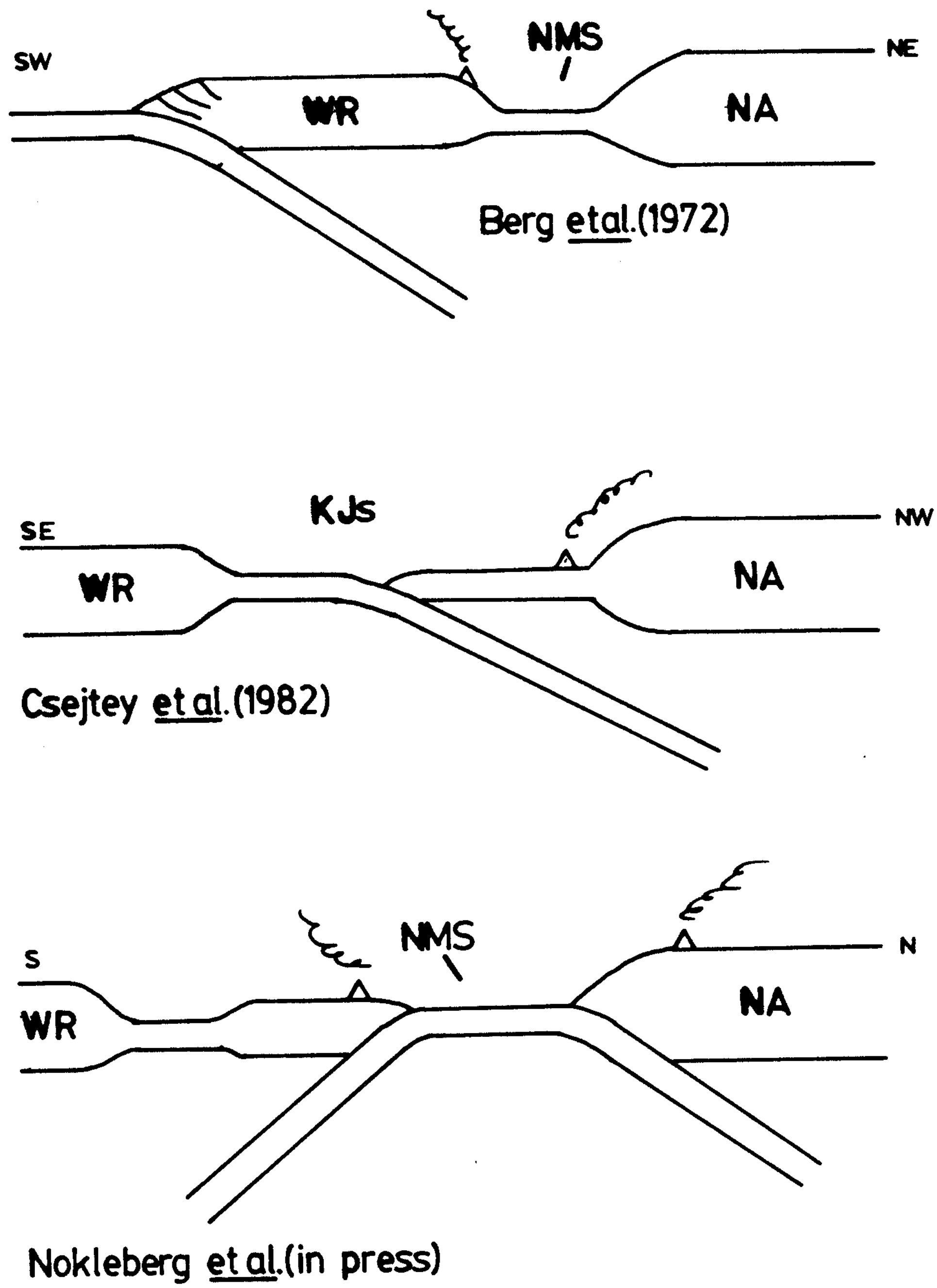

Figure 4-3: Cartoons of previous tectonic models for the origin of the Nutzotin Mountains Sequence and the accretion of Wrangellia.

from the uplift and erosion of Wrangellia. The contribution of volcanic detritus from an active arc was considered minimal.

The Nutzotin Mountains Sequence and the overlying Chisana Formation volcanics are grouped with other late Mesozoic flysch and volcanic assemblages of the Cordillera into the Gravina-Nutzotin Belt (Berg et al, 1972). The belt extends from the Gravina Island area to the Nutzotin Mountains and shows marked consistency in the ages and lithologic types of the plutons and sedimentary rocks. Because the belt has been interpreted to be an overlap assemblage between the Wrangellia and Alexander Terranes, the age of the Gravina-Nutzotin Belt is often cited as the minimum age of accretion of the two terranes (see, for example, Coney et al (1980), Yorath and Chase (1981)).

Csejtey et al (1982) cite the continuity of metamorphic isograds across the McKinley Strand of the Denali Fault as evidence for small amounts of Cenozoic displacement on the fault system. The authors infer from their data set that most Mesozoic faulting in the central and western portions of the Denali Fault was thrust faulting and that it was southeast over northwest in nature. Based on this extrapolation of the data, a Mesozoic plate geometry for central Alaska in which oceanic crust is subducted under stable North America in a northwestward dipping subduction zone (Figure 4-3b) was proposed. The very southern edge of the continental margin is thought to have been a right-lateral transform fault. The collision of Wrangellia and other terranes (the "Talkeetna Superterrane") with North America is postulated to have occured in the middle Cretaceous. A strike-slip origin for the Nutzotin Mountains Sequence is implicit in this model although the nature of it is not directly approached by the authors.

Nokleberg et al (1984) interpret the Denali Fault to be an entirely post-accretion structure, not a transform fault active during accretion. In this model, Wrangellia and other terranes collided with North America in the middle to Late Cretaceous. A Molucca Sea type plate geometry (namely, oppositely dipping subduction zones) is proposed (Figure 4-3c). The Nutzotin Mountains Sequence flysch is thought to have been deposited and accreted in the trend of a Jurassic-Cretaceous southward dipping subduction zone, also associated with a short-lived volcanic arc. The quartzite clasts in the conglomerates of the Nutzotin Mountains Sequence are cited as evidence for the encroachment of Wrangellia toward North America during the middle Cretaceous. This model is based largely on a compilation of structural and stratigraphic data from the central and eastern portions of the Alaska Range.

Looking at the age of motion on the Border Ranges Fault (see Plate I), Pavlis (1982) hypothesized that the "Talkeetna Superterrane" collided with North America in the middle Cretaceous, and subsequently experienced several hundreds of kilometers of dextral displacement. In this model, three elements of a typical volcanic arc are recognized in the regional geology: a subduction complex (the Valdez Group), a volcanic arc (the Gravina-Nutzotin Belt, including the Chisana Formation), and a closing ocean basin (the Gravina-Nutzotin Belt, including the Nutzotin Mountains Sequence). To account for the decreasing degrees of deformation and metamorphism of the Gravina-Nutzotin Belt from British Columbia up to central Alaska, the middle Cretaceous collision is postulated to have been oblique and along an irregular North American margin.

The tectonic interpretations for southern Alaska that are based on paleomagnetic data are generally concerned with constraining the times of "arrival" of the allochthonous terranes by specifying their change in latitude with time and not with identifying the types of collisions involved in the accretion events. The paleomagnetic data that favor minimal post-collisional displacement of Wrangellia and the other terranes place Wrangellia at roughly 15 or 13.9 degrees north in the Triassic (Hillhouse, 1977; Hillhouse, 1984) and the Alexander Terrane at 23 degrees north in the Triassic (Hillhouse and Gromme, 1980). (data from the later Mesozoic are unavailable from these workers.) The interpretation of these data is hampered by polar ambiguity. Hillhouse (1984) cites the deformation of the Late Jurassic-Early Cretaceous flysch (i.e., the Nutzotin Mountains Sequence, the Dezadeash, and other flysch belts in central Alaska) as evidence for a post middle Cretaceous Wrangellia/North America collision. Paleomagnetic work on the Paleocene Cantwell Formation in the central Alaska Range suggests that the Cantwell Formation has undergone a maximum of 550 kilometers of northward displacement relative to the craton since the Paleocene (Hillhouse and Gromme, 1982). Arguing that the Cantwell Formation volcanics are probably cogenetic with early Tertiary plutons of the southern Alaska allochthonous terranes, these authors further suggest that large amounts of northward motion of the allochthonous terranes ended before the early Tertiary.

Other paleomagnetic work in the Wrangellia, Peninsula, and Alexander Terranes suggests large amounts of post-collisional displacement of the terranes. Stone et al (1982) concluded that 1) Wrangellia moved southward in the Jurassic, 2) joined with the Alexander and Peninsula Terranes to form a composite terrane sometime in the Early to Middle Jurassic, and 3) this "superterrane" subsequently moved northward from then until the present. Panuska (1983) determined a Late Cretceous paleolatitude of 32 degrees north for the MacColl Ridge Formation clastics of Wrangellia and suggested that the terrane "arrived" at its present position in the Tertiary. According to these interpretations of the paleomagnetic data, Wrangellia and the other southern Alaska terranes collided with North America at low latitudes in the very latest Cretaceous and "docked" at the southern margin of Alaska sometime in the early Tertiary.

It is possible that the origin of the Nutzotin Mountains Sequence is related to the accretion of the Wrangellia and Alexander Terranes. That the Alexander and Wrangellia Terranes were joined by the Late Jurassic is supported by field evidence from Wrangellia. Coarse clastics from central Wrangellia (the Middle-Late Jurassic Root Glacier Formation) are reported to have a west/northwest paleocurrent direction; Panuska (1984) linked the origin of these sediments to uplift caused by the "amalgamation" of the Alexander Terrane to Wrangellia. Yorath and Chase (1981) cite a Middle to Late Jurassic suite of plutons that intrude both the Alexander and Wrangellia Terranes on Queen Charlotte Island as evidence for a Late Jurassic age of amalgamation.

Further support for large amounts of Mesozoic and Tertiary displacement of the allochthonous terranes is derived from fossil evidence. For example, Early Triassic ammonites found in the south-central Alaska Chulitna Terrane are similar to those found in Triassic sequences located thousands of kilometers to the south in North America; the North America location was at a latitude of 10 degrees N/S during the Triassic (Nichols and Silberling, 1979). Moreover, the acicular nature of the ammonite-bearing limestones suggests a tropical climate of deposition (Nichols and Silberling, 1979).

The conflicting interpretations of the paleomagnetic data do not resolve the question whether Wrangellia has moved hundreds or thousands of kilometers since its collision with North America and therefore does not resolve the question, is the Nutzotin Mountains Sequence itself allochthonous?

THE ORIGIN OF THE NUTZOTIN MOUNTAINS SEQUENCE

The composition of sandstones from the Nutzotin Mountains Sequence and the Dezadeash Group indicate that the flysch was most likely derived from an active island arc, and the paleocurrent data indicate that the basin was primarily fed from one direction, namely from the southwest. That the flysch contains mere traces of continental-type detritus implies either that 1) the depositional basin and the arc were isolated from the margin of North America, as in an intraoceanic arc, or 2) the continental margin was subsiding and buried by sediments. The flysch may have been deposited in an intra-arc or fore-arc basin. Quartzite conglomerate clasts are present in small quantities in the Nutzotin Mountains Sequence according to Berg et al (1972). Normal or strike-slip faulting associated with basin subsidence and deposition is indicated by Triassic(?) limestone blocks within Jurassic and Jurassic-Cretaceous sections of the flysch (restricted to the southern and central regions of the belt). The presence of Chisana Formation volcanics overlying both the flysch and Wrangellia suggests that the arc was built either on or adjacent to Wrangellia.

That the limestone blocks within the Nutzotin Mountains Sequence and the Dezadeash are fault-related is speculative, but a fault debris origin for the conglomerates is at least compatible with the notion that the basin was extensional or strike-slip in nature. The quartzite clasts in the Nutzotin Mountains Sequence, however, call into question this simple interpretation. The implication of these clasts is that the continental margin was a part of the depositional system at some time during flysch deposition. On the basis of a report of one outcrop of quartzite-bearing conglomerate, it is impossible to speculate on how significant the continental margin was as a source. Only through further mapping of the flysch belts may this question be answered.

REGIONAL SIGNIFICANCE OF THE NUTZOTIN MOUNTAINS SEQUENCE

In developing a model for the accretion of the Wrangellia Terrane and the origin of the Nutzotin Mountains Sequence that incorporates the known information (as listed above), it is useful to look at the stratigraphy of Wrangellia and compare the events of this terrane to that of the flysch and volcanic belt (Figure 4-4), and to consider the deformation of the Nutzotin Mountains Sequence.

Comparison of Northern and Central Wrangellia Stratigraphies

From the stratigraphy of Wrangellia, it is reasonable to hypothesize that Wrangellia represents an oceanic plateau underlain by an island arc complex. The association of oceanic plateau basalts (the Nikolai Greenstone) over island arc rocks is unusual; it could be that the contact between the two formations is structural (Kidd, pers.comm., 1984). Wrangellia appears to have been a gradually subsiding oceanic plateau during the Mesozoic. This is suggested by the conformable relationship between the Nikolai Greenstone, the overlying Triassic transgressive carbonate sequence, and the deepening-upward Jurassic

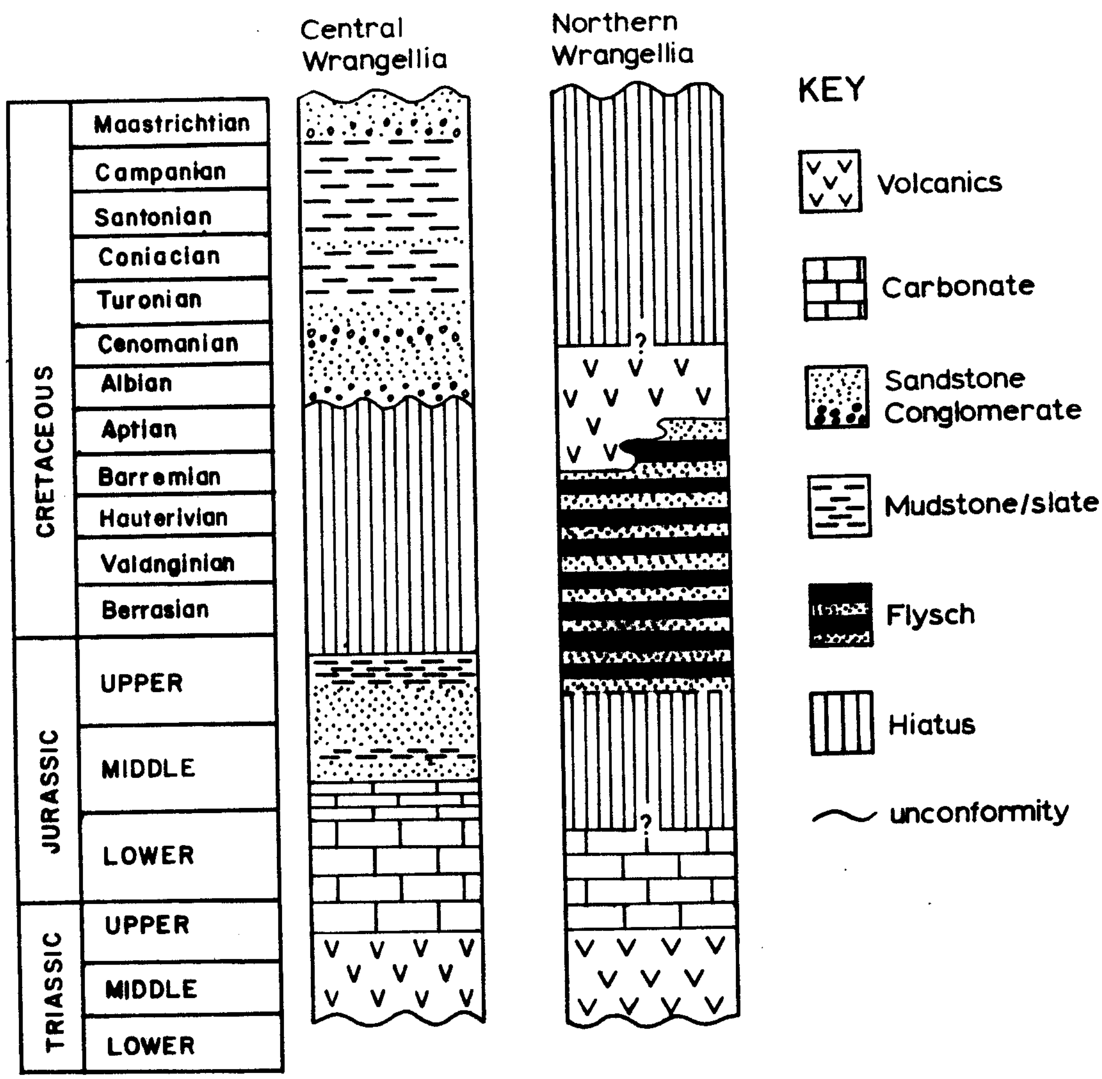

Figure 4-4: Comparison of Mesozoic stratigraphies from the northern and central/southern portions of Wrangellia (compiled from Jones and MacKevett, 1969; MacKevett, 1969; MacKevett, 1978; Richter, 1976).

clastic sequence.

It is in the Jurassic that the depositional histories of the northern and central/southern portions of Wrangellia diverge. In the northern part of Wrangellia, the Jurassic was a period of nondeposition or erosion. In central Wrangellia, however, clastic sedimentation (shallow marine clastics) continued until the Oxfordian.

In the Late Jurassic to Early Cretaceous, central and southern Wrangellia experienced uplift and erosion (as indicated by the angular unconformity). Northern Wrangellia, however, experienced flysch deposition (Nutzotin Mountains Sequence) and volcanism (Chisana Formation) from the late Kimmeridgian to sometime in the middle part of the Cretaceous, possibly the Late Cenomanian.

The Cretaceous clastics of Wrangellia represent a deepening-upward sequence followed by coarse clastic sedimentation in the Maastrichtian. The older formations of the Cretaceous section and perhaps the youngest formation of the Jurassic section are the only clastics in central and southern Wrangellia with a definite volcanic signature. Perhaps these clastics represent, in part, the central and southern Wrangellia equivalents of the Nutzotin Mountains Sequence. The volcanic character of the Kennicott Formation (Panuska, pers.comm., 1984) may suggest that at least some of the volcanic detritus from the "Chisana volcanic arc" was shed into a depositional basin to the south/southwest. Neither provenance nor paleocurrent data are available from the Cretaceous clastics to test this hypothesis. If the "Chisana volcanic arc" was built on Wrangellia, it is reasonable to expect some volcaniclastic sedimentation on the outboard side of the arc.

Deformation of the Nutzotin Mountains Sequence

The age of deformation of the Nutzotin Mountains Sequence is poorly constrained. Open to isoclinal folding of the flysch and the Chisana Formation occurred sometime after volcanism ceased, but an upper age limit on the deformation is lacking. The Antler Creek pluton appears to cross-cut the northwest trending fold axes; the pluton also lacks a northwest striking foliation that might be expected if it were involved in the folding. However, the age of intrusion for the pluton is believed to be 111±6 m.y. (Richter et al, 1975), older than or the same age as the Chisana Formation. The dikes that intrude the flysch do not appear to have been involved in the folding (see the maps of Richter (1973) and Richter and Schmoll (1975)), but have not been isotopically dated.

Discussion

In the model of Berg et al (1972), the Nutzotin Mountains Sequence, the volcanism represented in the flysch and the Chisana Formation, the Jurassic clastics of Wrangellia, and the Valdez Group (of the Chugach Terrane) represent a backarc basin, arc, forearc basin, and trench respectively. The Nutzotin Mountains Sequence possesses several backarc basin characteristics: 1) it contains volcaniclastic sediments, 2) it is intruded by numerous mafic/intermediate dikes and sills, possibly indicative of limited extension and backarc basin-type magmatism, and 3) it contains evidence of extensional or strike-slip faulting during deposition. The inference that the clastic sequences on Wrangellia are forearc in origin is highly speculative owing to the lack of data from these sequences. Not being far from the down-going slab, forearc regions tend to have low heat flow; that is, low compared to backarc regions. The lack of Jurassic and Cretaceous dikes and sills in the clastics of Wrangellia is at least compatible with the notion that these are forearc in origin. Moreover, these clastics are in part volcanogenic. The Valdez Group consists of metamorphosed flysch and in other quadrangles it is associated with melange. The Valdez Group is believed to be largely late Cretaceous in age, but it may contain older, possibly late Jurassic sections (MacKevett, 1978).

There are several problems in this interpretation. First, the age of the Valdez Group (Late Cretaceous) does not correspond well to the age of the Nutzotin Mountains Sequence. Second, the model fails to satisfactorily account for the Jurassic-Cretaceous angular unconformity in Wrangellia. This "orogenic event" may be attributed to activity in the arc or the subduction complex. It is also possible that the unconformity is related to the amalgamation of the Alexander and Wrangellia Terranes (discussed later). Third, the age of the dikes intruding the flysch is not known. Finally, a sedimentary link with North America is implied in this model, and as previously discussed, this assumption is weak.

In the light of what is known about the latitude of Wrangellia relative to North America during the Mesozoic and the composition of the Nutzotin Mountains Sequence, it is more likely that the Nutzotin Mountains Sequence represents a depositional basin unrelated to the subduction events associated with the Valdez Group melange in southern Wrangellia, and only partially (if at all) related to the continental margin. The Wrangellia accretion scenario proposed by Nilsen and Zuffa (1982), for example, requires that the volcanic arc and sedimentary basin associated with Late Jurassic-Early Cretaceous subduction under

Wrangellia ceased to be active in the Late Cretaceous and that Wrangellia "arrived" in the early Tertiary bearing the inactive arc terrane. The model of Nokleberg et al (1984) might be improved by eliminating the sedimentary link between North America and Wrangellia and regarding the Nutzotin Mountains Sequence as an intra-arc basin.

Speculating on plate geometries (i.e., northward- or southward-dipping subduction zone under Wrangellia during the Late Jurassic-Early Cretaceous) is impossible owing to the complications imposed by strike-slip faulting during the Late Cretaceous and Tertiary. If, as seems reasonable, Wrangellia converged on North America at latitudes much farther south than its present location, then subsequent strike-slip removed large-scale clues (e.g., plutons, volcanics and sediments) as to the sites of subduction zones.

Although we cannot speculate on plate geometries, we can say that the net northward migration of Wrangellia during the Mesozoic requires a subduction zone between Wrangellia and North America sometime between the middle Mesozoic and the time of collision. For instance, in the Middle Jurassic, Wrangellia is estimated to be at a latitude of 26 degrees North of the paleoequator (see Stone et al, 1982), and a point on stable North America now opposite Wrangellia to be at roughly 60 degrees North. If Wrangellia moved strictly northward in this time, nearly 3800 km of ocean floor would had to have been consumed. It is impossible to guess the amount of ocean floor that would have been consumed in an east-west convergence with North America. A more reasonable case may be one in which the convergence of Wrangellia and North America was oblique. The models of Pavlis (1982) and Nokleberg et al (1984) for the accretion of Wrangellia both involve a middle Mesozoic subduction zone between Wrangellia and North America, although their proposed plate geometries are different.

Deformation of the flysch is important in that it probably documents the collision of Wrangellia with North America. Folding of the Nutzotin Mountains Sequence (and the Chisana Formation) probably occurred before and during actual collision. The Nutzotin Mountains Sequence would deform more readily than Wrangellia, a relatively rigid block. As Wrangellia approached the continent, then, the flysch deformed by folding. The later parts of the collision would be characterized by more folding in the flysch, and thrust faulting in both the flysch and Wrangellia. The thrust fault mapped in the Nabesna A-2 quadrangle in the Nutzotin Mountains Sequence does seem to have cut through earlier folds. The time of thrust faulting in Wrangellia is not known.

Other Terranes

Allochthonous terranes that lie inboard of Wrangellia (and southwest of the Tintina fault) include the Yukon-Tanana, Tracy Arm, Cache Creek, and Stikine Terranes. Deformation and metamorphic events documented in these terranes provide possible clues to the accretion events of the outboard terranes.

Two regional deformation events are recognized in the Yukon (both the Yukon-Tanana and Stikine Terranes) (Templeman-Kluit, 1974; Templeman-Kluit, 1979): one folding event in the Early Mesozoic (accompanied by metamorphism) and a second event of folding, thrust faulting, and imbrication in the Early Cretaceous. The collision betwen the Stikine Terrane and North America is believed to have begun in the Middle Jurassic and persisted until the end of the Early

Cretaceous (Templeman-Kluit, 1979) (Figure 4-5). It is interesting to speculate on the position of Wrangellia and the Nutzotin Mountains Sequence-Dezadeash flysch basin relative to the Stikine Terrane and North America during this collision.

The Yukon-Tanana in Alaska yields two metamorphic ages (Cushing et al, 1984): a major event in the Late Triassic-Middle Jurassic, and a minor event in the Cretaceous (110 m.y). Folding in the terrane occurred around the Middle Jurassic and thrust faulting after the Middle Jurassic (Foster et al, 1984). A Jurassic age of deformation in the Yukon-Tanana compares well with the initiation of collision of the Stikine Terrane and North America. As Cushing et al (1984) and Foster et al (1984) suggest, the deformations in the Yukon-Tanana may be associated with the accretion events of the other terranes. It is possible that the Cretaceous metamorphism in the Yukon-Tanana is related to the collision of Wrangellia with North America.

Conclusion

The available paleomagnetic, stratigraphic, structural, metamorphic, and age data from Wrangellia, the Late Jurassic-Early Cretaceous flysch, and the other allochthonous terranes allow the following broad statements to be made. As Wrangellia migrated thousands of kilometers northward, subduction under the terrane during the Jurassic-Cretaceous led to the growth of a volcanic arc on top of Wrangellian basement. The Nutzotin Mountains Sequence-Dezadeash basin adjacent to the arc was isolated from the North American continent. As Wrangellia encroached on North America in the mid to Late Cretaceous, the Nutzotin Mountains Sequence deformed by folding and thrust faulting.

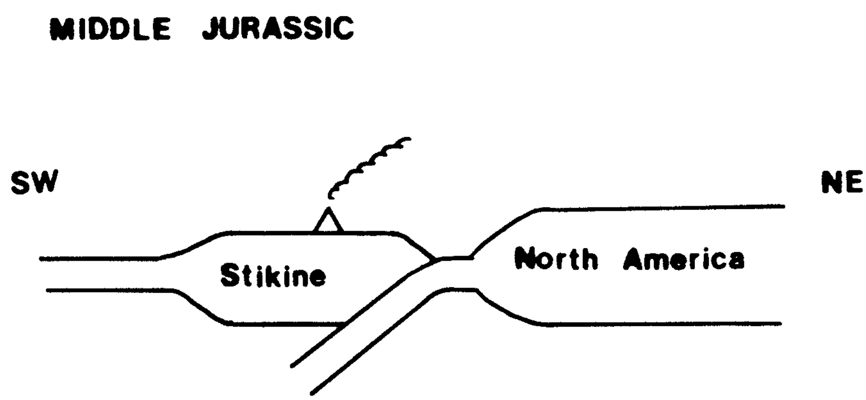

Figure 4-5: Model for the accretion of the Stikine Terrane (Templeman-Kluit, 1979).

Whatever tectonic model is invoked for the origin of the Nutzotin Mountains Sequence and the significance of the flysch in terms of the accretion of Wrangellia, it must account for 1) the strong volcanic signature of the flysch, 2) silicic volcanism synchronous with flysch deposition, and 3) what seems to be a single sediment transport direction. The quartzite clasts within the Nutzotin Mountains Sequence may have significance in terms of the proximity of the continental margin to the depositional basin.

CONCLUSIONS REGARDING THE NUTZOTIN MOUNTAINS SEQUENCE AND OUTSTANDING PROBLEMS

The compositional data acquired in this study demonstrate that the Nutzotin Mountains Sequence was largely derived from an active volcanic arc. Minor provenances include the older rocks of the Wrangellia Terrane and perhaps autochthonous North America. The volcanic source was intermediate/mafic and is proposed to represent the precursor of the Chisana Formation. Paleocurrent data collected in this study indicate a north/northeast directed current direction. The depositional basin was proximal to the source and was dominated by turbidite deposition. Inner and middle fan, and possibly slope facies are represented in the sections along Bonanza Creek and Sheep Creek. An overall coarsening-upward sequence suggests that the flysch examined in this study was deposited on a prograding fan system. The Sheep Creek suite of sandstones are richer in potassium feldspar than are the sandstones from the Bonanza Creek section. This difference suggests that the two suites are distinct petrofacies and are consequently of different ages.

The composition of and stratigraphic relationships in the Nutzotin Mountains Sequence compare well to Eisbacher's (1976) speculations. Based on compositional similarities, the continuity of flysch facies across the two flysch belts, and the consistent paleocurrent directions from the two sequences, the Nutzotin Mountains Sequence and the Dezadeash Formation can reasonably be interpreted as a once continuous flysch basin. Eisbacher's (1976) estimate of 400 km of displacement on the Denali Fault based on the match of these two flysch sequences is therefore strengthened by this work.

The Nutzotin Mountians Sequence was most likely deposited in an intra-arc or backarc basin. Limestone blocks (of Wrangellian basement affinity) found in the flysch may possibly indicate either normal or strike-slip faulting during deposition, suggesting that the depositional basin was extensional to some extent.

The structural geology in the Nutzotin Mountains Sequence and the Dezadeash is poorly known. The monotony of flysch tends to obscure even large-scale structures such as faults. Consequently, the flysch may be more disrupted than is presently believed. In this study, for example, evidence of possible thrust faulting was observed in the Lower Sheep Creek area. The Nutzotin Mountains Sequence and the Dezadeash are believed to possess two orientations of folds. Eisbacher (1976) interprets these to be two generations of folds, and on a sketch map, one set is shown to refold the other. This distinction has not been made in the Nutzotin Mountains Sequence. Mapping the structures in the Nutzotin Mountains Sequence would permit profitable paleomagnetic study of the flysch. In this way it would contribute to the understanding of the evolution of the Nutzotin Mountains Sequence depositional basin and to the accretion of Wrangellia.

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APPENDIX I

Point-Count Data for Sandstones of the Nutzotin Mountains Sequence, Bonanza Creek Section, Chisana, Alaska

Sample	Qp	Qm	Plag	Kspar	Vm	Vsi	Ls	Mica	Pyx,Hblde	Opaque	$CaCO_3$	Matrix	Other
12-BP-81	3	1	206	10	38	0	8	9	1	15	11	236	128
BNZ8A	31	11	142	27	183	9	16	3	0	29	23	205	14
B10A	5	23	189	96	40	NA	1	2	0	15	0	125	2
B10B	14	80	224	62	9	NA	0	0	0	4	1	104	0
B10i	25	4	91	0	393	10	17	4	1	50	27	129	60
B21	9	13	152	8	109	2	13	6	0	82	145	54	129
B30	23	20	85	3	394	2	50	2	3	22	178	90	6
B30A	49	17	296	6	118	15	34	9	17	168	19	263	22
B32	20	8	110	0	169	11	11	13	41	3	156	189	12
B32B1*	2	0	83	10	60	1	9	8	14	50	107	151	21
B33	30	3	85	8	382	6	9	14	101	20	178	190	20
B33B	11	6	105	14	113	18	8	3	5	26	50	110	20
B34B	1	0	89	2	137	0	100	1	9	17	35	109	29
B35	19	0	33	2	260	35	13	2	3	35	43	46	13
B37A	2	0	89	7	107	7	111	11	19	19	33	104	18
B37	16	0	145	13	55	2	120	13	4	31	14	98	9
B38	4	0	88	7	179	2	18	4	6	28	53	161	28
B381	9	5	82	3	130	6	9	3	46	71	69	149	6
B38A	10	8	94	3	105	9	15	2	14	48	73	132	15
B39	12	0	96	5	216	1	21	0	0	13	30	60	69
V2	25	18	73	3	217	23	46	3	0	15	0	96	17
B45	4	0	112	4	125	0	54	5	15	34	66	93	23
B49V	0	1	31	1	296	4	34	4	14	18	23	99	123
B49A	12	11	114	7	169	15	53	1	0	40	16	166	78
19-BP-81	16	17	73	12	175	19	19	1	31	20	36	77	54
20-BP-81	21	22	109	24	183	13	27	0	3	27	6	112	50
21-BP-81	18	20	108	5	163	13	26	2	1	46	17	115	32
22-BP-81	9	15	136	19	142	16	3	3	0	83	0	164	11
23-BP-81	6	15	140	5	151	18	4	1	0	109	3	179	42
B50X	1	1	86	3	301	1	40	4	8	19	27	101	59
B50Z	19	6	98	2	209	12	70	1	0	32	14	126	51
B53	1	0	78	2	165	0	14	3	16	16	1	113	6
B54A	8	0	106	6	234	11	43	5	30	14	12	118	28
B55A	10	1	88	14	184	6	16	12	2	29	2	97	38
MC-19B	29	5	102	16	318	12	28	3	2	13	8	175	17
MB-4	1	5	27	1	263	22	8	1	6	13	1	129	25
MF1	12	2	89	12	490	22	38	17	8	37	7	103	41
MG-6A	29	23	55	0	181	15	6	6	1	11	3	40	NA

APPENDIX II

Point-Count Data for Sandstones of the Nutzotin Mountains Sequence, Sheep Creek Section, Alaska

Sample	Qp	Qm	Plag	Kspar	Vm	Vsi	Ls	Pyx, hblde	Opaque	$CaCO_3$	Matrix	Mica	Other
UC1A	38	18	111	80	149	7	2	0	23	0	107	10	18
UC1B	24	11	118	68	197	8	25	1	22	0	217	5	32
UC2B	19	14	137	72	177	4	8	4	21	1	137	4	26
UC3A	18	12	98	27	229	11	18	0	15	0	109	7	38
UC3B	17	15	80	37	218	13	3	2	14	1	55	5	50
UC3D	23	36	138	37	139	19	17	5	32	2	116	11	51
UC3E	22	25	93	26	224	12	2	7	13	3	113	1	34

APPENDIX III: MAP OF OUTCROPS ALONG BONANZA CREEK
(only outcrops mentioned in text are shown)