SEDIMENTOLOGY OF THE UPPER CRETACEOUS WINTHROP SANDSTONE, NORTHEASTERN CASCADE RANGE, WASHINGTON

A Thesis

Presented to

Eastern Washington University

Cheney, Washington

In Partial Fulfillment of the Requirements

for the Degree

Master of Science

in

Geology

By

Robert L. Rau

Summer, 1987

THESIS OF Robert L. Rau APPROVED BY:

Dr. John P. Buchanan — 30 July 1987
Date

Chairman, Graduate Study Committee

Dr. Russell C. Boggs — July 30, 1987
Date

Member, Graduate Study Committee

Professor Dale F. Stradling — July 30, 1987
Date

Member, Graduate Study Committee

Dr. Theophil M. Otto — July 30, 1987
Date

Librarian

ABSTRACT

The Upper Cretaceous Winthrop Sandstone (early Cenomanian to late Turonian) is part of the Early Jurassic to Upper Cretaceous Methow Basin sequence which presently constitutes the northeastern-most extension of the Cascade Range, Washington. The Winthrop consists dominantly of a sandstone lithofacies with minor amounts of siltstone and conglomerate. It is conformably underlain by the Virginian Ridge Formation and conformably overlain by the Midnight Peak Formation. Stratigraphic relationships suggest the Winthrop is less than half as thick as previously thought, and attains a maximum thickness of approximately 1700 meters.

The sandstone lithofacies consists dominantly of plagioclase arkoses and lithic arkoses which contain a variety of sedimentary structures. Siltstones and matrix supported conglomerates together comprise only 7% of the Winthrop section.

A study of paleocurrent indicators shows a strong east to west direction of sediment transport in the Winthrop Sandstone. Potential source rocks currently exposed in the Okanogan highlands to the east of the Methow Basin include the Summit-Frazer Trondhjemite Gneiss and a variety of mafic

to intermediate plutons of Late Triassic to Early Jurassic age.

The overall depositional system represented by the Winthrop Sandstone is a prograding paralic system, grading upward into a mobile channel, bed-load dominated fluvial system of low sinuosity. Critical arguments for this interpretation are: 1) facies relationships with the marine deposits of the Virginian Ridge Formation; 2) lack of marine fauna within the Winthrop; 3) presence of plant fossils; 4) evidence of subaerial exposure (rooting); 5) abundance of chemically unstable framework grains such as plagioclase and rock fragments; 6) lack of wave formed features; 7) inferred channel sequences, laterally extensive and generally less than ten meters thick; and 8) overall facies relationships.

ACKNOWLEDGMENTS

I wish to gratefully acknowledge my advisor Dr. John P. Buchanan who played an integral role in this project from its beginning. Thanks to Dr. Russell C. Boggs for his critical review of the manuscript, and for introducing me to the Methow sequence during a graduate seminar. Thanks also to Professor Dale F. Stradling for his review of the manuscript.

I wish to give special thanks to the Washington Department of Natural Resources for funding this study, and specifically to Keith Stoffel for his encouragement and willingness to share information. Appreciation is also expressed to David Crabtree of the University of Montana for his identification of plant fossils, and to Jordan Kassalow for his field assistance.

Finally, I would like to extend my sincere gratitude to family, friends, and especially Terri Smith, for their support, tolerance, and love during this endeavor.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

LOCATION OF STUDY AREA

The study area is contained entirely within the Methow Basin, which presently constitutes the northeastern most extension of the Cascade Range (Figure 1). Outcrops of Winthrop Sandstone occupy the center of the basin, and extend approximately 56 km in a northwest to southeast direction and 16 km in a northeast to southwest direction. This belt traverses the Robinson Mountain, and the northern portions of the Twisp (1:100,000) topographic sheets, in north-central Washington. The area is drained by the Methow and Okanogan Rivers.

GEOLOGIC SETTING

The Methow Basin is the southernmost of a series of Mesozoic sedimentary basins lying within the western Cordillera of Washington and British Columbia (Trexler, 1984)(Figure 2). These basins have been described as "successor basins" (Eisbacher, 1974, 1981) because they are younger than adjacent accreted terranes which formed the Cordillera. The area is often informally refered to as the "Methow Graben", however, it is not a graben in the

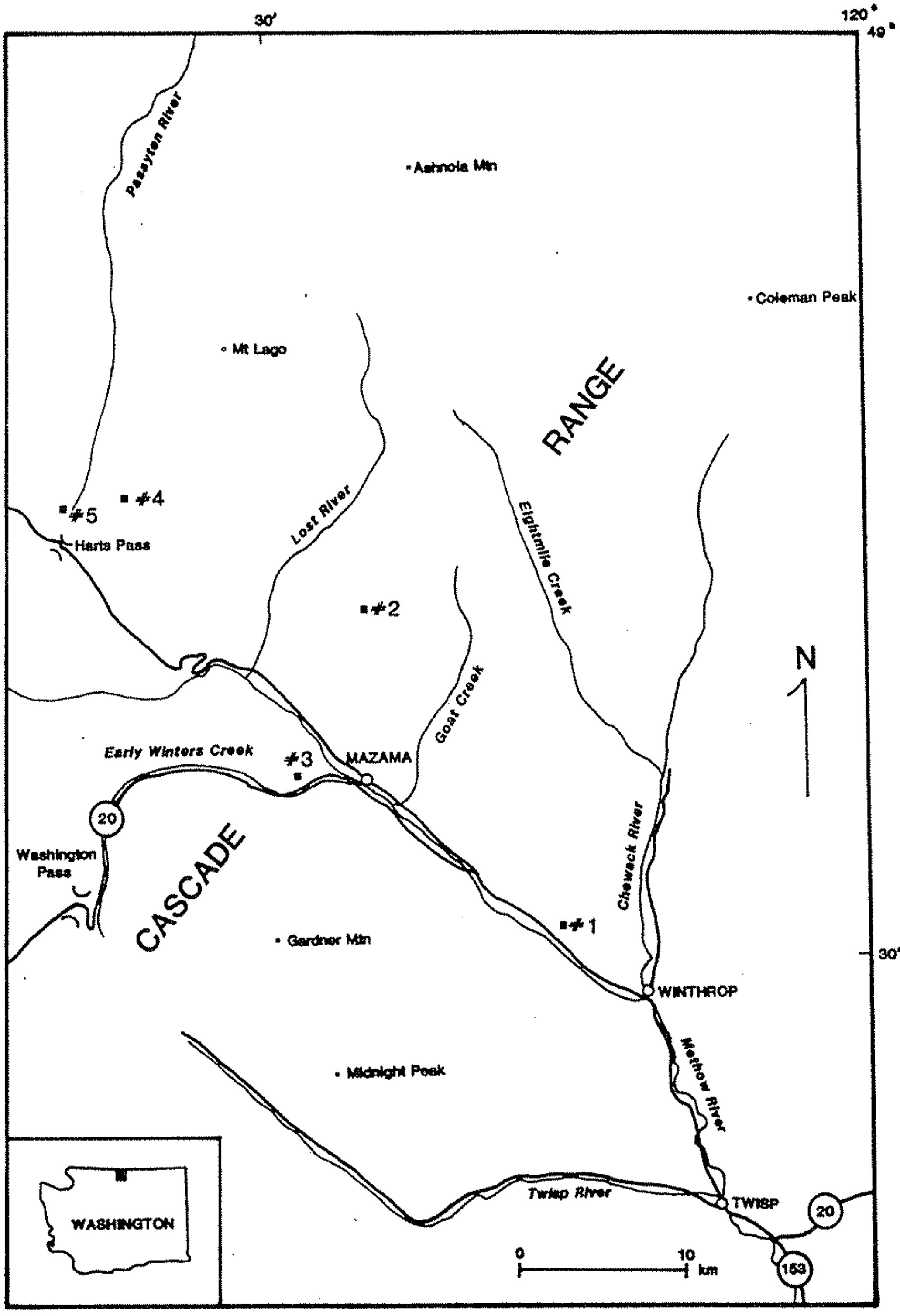


Figure 1. Geographic location of the study area. Locations of measured sections (numbers 1-5) correspond to section numbers given in Appendix 1.

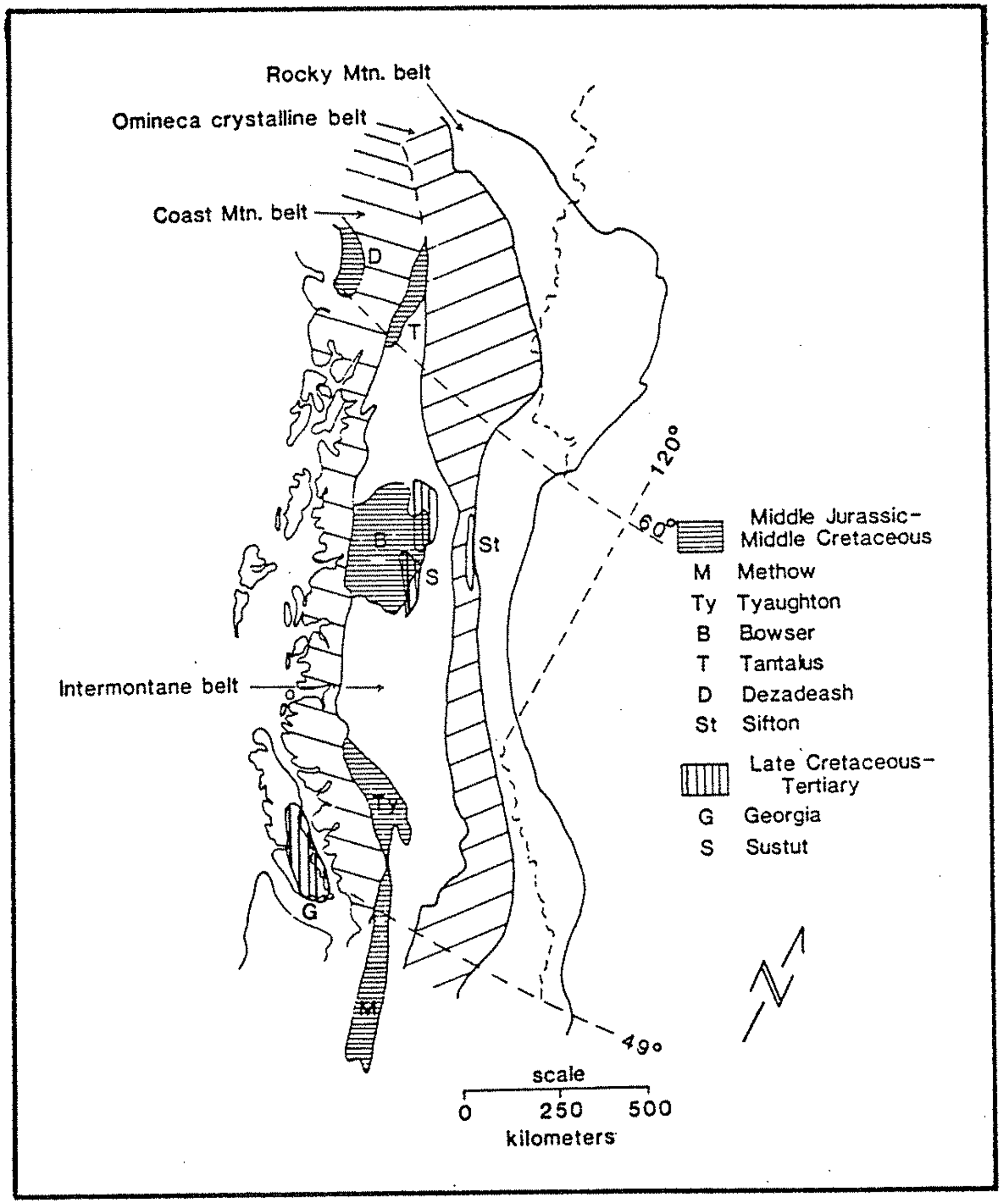


Figure 2. Successor basins of the North American Cordillera. The Methow Basin is shown at the southern end of the map (Trexler, 1984).

structural sense, nor is it currently a topographic depression.

Structure within the basin consists of northwest-southeast trending faults, and large folds that generally plunge southward. The Methow Basin is separated from the Okanogan Terrane on the east by the Pasayten Fault. The western boundary fault separating the basin from "Cascadia" is actually a complex fault system which includes the Ross Lake and the Hozameen-Jack Mountain Faults (Figure 3). These faults are generally high angle, with significant components of right-lateral motion, but the details of their history remains in debate (Kleinspehn, 1984; Trexler, 1984). The major tectonostratigraphic terranes and sutures assembled in the south-central Cordilleran collage are shown in Figure 3.

The stratigraphy of the Methow Basin (Figure 4) was established principally by Barksdale (1975). The sedimentary column within the basin reaches a maximum thickness of 15-20 km (Tennyson and Cole, 1978). The oldest sedimentary rocks are the Jurassic to Lower Cretaceous volcaniclastics of the Newby Group. These rocks were presumably derived from the Okanogan volcanic arc to the east, and deposited on a west facing marine platform (Tennyson and Cole, 1978).

Middle and Upper Cretaceous rocks comprise two distinct

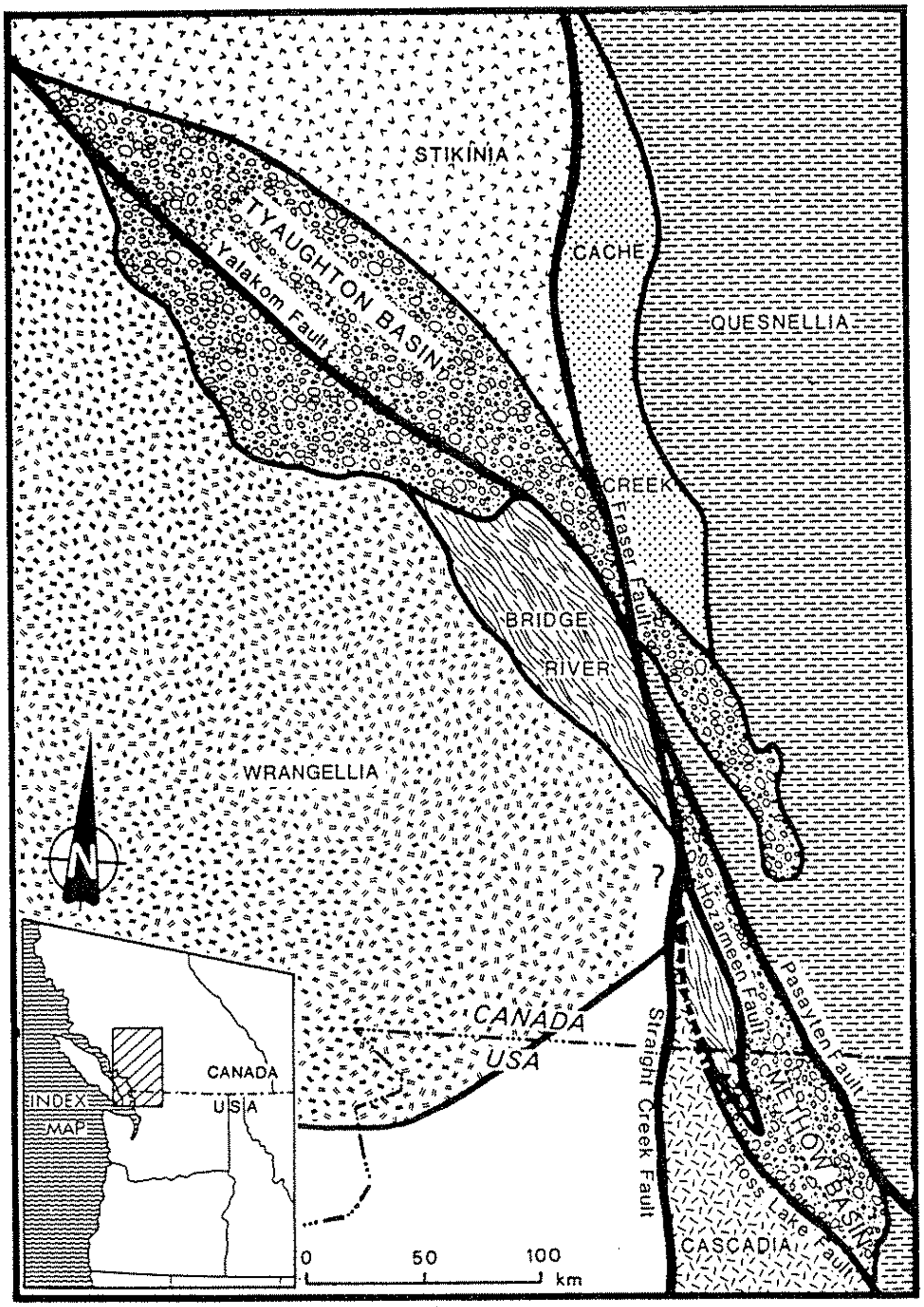


Figure 3. Tectonostratigraphic terranes and sutures of the south-central Cordillera. The Methow Basin is located in the southeastern corner of the map (Kleinspehn, 1984).

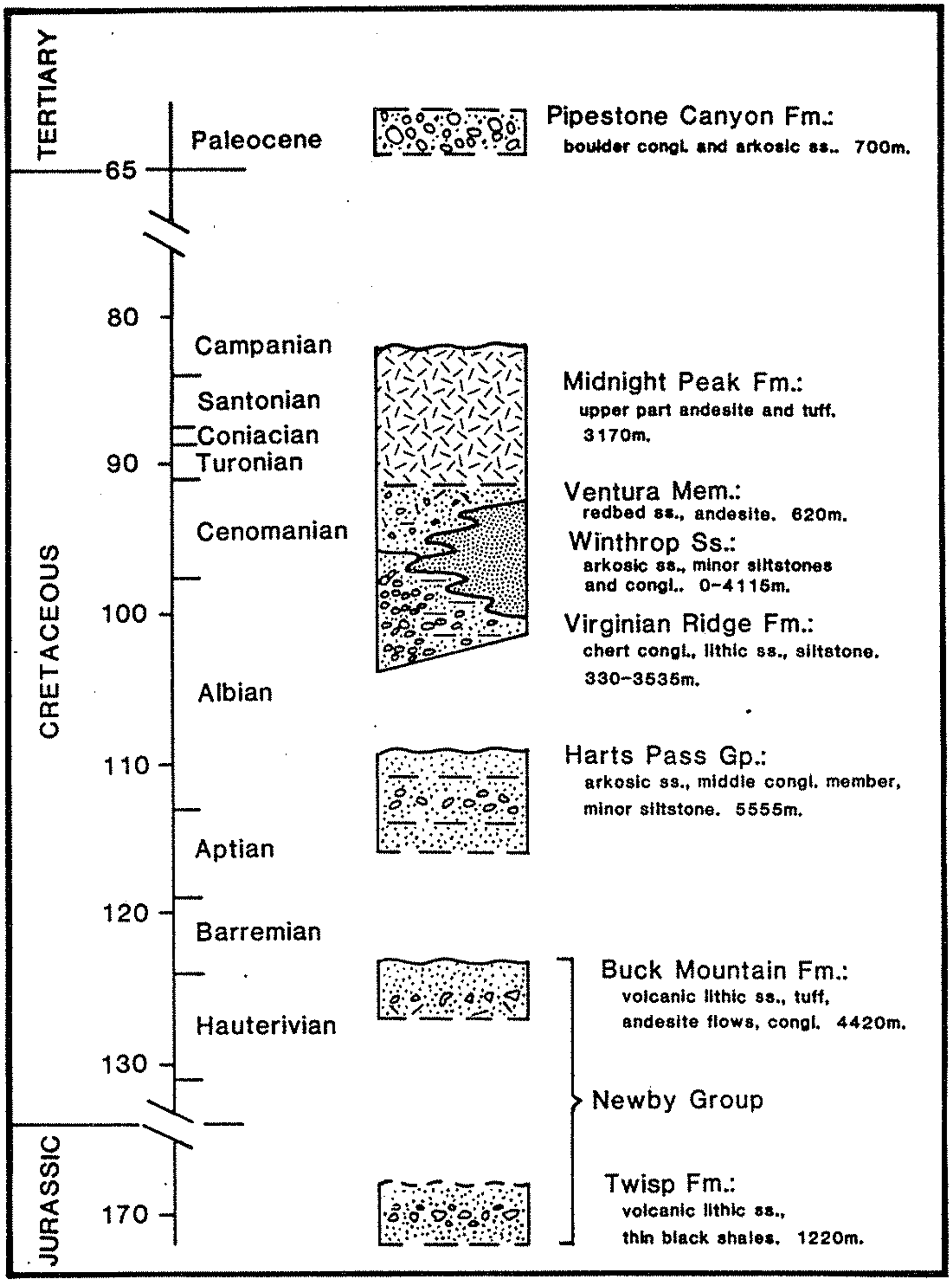


Figure 4. Stratigraphy of the Methow Basin (after Barksdale, 1975).

sedimentary packages with sources both east and west of the basin. These include the Aptian to Albian age Harts Pass Group, and the Albian to Campanian age sequence that includes the Virginian Ridge Formation, Winthrop Sandstone, and Midnight Peak Formation. The Harts Pass Group is inferred to have been deposited on an open marine shelf/slope in a forearc setting (Tennyson and Cole, 1978). These eastward derived sandstones are generally arkosic in composition, and reflect continued erosion in the Okanogan arc to expose the intrusive core (Tennyson and Cole, 1978). Younger rocks record the development and destruction of a restricted marine basin in response to the arrival of exotic terranes to the west (Trexler, 1984). Deposition of Virginian Ridge sediments documents the first appearance of westward derived detritus in the Methow Basin. These sediments are interpreted to have been deposited in a fan-delta system prograding eastward and northward into a shallow, restricted marine basin (Trexler, 1984).

The Winthrop Sandstone, designated by Russell (1900), represents a shift back to sedimentation from an eastern source, and is inferred to have been deposited in a fluvio-deltaic system (Tennyson and Cole, 1978). Conformably overlaying the Winthrop Sandstone are the volcaniclastics and intermediate volcanics of the Midnight Peak Formation.

These rocks were derived from a western (?) and local source, and are accompanied by local stockwork.

PURPOSE

The objectives of this study are four-fold:

1) Provide a detailed sedimentologic description of the various facies comprising the Winthrop Sandstone;

2) Interpret the overall depositional system and the specific depositional environments represented in the Winthrop Sandstone.

3) Determine the provenance of the Winthrop Sandstone; and

4) Correlate stratigraphic intervals across the basin, and determine if the Winthrop can be divided into distinct members.

In order to achieve these objectives five measured sections were described across the basin. The names and relative locations of each section within the Methow Basin are: 1) type section (originally described by Russell, 1900) in the eastern basin; 2) Whiteface Creek section in the east-central basin; 3) Early Winters Creek section in the west-central basin; 4) North Devils Peak section in the north-central basin; and 5) Slate Peak section in the north-central basin. Complete stratigraphic sections along with their precise locations are given in Figure 1 and Appendices 1-7.

LITHOFACIES DESCRIPTION

GENERAL STATEMENT

The Winthrop Sandstone consists of three general lithofacies which, in order of increasing abundance, are conglomeratic facies, fine-grained facies and sandstone facies. Respectively, these three general lithofacies comprise 2%, 5%, and 93% of all sections measured. The sandstones are lithologically classified according to the terminology of Folk (1974).

SANDSTONE LITHOFACIES

Composition and Texture

The sandstone lithofacies is variable in color, and very light gray (N8; Goddard, 1963) to dark gray (N3) arkoses and lithic arkoses dominate. Olive gray (5Y 4/1) to greenish gray (5 6Y 6/1) sandstones are locally abundant. Much of the sandstone lithofacies, particularly at the type section, has a distinct mottled appearance.

Figure 5 summarizes the modal composition of the Winthrop Sandstone based on 200 point counts on 35 thin sections. Modal point plots trend from the lithic corner

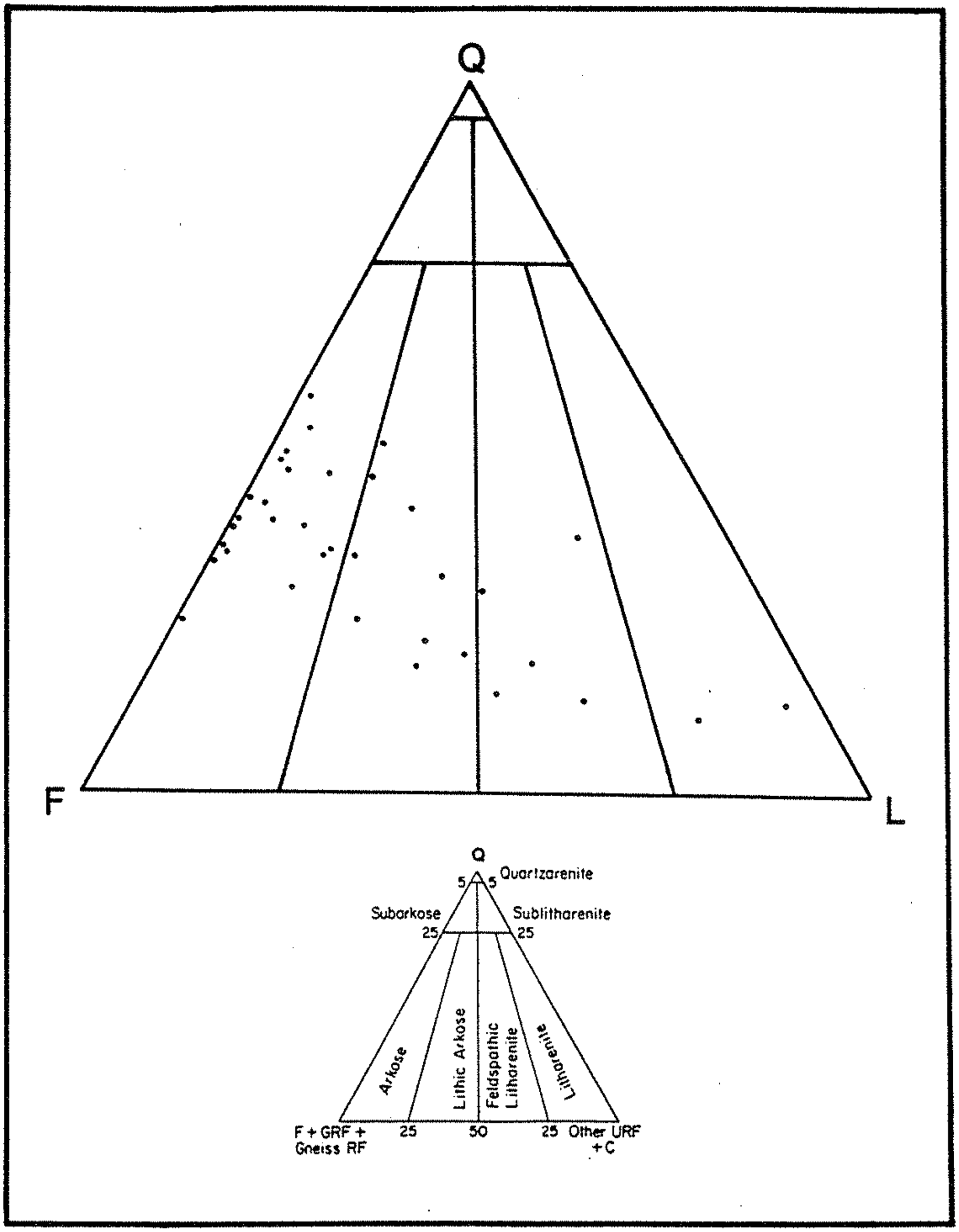


Figure 5. Compositional modes of 35 sandstone samples using the classification of Folk (1974).

upwards toward the quartz-feldspar base line and display a variety of compositions ranging from litharenites to arkoses. Overall compositional mode is $Q_{32}F_{48}L_{20}$, which plots as a lithic arkose, although arkoses are the most common rock type. Plagioclase constitutes nearly 100% of all feldspar grains. The composition of the sandstone lithofacies will be discussed in detail in the petrography section of this report.

Medium-grained sandstones are most abundant however, sandstones vary from very fine-grained to very coarse-grained. Lithic fragments, most commonly volcanics and chert, are the largest detrital grains within the Winthrop. Quartz grains are generally larger than feldspars, although in many samples there is no significant variation in this trend.

Individual sandstone samples are commonly poorly to moderately sorted. Beds either show little variation in grain size throughout their thickness or are normally graded. Within these fining upward sandstone beds, changes in size sorting symmetry from positive skewness at the base to negative skewness at the top are commonly observed. This trend is particularly apparent in those beds containing abundant lithic fragments.

Most detrital grains are angular to subangular in shape. Quartz and feldspar generally show similar degrees of rounding. Smaller grains tend to be better rounded; however, within the same size class, grains range from very angular to subrounded.

Sedimentary Structures

Sandstones display a variety of primary sedimentary structures which are summarized using facies codes developed by Miall (1978). Facies codes and their corresponding sedimentary structures are listed in Table 1 for each of the three major lithofacies encountered in this study. The addition of facies code Sm (massive sandstone) was included to describe this common element within the Winthrop Sandstone.

Facies Sm: Massive or crudely bedded sandstones, predominantly medium-grained but varies from fine-coarse grained. May show gross overall fining upward trends.

Facies Sp: Crossbedded sandstones with planar to wedge shaped set boundaries (Figure 6). Generally medium-grained to coarse-grained, may be pebbly (commonly intraclasts). Foreset inclination varies from one to 30 degrees. Foresets terminate with either straight or tangential basal contacts; straight contacts being more common. Set thickness ranges

Table 1. Lithofacies and sedimentary structures of the Winthrop Sandstone.

Facies Code	Lithofacies	Sedimentary Structures
Sm	sandstone, fine to coarse-grained	massive to crudely bedded
Sp	sandstone, fine to coarse-grained, may be pebbly	planar crossbeds
St	sandstone, medium to very coarse-grained, often pebbly	trough crossbeds
Se	sandstone, medium to very coarse-grained	crudely developed crossbeds
Sr	sandstone, fine to very fine-grained	ripples
Sh	sandstone, very fine to medium-grained	horizontal laminations
Gms	conglomerate, matrix supported	massive
Gm	conglomerate, matrix supported	massive to crudely bedded
Gp	conglomerate, matrix supported	planar crossbeds
Gt	conglomerate, matrix supported	trough crossbeds
Fl	siltstone	laminations and ripples
Fsc	siltstone	massive to laminated

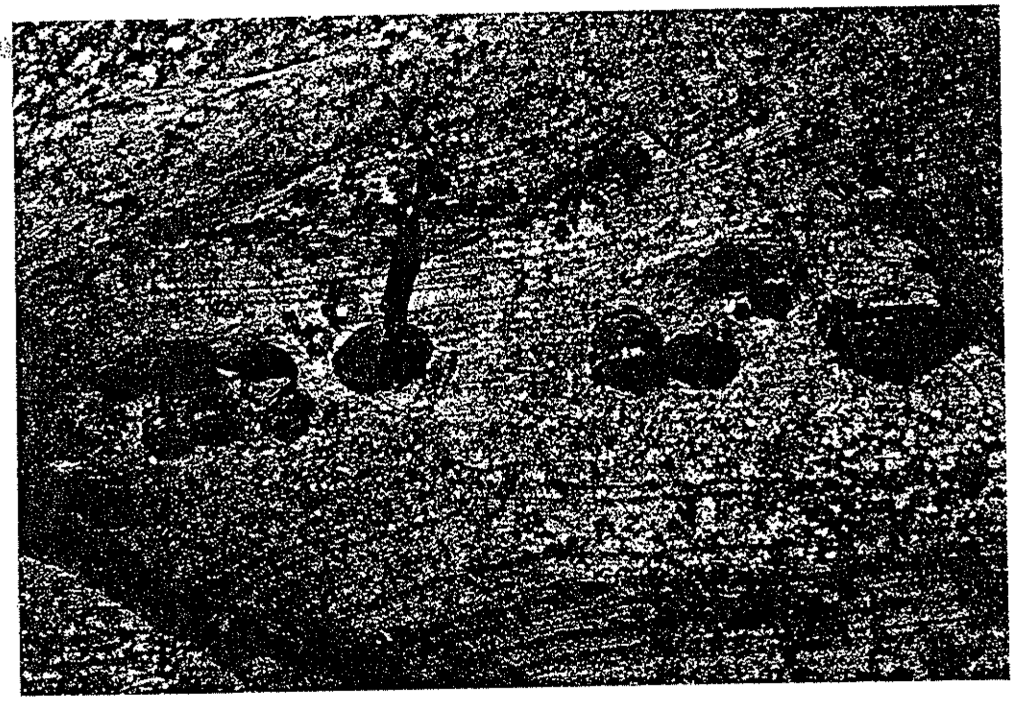


Figure 6. Planar crossbedded sandstone (facies Sp) overlying horizontally laminated sandstone (facies Sh). Foreset beds terminate with tangential basal contacts. Note the presence of diagenetic nodules.

from 15 cm to one meter with cosets up to four meters thick. Individual sets commonly do not show size grading where as cosets often show an overall fining upward trend.

Facies St: Crossbedded sandstones with trough-shaped set boundaries. Medium-grained to very coarse-grained, often pebbly (commonly intraclasts). Often grades upward or laterally into facies Sp. Set thickness varies from 20 cm to 1.2 m with cosets up to eight meters thick. Grading, within or between sets, is not commonly present.

Facies Se: Sandstone with crudely developed crossbedding. Scour and fill structures are common with scours up to 0.75 m in depth and two meters in width. Scour fills consist of Sp, St, or Sh facies.

Facies Sr: Ripple and ripple drift cross laminated sandstones. Usually fine-very fine-grained. Commonly asymmetrical in profile but symmetric ripples are present. Rare bedding plane exposures show undulatory to straight crest patterns with rare bifurcations. Often associated with facies Sh.

Facies Sh: Horizontally bedded and laminated sandstones. Grain size varies from very fine-grained to medium-grained;

pebbles are uncommon. Unit thickness ranges from thinly laminated to thickly bedded. Parting lineation is commonly present.

CONGLOMERATIC LITHOFACIES

Composition and Texture

Conglomerates are a minor portion of the Winthrop Sandstone and comprise only 2% of all section measured. Matrix supported conglomerates are most abundant with angular to subangular clasts ranging in size from 0.5 cm to 10 cm. Clast imbrication is not apparent in most beds. Conglomerate beds are not laterally persistent, and grade laterally into the sandstone and fine-grained lithofacies.

Clasts within the conglomerate lithofacies consist of, in order of decreasing abundance: intraclasts, chert, and volcanic lithic fragments. Intraclasts are composed of very fine-grained to medium-grained sandstones, and siltstones from the fine-grained lithofacies. The origin of the intraclasts can often be related to laterally adjacent or underlying lithologies. Chert pebble conglomerates are second in abundance and are identical in nature to those of the underlying Virginian Ridge Formation. Their occurrence is generally limited to the basal sections of the Winthrop

Sandstone. There is no mixing of chert pebble conglomerates with those of other types of conglomerate, where black chert constitutes nearly 100% of clast lithologies. Volcanic lithic pebbles occur in conglomerate beds most often in association with intraclasts. Their composition is identical to those fragments contained within the sandstone lithofacies (see petrography section).

Sedimentary Structures

Facies Gms: Massive, matrix supported conglomerate. May show a general preferred orientation of clasts either parallel or perpendicular to the inferred direction of flow.

Facies Gm: Massive or crudely bedded, matrix supported conglomerate. Pebble to cobble sized clasts may show a preferred orientation. Sandstone lenses up to 0.75 m in thickness are commonly interbedded with facies Gm.

Facies Gp: Planar crossbedded, matrix supported conglomerate. Set thickness varies from 40 cm to 1.2 m with cosets up to three meters thick. Where preserved, foreset-bottomset bed contacts are commonly straight. Normal grading within individual sets is often present. Usually grades upward into facies Sp or St.

Facies Gt: Trough crossbedded, matrix supported conglomerate. Set thickness ranges from 0.5 m to two meters with cosets up to eight meters thick. Normal grading within individual sets is often present. Commonly grades upward into facies Sp or St.

FINE-GRAINED LITHOFACIES

The fine-grained lithofacies consists of greenish black (5GY 2/1) to grayish black (N2) siltstones with minor amounts of claystone. Siltstone intervals average 0.5 m to one meter in thickness, although they vary from two centimeters to five meters thick. Siltstone units are non-resistant and generally weather to a dark regolith, they are well indurated but lack fissility.

Although no detailed petrographic examinations of the fine-grained lithofacies were made, it appears to consist mainly of grains of plagioclase, quartz, biotite and disaggregated volcanic lithic fragments. Plant debris is common, and in some intervals it accounts for a significant portion of the framework element (approximately 20%). In beds containing abundant plant fossils, bioturbation in the form of rooting can be abundant.

Based on sedimentary structures, the fine-grained lithofacies is further subdivided into two facies. Facies

Fl designates laminated siltstones with very small ripples. Facies Fsc describes massive to laminated siltstones. Laminations are very discontinuous, where individual laminae cannot be traced for distances greater than about one meter. This characteristic is generally true throughout the study area, with the exception of siltstones at the Slate Peak section. At this locality, individual laminae can often be traced along bedding planes for distances of several meters.

CYCLIC SEDIMENTATION

General Statement

Cyclic sedimentation in the Winthrop Sandstone has resulted in the deposition and preservation of characteristic "sediment packages" observed in the section. These cycles, defined on the basis of the vertical variation of grain size are: 1) fining upward cycles; 2) coarsening upward cycles; and 3) sedimentation units showing no grain size trends vertically through the section. Identification and description of these sedimentation cycles is a critical first step towards interpreting the environments of deposition of the Winthrop Sandstone.

Fining Upward Cycles

The most characteristic sediment package within the Winthrop are fining upward sandstone cycles, commonly between five and eight meters thick (Appendix 3; intervals 1022-1036, 1132-1144). Some cycles show a complete gradation from basal conglomerates, fining upwards into siltstones and shales. However, grain size is more commonly seen to vary from coarse sand upward into fine sand. Fining upward cycles are often laterally extensive. At the type section, excellent exposure along strike permits beds to be traced laterally for many tens or hundreds of meters. In addition, fining upward cycles are often seen vertically stacked on top of each other throughout the section. The resulting architectural geometry would best be described as multilateral, multistoried fining upward cycles (Friend, 1983; Miall, 1985).

Decreasing grain size is often accompanied by a change in sedimentary structures, that in turn reflect a decrease in flow regime. Cycles may fine upwards from crossbedded coarse-grained sandstones to ripple laminated or plane laminated siltstones. However, complete transitions in bedforms and associated grain size trends are often not present in the Winthrop. In particular, ripples and plane lamination are usually not observed towards the top of the sequence. In crossbedded sandstone facies, set thickness typically decreases upwards as does bedding thickness through an entire fining upward cycle.

Coarsening Upward Cycles

Stratigraphic relationships define two types of coarsening upward cycles within the Winthrop Sandstone. Most occur laterally adjacent to, or overlaying the larger scale fining upward cycles to which they are clearly associated. These upward coarsening sediment bodies are typically lens-shaped and grade laterally into either fining upward sandstone cycles or siltstones of the fine-grained lithofacies. Coarsening upward cycles usually grade from very fine-grained basal sandstones to medium-grained sandstones. They average three to five meters in thickness and often contain abundant plant debris (Appendix 3; intervals 891-893, 1077-1086).

A second type of coarsening upward cycle is also recognized in the Winthrop, characterized by laterally persistent sandstone units less than ten meters thick which generally lack plant fossils. These coarsening upward cycles are most abundant in the lower part of the section overlaying the Virginian Ridge Formation, but they can occur throughout the entire Winthrop stratigraphic column

(Appendix 3, interval 107-136).

Non-Graded Sedimentation Units

Two types of non-graded sedimentation units are present in the Winthrop Sandstone. The first is characterized by massive to crudely bedded sandstone (facies Sm). Massive sandstones are typically between two and six meters thick (Appendix 3, interval 977-990). A second type shows an upward change in sedimentary structures reflecting a decrease in flow regime while grain size remains constant. For example, in the interval 837-843 m at the type section (Appendix 3), coarse-grained sandstones grade from large scale trough crossbedded facies (St) upward into laminated facies (Sh) with an accompanying decrease in crossbed set thickness.

LATERAL AND VERTICAL TRENDS

Latest Mesozoic and Tertiary deformation resulting in east to west telescoping of beds with steep to overturned folds prevents the tracing of formations directly across the Methow Basin (Trexler, 1984). In addition, the lack of and/or limited extent of distinctive horizons within the Winthrop, combined with mediocre outcrop exposure across the basin, eliminates the possibility of correlating stratigraphic intervals or dividing the Winthrop into recognizable members.

Despite these shortcomings, it is possible to identify variations and trends both laterally across the basin and vertically through the section. Specifically, the sandstone lithofacies is seen to become progressively finer-grained towards the western half of the basin. Sand:shale ratios average 25:1 for the type and Whiteface Creek sections as compared to 6:1 for the North Devils and Slate Peak sections in the western half of the basin. The sandstone lithofacies also becomes progressively depleted in volcanic lithic fragments in a westward direction. In addition, bedding thickness decreases towards the west as well as upward through the section.

SUMMARY OF FACIES CHARACTERISTICS

The Winthrop Sandstone consists of three general lithofacies which, in order of increasing abundance, are conglomerate facies, fine-grained facies and sandstone facies. Respectively, these three general lithofacies comprise 2%, 5% and 93% of all section measured.

Overall compositional mode of the sandstone lithofacies is $Q_{32}F_{48}L_{20}$ which plots as a lithic arkose, although arkoses are the most common rock type. Plagioclase constitutes nearly 100% of all feldspar grains. The sandstones can be divided into six separate facies on the basis of sedimentary structures. These facies are: Sm, massive to crudely bedded sandstone; Sp, planar crossbedded sandstone; St, trough crossbedded sandstone; Se, crudely crossbedded sandstone; Sr, ripple laminated sandstone; and Sh, horizontally bedded and laminated sandstone.

The fine-grained facies consists of siltstones with minor amounts of claystone. Siltstone intervals average 0.5 m to one meter in thickness, although they vary from two centimeters to five meters thick. Fossilized plant debris is common, and in some intervals accounts for a significant portion of the framework element. Based on sedimentary structures, the fine-grained lithofacies is further subdivided into two facies: Fl, laminated siltstones with very small ripples; and, Fsc, massive to laminated siltstones.

Conglomerates are dominantly matrix supported with angular to subangular clasts ranging in size from 0.5 cm to ten centimeters. Clast lithologies consist of, in order of decreasing abundance: intraclasts, chert and volcanic lithic fragments. Chert pebble conglomerates are generally confined to the basal sections of the Winthrop, and are identical in nature to those of the underlying Virginian

Ridge Formation. Based on sedimentary structures, conglomerate facies are: Gms, massive, matrix supported conglomerate; Gm, massive to crudely bedded, matrix supported conglomerate; Gp, planar crossbedded conglomerate; and, Gt, trough crossbedded conglomerate.

Cyclic sedimentation units, defined on the basis of vertical trends in grain size, are: 1) fining upward cycles; 2) coarsening upward cycles; and 3) sedimentation units showing no grain size trends vertically through the section. Fining upward cycles are the most characteristic sediment package within the Winthrop Sandstone and often display a multilateral-multistoried architecture.

The lack of distinctive horizons within the Winthrop eliminates the possibility of correlating stratigraphic intervals or dividing the Winthrop into recognizable members. However, lateral and vertical trends observed in the Winthrop across the Methow Basin include: 1) a westward decrease in average grain size; 2) a westward decrease in sand:shale ratios; 3) a westward decrease in volcanic lithic fragments; and 4) a westward and upward decrease in bedding thickness.

PETROGRAPHY

GENERAL STATEMENT

In the field, rock samples were taken at random intervals where composition and texture depicted the overall characteristics and variability of the Winthrop. Modal analyses were done on 35 thin sections of sandstone samples by counting 200 points on each slide. Only samples from the sandstone lithofacies were subjected to modal analyses. Overall compositional mode of the Winthrop Sandstone is $Q_{32}F_{48}L_{20}$. The variability in framework composition, when classified according to Folk (1974) is shown in the triangular plot in Figure 5 for each of the 35 samples. Sandstones include plagioclase arkoses (54%), lithic arkoses (26%), feldspathic litharenites (14%), and litharenites (6%). Litharenites and feldspathic litharenites include both volcanic arenite and chertarenite. Complete petrographic data for each of the 35 sandstone samples is summarized in Appendix 8.

COMPOSITION

Quartz accounts for 32% of the detrital grains in the Winthrop, of which 83% is monocrystalline quartz and 17% is polycrystalline quartz. Polycrystalline grains commonly show straight boundaries between individual crystals but sutured or crenulated boundaries are also present. All grains of polycrystalline quartz display strongly undulose extinction angles. Monocrystalline grains are angular to subangular and show slight to strong undulose extinction. Vacuoles are not abundant, but when present occur aligned along fractures and randomly scattered across their host grains. Microlite inclusions are common, however positive identification was not possible due to their minute size. Myrmekitic textures, intergrowths of quartz and plagioclase, were observed in some samples.

Feldspar is the most common framework mineral, nearly all of which is plagioclase. Thin sections were stained to facilitate the distinction between alkali and plagioclase feldspars. Most grains are untwinned and angular to subangular. However, albite, Carlsbad, pericline and tartan twins are all present, with albite twinned grains being most abundant. Plagioclase composition was determined using the A-normal and Michel-Levey methods. Composition tends toward the sodium rich end members, oligoclase being most common, but anorthite contents of up to 74% were observed in some specimens. Perthite and antiperthite are present in minor amounts as are grains showing normal zoning.

Rock fragments account for 20% of the detrital fraction for all sandstones, and up to 82.5% in some samples. Volcanic lithic fragments are most abundant and are divided into two separate categories, those containing little or no quartz and those containing abundant quartz. Quartz deficient volcanic rock fragments dominate, and display a variety of textures. Many are entirely aphanitic, or contain plagioclase phenocrysts set in a microcrystalline groundmass of mafic material and devitrified volcanic glass. Pilotaxitic textures, where plagioclase laths or microlites are flow aligned in a parallel to subparallel orientation, are also common. Plagioclase composition within the volcanic rock fragments is variable, but tends to be enriched in calcium as compared to detrital feldspar grains. Some samples have zoned plagioclase phenocrysts in a hyalopilitic texture. Other phenocrysts include pyroxene, amphibole and biotite. Volcanic rock fragments with abundant quartz are not common, but typically have a mafic groundmass similar to the quartz poor fragments. Plutonic rock fragments are very uncommon and only two occurrences were noted.

Chert accounts for the majority of the sedimentary rock fragments and are the second most abundant lithic fragment present. Siltstone and mudstone rock fragments are also present, however they appear to have been largely derived from within the basin of deposition. One siltstone lithic fragment has a chert rock fragment incorporated into it indicating either second cycle sedimentation, or, more likely the siltstone was deposited as an intraclast.

Metamorphic rock fragments are present in variable amounts, with low to middle rank foliated lithic fragments the most common. Constituent minerals include quartz, muscovite, biotite, epidote, chlorite and other phyllosilicates. Non-foliated metamorphic rock fragments are rare, and are composed almost entirely of sheared quartz where individual crystals are elongated in a preferred direction.

Biotite and muscovite are present in minor amounts with biotite being more common. Because these minerals constitute such a small percentage of the detrital fraction, they are included under accessories (Appendix 8). Other accessories include chlorite, amphibole, pyroxene, apaptite, rutile, epidote, zircon, titanite and opaques. While not present in any of the 35 samples observed, plant fragments account for a significant proportion of the detritus in some rocks (approximately 20%).

Detrital matrix averages 5% for all samples, and ranges up to 63.6% in some very fine-grained, poorly sorted sandstones. Distinguishing between the different types of matrix reported by Dickinson (1970) is difficult due to the extent of diagenetic overprints. Only those grains of definite detrital origin, and smaller than .0625 mm were counted as matrix in this study. Matrix minerals include feldspar, quartz and a variety of phyllosilicates.

Authigenic cements account for an average of 8.8% of the total rock and up to 24% in some samples. In order of decreasing abundance, cement types include phyllosilicate, calcite, zeolite and iron oxide.

DIAGENETIC EFFECTS

General Statement

The diagenetic features observed in the Winthrop Sandstone are similar to those reported by Galloway (1974) and Burns and Ethridge (1979) in their studies of litharenites and feldspathic litharenites. Because all sampling of the Winthrop Sandstone was done on surface outcrops, the effect of weathering is overprinted on diagenetic features obscuring their textures. The most significant post depositional diagenetic features observed in the Winthrop include: authigenic cements, replacement and compaction features.

Authigenic Cements

Four kinds of cements are present in the Winthrop Sandstone: phyllosilicate, calcite, zeolite and iron oxide. Phyllosilicate cements are most common and occur in a variety of habits including clay coats on framework grains, radiating porefill and clay rims, and unoriented microcrystalline aggregates. Non-radiating phyllosilicate cements, present as clay coats and unoriented aggregates, are most abundant. The terms orthomatrix and epimatrix (Dickinson, 1970) were not adopted in this study, but instead are classified as cement because this material is not necessarily detrital in nature. In addition, the extent of diagenetic overprints makes their distinction tentative. However, unoriented aggregates appear to be recrystallized detrital matrix and could be termed orthomatrix. Phyllosilicate mineralogy includes chlorite, illite and montmorillite.

Calcite cement is common, but is limited to those samples with abundant volcanic rock fragments. In thin section, sparry calcite not only fills pore spaces, but replaces matrix, detrital grains and lithic fragments. In the field, calcite cemented rocks react readily with dilute hydrochloric acid.

The zeolite mineral laumontite is present in minor amounts as non-radiating pore fill cement and fracture filling. Cole (1973) confirmed the presence of laumontite in the Winthrop Sandstone by X-ray diffraction analysis. In this study, laumontite was characterized by its low birefringence, two perfect cleavages and length slow orientation.

Iron oxide cement is uncommon and difficult to distinguish from surface weathering effects. It appears to consist mainly as grain surface coats in the form of hematite, but the timing of its precipitation remains in doubt.

A tentative paragenetic sequence for authigenic cement precipitation can be proposed based on the nature of cement-grain relationships. Stage 1 consists of the formation of patchy calcite porefill cement or clay coats on detrital grains. Stage 2 is characterized by the precipitation of radiating phyllosilicate porefill cement, unoriented microcrystalline aggregates or clay rims. Stage 3 is reached during advanced stages of diagenesis or burial metamorphism where zeolites occur as pore fill and fracture fillings.

Replacement

Alteration and replacement of mineral grains is the most obvious diagenetic feature in the Winthrop Sandstone. Plagioclase feldspar grains and volcanic rock fragments are highly susceptible to elements of chemical weathering and alteration in a shallow burial environment (Blatt and others, 1980). Distinguishing between the effects of these two processes is often difficult. Feldspar grains and rock fragments are commonly replaced by sericite, epidote, saussurite, montmorillonite, and titanite (Figure 7), and less commonly by laumontite, prehnite and stilpnomelane. In some samples it appears that incipient albitization of calcium rich feldspar may have been an active process. Such grains are often riddled with small zeolite inclusions, and show signs of solution activity or overgrowths on the grain surface (Pittman, 1970; Boles, 1982). Quartz grains have not been extensively altered, but are replaced in varying amounts by sericite and illite. Other replacement features include chlorite pseudomorphs after biotite (Figure 8), and devitrification of volcanic glass within rock fragments.

Compaction Features

Pseudomatrix (Dickinson, 1970) accounts for an average of 4% of total rock samples and up to 16.5% in some specimens. Pseudomatrix dominates in those rocks with abundant volcanic rock fragments and is lithologically

Figure 7. Titanite occurs as both detrital and authigenic species. This photograph shows diagenetic titanite growing on a plagioclase grain partially replaced by sericite. Note the euhedral grain outlines (magnification=50X).

Figure 8. Photomicrograph showing a variety of replacement features commonly seen in the Winthrop Sandstone. Biotite is being partially replaced by chlorite. Also shown are plagioclase grains being replaced by sericite and epidote, along with a relatively unaltered feldspar grain with albite twins (magnification=50X).

identical to their parent lithic fragments but was not counted as such in modal QFL analyses. Other evidence of mechanical compaction include bent micas and deformed labile sedimentary rock fragments.

DISCUSSION

The absence of cleavage, recrystallized rock fabrics or quartz overgrowth cement suggests that penetrative deformation and pressure solution did not accompany the uplift and folding of the Methow sequence. In addition, since the Winthrop occurs near the top of the Methow sequence, it was evidently not exposed to excessive amounts of overburden pressure. Yet the presence of alteration minerals such as epidote, laumontite and prehnite, along with incipient albitization of plagioclase feldspars, suggests these rocks were subject to low rank burial metamorphism. Best (1982) notes that particular mineral assemblages occur at significant different depths in various rock bodies around the world, and suggests that temperature may be more important than pressure in determining which minerals are present. Temperature would be particularly important in active geothermal areas such as the Methow Basin in the middle Cretaceous. At the type and Early Winters Creek sections (Appendices 3 & 5) the rocks of the

Winthrop Sandstone are intercalated with hypabyssal igneous rocks in the form of shallow dikes and sills. Intercalated igneous rocks are most abundant at the Early Winters Creek section where they occur frequently throughout the stratigraphic section (Appendix 5). In addition, stocks intruding the Winthrop at the type section, the overlaying volcanics and volcanoclastics of the Midnight Peak Formation, and the developing arc-trench system to the west all indicate igneous activity and accelerated geothermal gradients during and after deposition of the Winthrop Sandstone. This may explain the development of low rank zeolite-prehnite metamorphic facies at burial depths where they would normally not occur (approximately 100°-$300^{\circ}C$, 2-3 kb) (Hyndman, 1972). Helmold and van de Kamp (1984) note that albitization and formation of the zeolite laumontite can occur together as given by the equation:

$$\text{Ca plag.} + SiO_2 + H_2O + Na^{+} = \text{Albite} + \text{laumontite} + .5Ca^{+2}.$$

This reaction requires the presence of abundant pore waters enriched in sodium and silica, conditions that are not normally present in terrestrial groundwaters infiltrating through feldspathic sandstones. Two possible sources of these fluids in the Winthrop are from the conversion of smectite to illite (Helmold and van de Kamp, 1984) and from the dewatering of the underlying Virginian Ridge Formation.

SUMMARY OF PETROGRAPHY

Figure 5 summarizes the composition of the Winthrop Sandstone based on modal analyses of 200 point counts of 35 sandstone samples. Overall compositional mode of the sandstone lithofacies is $Q_{32}F_{48}L_{20}$ which plots as a lithic arkose, although arkoses are the most common rock type. Complete petrographic data for each sample is given in Appendix 8.

Framework elements in the Winthrop sandstone include quartz, feldspar, lithic fragments and accessory minerals. Feldspar is the most common mineral constituent, nearly all of which is plagioclase. Plagioclase composition tends toward the sodium rich end members, oligoclase being most common, but anorthite contents of up to 74% were measured in some samples. Quartz accounts for 32% of the detrital grains in the Winthrop, of which 83% is monocrystalline quartz and 17% is polycrystalline quartz. Rock fragments account for 20% of the detrital fraction in all sandstone samples, and up to 82.5% in some samples. Volcanic lithic fragments of intermediate composition, and chert, respectively rank first and second in abundance. Accessory minerals include biotite, muscovite, chlorite, amphibole, pyroxene, apatite, rutile, epidote, zircon, titanite, and opaques.

Detrital matrix averages 5% for all samples, and ranges up to 63.6% in some very fine-grained, poorly sorted sandstones. Authigenic cements account for an average of 8.8% of the total rock. In order of decreasing abundance, cement types include phyllosilicate, calcite, zeolite and iron oxide.

Alteration and replacement of mineral grains is the most obvious diagenetic feature in the Winthrop Sandstone. Feldspar grains and volcanic rock fragments are commonly replaced by sericite, epidote, saussurite, montmorillonite and titanite, and less commonly by laumontite, prehnite and stilpnomelane. Quartz grains have not been extensively altered, but are replaced in varying amounts by sericite and illite. Other diagenetic effects include the development of pseudomatrix, bent micas and deformed labile sedimentary rock fragments.

STRATIGRAPHY

BASAL FORMATION CONTACT

General Statement

The contact between the Winthrop Sandstone and the underlying Virginian Ridge Formation is conformable throughout the basin, however, the nature of this contact varies considerably. At the type section, the two units are gradational over approximately 350 meters of section while at Whiteface Creek, the contact is sharp. Farther to the northwest, at Slate Peak, lithologies typical of the Winthrop and Virginian Ridge are completely interbedded throughout the stratigraphic interval normally occupied by the Winthrop Sandstone. In each case, the Winthrop Sandstone directly overlies the Slate Peak Member of the Virginian Ridge Formation. This stratigraphic relationship is true throughout the Methow, except in the southern part of the basin, between Patterson Lake and the Twisp River, where the Winthrop overlies the Patterson Lake Member (Trexler, 1985).

Type Section

At the type section, the basal contact with the underlying Virginian Ridge is obscured by an intrusion of feldspar porphyry. The base of the type section ends in modern colluvial debris, from where it is approximately 100 meters to the stratigraphic top of the intrusion (Appendix 3). Despite this, the contact appears gradational, where the lower 350 meters of the type section shows characteristics of both the Winthrop and the Virginian Ridge ("transition zone"). Specifically, the presence of chert pebble conglomerates up to nine meters thick (Appendix 3; intervals 54, 190 & 326), and black shales are typical of the Virginian Ridge Formation.

The fine-grained facies of the Virginian Ridge and the Winthrop can often be distinguished from one another in the field by their color. Siltstones in the Winthrop are grayish black (N2) to greenish black (5GY 2/1) whereas those of the Virginian Ridge are black (N1). Most of the fine-grained rocks exposed in the transition zone are more characteristic of the Virginian Ridge Formation. Within this zone, rocks typical of the Winthrop are predominantly lithic arkoses. Most of these rocks are organized into massive sediment packages with no size grading. However, as previously stated, laterally persistent coarsening upward cycles are more abundant in the basal Winthrop. At the type section, these coarsening upward cycles are between two and eight meters thick (Appendix 3).

Whiteface Creek

The rocks at the Whiteface Creek section (Appendix 4), in contrast to those at the type section, are in sharp basal contact with the underlying Virginian Ridge Formation. The contact is well exposed, and marked by the sudden appearance of numerous thick shale beds (2-15 m thick). Above the contact, the lower Winthrop is typical in that it is characterized by fining upward cycles and the lack of chert detritus.

Slate Peak

The Slate Peak stratigraphic section (Appendix 7) in this study corresponds to the lower 135 meters of Trexler's (1984) Slate Peak east section. It is located in the saddle between Slate Peak and Haystack Mountain, just within the boundaries of the Pasayten Wilderness Area. Although Trexler considered these rocks more characteristic of the Virginian Ridge Formation, and indicated the Winthrop was missing from the section here, Tennyson (1974) mapped them as Winthrop Sandstone or "Winthrop equivalent". Pierson (1972), looking at a similar suite of arkosic rocks several miles south of Harts Pass, also considered them to be "Winthrop equivalent".

The rocks just west of the summit of Slate Peak clearly belong to the Virginian Ridge Formation as evidenced by the marine fauna contained in black shales. However, the 370 meters of section between the top of Slate Peak and the volcanic rocks of Haystack Mountain contain no marine macrofossils and show characteristics of both the Winthrop Sandstone and the Virginian Ridge.

The Slate Peak section (Appendix 7) is characterized by thinly-medium bedded arkoses and lithic arkoses organized into either fining upward sequences, or thinly laminated units showing no size grading. Siltstones are more abundant here than elsewhere in the Winthrop and average 15% of the section. Above this section, in the upper half of Trexler's Slate Peak east section (Trexler, 1984, Appendix A.4), chert pebble conglomerates, chert grain sandstones and litharenites dominate. This in turn grades upward into the Volcanic Member of the Midnight Peak Formation.

Farther to the north, at Buckskin Lake, sandstones mapped as "Winthrop equivalent" by Tennyson (1974) are interbedded with sediments typical of the Virginian Ridge. Hybrid lithologies are also common and the two units appear indistinguishable (McCroder, personal communication).

The focus of the problem is not necessarily whether these rocks should be mapped as Winthrop or Virginian Ridge, but rather what is the relationship between these two different sediment types, and under what conditions were they deposited? It is clear that the Winthrop Sandstone had reached its lateral limit in the north-central part of the Methow Basin near Slate Peak. No arkosic sandstones of Upper Cretaceous age have been noted further to the west. Trexler (1984) observed the abundance of arkoses low in the Slate Peak east section, beneath beds of chert pebble conglomerate. In contrast, arkoses are seen stratigraphicaly high in the Virginian Ridge in the eastern and southern part of the basin. This indicates that much of the Winthrop, or "Winthrop equivalent", is older than the Virginian Ridge in the northern basin while younger to the south. In other words, the Virginian Ridge was time transgressive to the north while the Winthrop was relatively stable within the basin (Trexler, 1984). Distinctive beds of chert pebble conglomerate thus provide useful constraints for relative dating in the Upper Cretaceous Methow sequence.

UPPER CONTACT

General Statement

The Winthrop Sandstone is gradationally overlain by the volcanics and volcanoclastics of the Midnight Peak Formation; however, local unconformities do exist. On the south slopes of Last Chance Point, the Winthrop is in angular unconformity with the Ventura Member, where boulder sized clasts of arkose are incorporated within the Ventura (Mohrig, personal communication). The upper contact of the Winthrop Sandstone is commonly associated with the Ventura Member of the Midnight Peak Formation; however, farther to the north in the Goat Peak Syncline, the Winthrop is overlain by both the Volcanic and Grasshopper Members. The upper contact of the Winthrop is described from two localities: Sandy Butte and the type section.

Discussion

On the north slopes of Sandy Butte, in the Looney Creek drainage, the contact between the Winthrop Sandstone and the Ventura Member appears to be gradational over approximately 50 meters of section. Although the actual contact is not exposed, gray arkosic sandstones are interbedded with red beds typical of the Ventura except they do not contain chert. Mixed lithologies are also common. Above this gradational zone, lie the classic Ventura Member, redbeds, chert and all

At the type section, the Winthrop is juxtaposed against the overlaying Ventura Member by the Boesel Fault. The fault zone is covered with vegetation and modern colluvial and alluvial debris.

At interval 1323 m in the type section, red beds typical of the Ventura Member are interbedded with the Winthrop (Appendix 3). In addition, at interval 1245 m, red clasts of volcanoclastic sediment are incorporated into trough crossbedded sandstone facies (St). If the relationship between the Winthrop Sandstone and the Ventura Member is similar to that observed at Sandy Butte; this suggests that the Boesel Fault did not truncate much, if any section off the top of the Winthrop. This interpretation has interesting implications regarding the overall thickness of the Winthrop in that the type section may well approximate its maximum thickness.

Barksdale (1975) states that 4,115 meters of Winthrop Sandstone is exposed in the northeast limb of the Goat Peak Syncline, and "no evidence that strata are structurally repeated could be found". Such extreme thickness' are difficult to explain in view of the relationships observed at the type section. In addition, since outcrop exposures in the northeast limb of the Goat Peak Syncline are poor at best, there is no evidence for or against any structural repetition. A measured interval of 1350 meters, combined with estimated maximum covered intervals on either end of the section, yield a total thickness of 1700 meters at the type section.

SUMMARY OF STRATIGRAPHY

The Winthrop Sandstone is conformably underlain by the Virginian Ridge Formation, although the nature of the contact varies considerably. At the type section, the two units are gradational over approximately 350 meters of section while at Whiteface Creek, the contact is sharp. Farther to the northwest, at Slate Peak, lithologies typical of the Winthrop and Virginian Ridge are completely interbedded throughout the stratigraphic interval normally occupied by the Winthrop Sandstone.

The Winthrop is gradationally overlain by the volcanics and volcanoclastics of the Midnight Peak Formation; however, local unconformities do exist. In the upper intervals of the type section, red beds of the Ventura Member of the Midnight Peak Formation are interbedded with lithologies typical of the Winthrop Sandstone. This relationship indicates that the Boesel Fault truncated little, if any section off the top of the Winthrop at the type section. This suggests that the complete type section (1700 m) may represent the maximum thickness of the Winthrop Sandstone as compared to the 4,115 m thickness reported by Barksdale (1975).

PALEOCURRENT DATA

Paleocurrent data consists of a total of 140 measurements taken from all of the five measured sections. Approximately 90% of this data is based on either the foreset inclination in tabular crossbedded facies (Sp or Gp), or the dip direction down the axis of trough crossbeds (facies St or Gt). Orientations of asymmetric current ripples, elongate pebbly clasts, tool marks and plant stems constitute a minor portion of the data set.

Figure 9 shows paleocurrent rose diagrams constructed for each of the five measured sections, and a combine rose illustrating overall directions of current transport. Vector means and vector magnitudes for each rose are also shown. Within each section there is little systematic variation in current azimuths in either the vertical or horizontal direction. On a larger scale, paleocurrent azimuths vary laterally across the basin from a dominantly southwestward transport direction at North Devils Peak (vector mean=210^{o}) to a northward transport direction at Early Winters Creek (vector mean=351^{o}). Each of the other three measured sections show paleocurrent vector means lying between these two end members (Figure 9). Paleocurrent data from the Early Winters section shows the highest degree of variance among data points based on relatively few

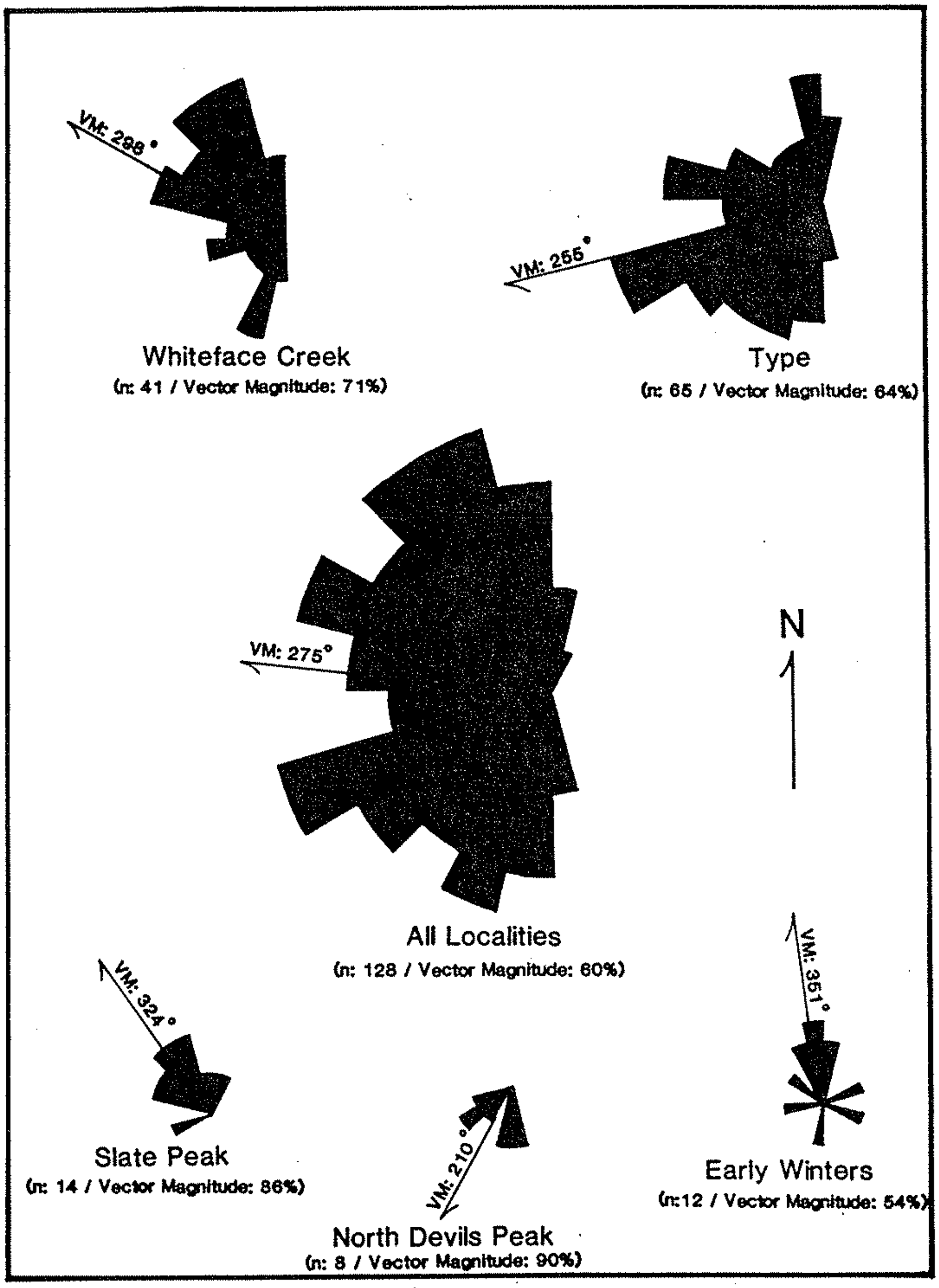


Figure 9. Paleocurrent rose diagrams for each of the five measured sections. The combined rose for all localities neglects data from the Early Winters Creek section. Also shown are vector means and vector magnitudes for each rose. The total number of observations is n.

measurements (vector magnitude=54%, n=12). In addition, poor outcrop exposure at this location provided questionable foreset bed attitudes. Due to these shortcomings, data from The Early Winters Creek section was omitted in calculating a combine paleocurrent rose for all sections.

The combine paleocurrent rose in Figure 9 summarizes transport directions in the Winthrop Sandstone, and shows an overall westward direction of sediment transport. Dominant azimuths vary from southwest to northwest with a vector mean of 275°.

In summary, sediment dispersal pathways in the Winthrop Sandstone are from east to west with a vector mean of 275°. Paleocurrent rose diagrams, vector means and vector magnitudes for each measured section are shown in Figure 9.

LITHOFACIES INTERPRETATION

GENERAL STATEMENT

The overall depositional system represented by the Winthrop Sandstone is interpreted to be a prograding paralic system, grading upward into a mobile channel, bed-load dominated fluvial system of low sinuosity. Critical arguments for this interpretation are: 1) facies relationships with the marine deposits of the Virginian Ridge Formation; 2) lack of marine fauna within the Winthrop; 3) presence of terrestrial plant fossils; 4) evidence of subaerial exposure (rooting); 5) abundance of chemically unstable framework grains such as plagioclase and rock fragments; 6) lack of wave formed features; 7) inferred channel sequences, laterally extensive and generally less than ten meters thick; and 8) overall facies relationships.

INTRODUCTION

Modern fluvial systems are classified according to either channel pattern or sediment load, however, the criteria of channel pattern is generally preferred due to the difficulty of accurately measuring stream bed load (Schumm, 1981; Friend, 1983). Four basic channel morphologies have been defined: braided, meandering, straight, and anastomosing. However, a complete spectrum of channel morphology has been observed between each of these end members (Schumm, 1981; Miall, 1985). Sedimentologists have adopted the nomenclature of fluvial geomorphologists in an effort to categorize or model ancient fluvial deposits. A list of commonly cited geomorphic and sedimentologic criteria used to distinguish these channel patterns is listed in Table 2.

Recent studies have indicated that there is no close correspondence between channel morphology and lithofacies (Jackson, 1978; Miall 1985). Many investigations have relied on the interpretation of vertical profiles, but streams of highly variable and differing morphologies can produce similar stratigraphy (Miall, 1985). This conclusion is well documented by both modern and ancient studies. For example, Nijman and Puigdefabregas (1978), working under perfect outcrop conditions, have described an Eocene coarse-grained meandering system with vertical profiles very similar to the South Saskatchewan type braided model of Cant and Walker (1978). In addition, studies on modern meandering streams by McGowen and Garner (1970), Jackson (1978), and Bridge and Leeder (1979) have indicated extreme variability in internal stratigraphy and grain size trends. These ideas must be mentioned because the Winthrop Sandstone

Table 2. Commonly cited geomorphological and sedimentological criteria distinguishing meandering and braided streams (Jackson, 1978; Schumm, 1981).

Criteria	Braided	Meandering
Gradient	High	Low
Channel flow	Unconfined	Confined
Bed-suspended load	High	Low
Stream power	High	Low
flow velocity	High	Low
Bank Stability	Low	High
Sandstone:mudstone	High	Low
Sandstone geometry	Sheet-multilateral	Multilateral/story
Vertical sequence	None consistent	Fining upwards
Epsilon surfaces	Absent	Common
Scouring	Abundant	Uncommon
Scroll bars	Absent	Common
Levees	Minor	Often prominent
Mud channel fill	Minor & short	Often common
Exumed meanderbelt	Absent	Often present
Paleocurrents	Small dispersion	Large dispersion

contains elements characteristic of both meandering and braided stream deposits. For these reasons, the geomorphic terms meandering and braided were not adopted in describing the Winthrop Sandstone; however, they appear in this report where relevant in describing sedimentation considered typical of their fluvial processes.

Friend (1983) has proposed a two-fold architectural classification of fluvial deposits where channel and interchannel deposits are recognized. Channels are further classified according to three types: fixed, mobile and sheet. Fixed channels tend to develop where abundant fine-grained sediment has stabilized the channel position whereas sheet sands are essentially the product of unchannelized flow. Mobile channels generally lack cohesive banks, and extensive lateral migration produces a multi-lateral to "sheet" like geometry. This classification proved to be both descriptive and useful in this study. In addition, this classification scheme focuses on the nature of the sediments themselves, and removes any connotation of the stream pattern which deposited them.

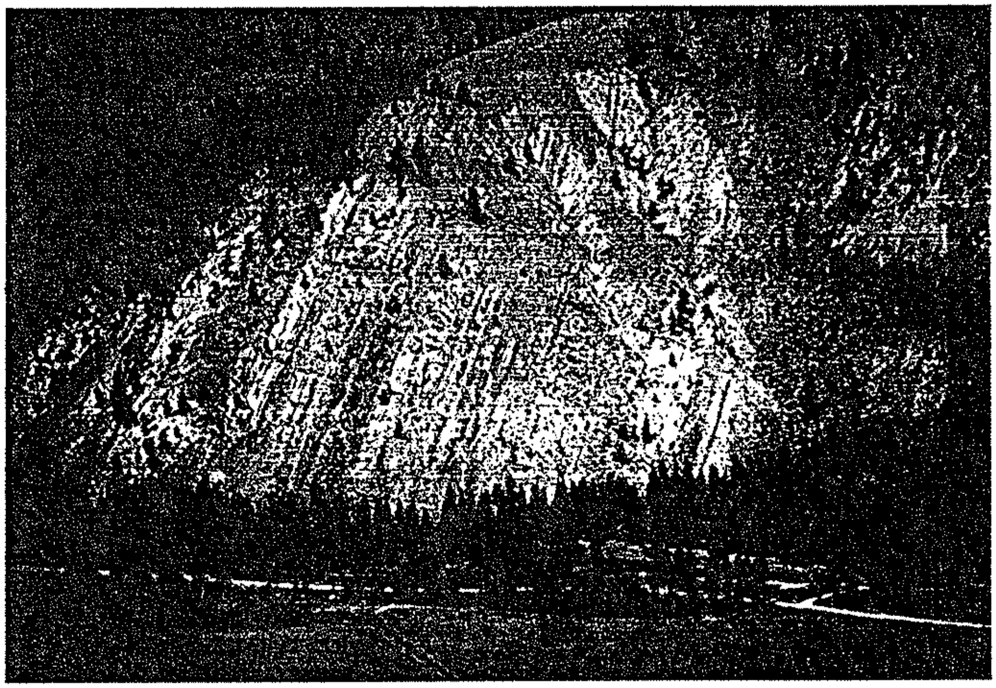


Figure 10. Photograph of the upper part of the type section. Excellent exposure along strike permits the tracing of multi-lateral channel sequences for distances of hundreds of meters. Prominent beds are coarser grain channel sequences. Beds dip approximately 75° to the west.

floods have rarely, if ever been observed. This is due, in part, to the fact that these are degrading fluvial systems. Aggrading fluvial networks, such as the one responsible for depositing the Winthrop, tend to lack channel incision and as aggradation rates increase, the amount of channel incision decreases (Miall, 1978, 1985). Nevertheless, sheet floods and unchannelized flow are probably uncommon in sandy fluvial systems traversing vegetated areas. In as much as the Methow Basin probably had a warm, humid climate in the middle Cretaceous (see Paleoclimate section), it appears that sediment was likely transported via a network of mobile channels. Mobile channels could produce the observed non-incised, multi-lateral geometry through steady migration and the lateral coalescing of channels. It must also be mentioned that incised channels, while very uncommon, are difficult to detect due to the low angle of channel perimeters, the uniformity of sediments, and unsuitable outcrop exposures. In addition, laterally coalescing sand bodies would tend to rework their own deposits and favor the development of a sheet sand geometry.

Multi-story Channel Deposits

Vertically stacked channel sequences displaying multi-story geometry are also common in the Winthrop Sandstone

(Appendix 3, interval 858-880, 1022-1042; Appendix 4, interval 420-455). In fact, they are often part of the multi-lateral systems in that many stacked channel sequences are also laterally extensive. Many of these sequences are organized into pointbars, although notably lacking is the presence of upper pointbar and overbank deposits. This however does not imply that this part of the sequence was not deposited. The occurrence of these deposits near the top of the stratigraphic sequence places them in a position most vulnerable to erosion. Similar stratification types have been described in the Eocene Simsboro Sandstone, along with modern analogs in the coarse-grained meandering Amite and Colorado Rivers (McGowen and Garner, 1970). In these modern rivers, erosion on the surface of the alluvial plain has removed much of the upper pointbar and overbank deposits.

Vertically stacked channel sequences also form aerialy restricted sedimentation units which are bounded laterally by interchannel siltstone deposits. Such sequences tend to show a greater degree of internal organization, both in primary structures and vertical grain size trends. In contrast to channel belts formed by lateral migration and bank erosion, well ordered stacked channel sequences are characteristic of vertical aggradation resulting from upstream avulusion (Miall 1978b, 1980).

INTERCHANNEL DEPOSITS

Overbank Deposits

Overbank sedimentation in fluvial systems occurs primarily in channels that have a high degree of bank stability where flood waters rise over the banks and deposit siltstones across the flood plain. However, where noncohesive sandy banks are present, channels will widen and new channels will form during flooding episodes. The result is that fine-grained sediments will be transported through the system rather than deposited on the flood plain.

As previously noted, the Winthrop is characterized by the lack of shale. Claystone and siltstone account for only 5% of all section measured, and overall, medium-grained arkoses dominate. Given the chemically unstable nature of these arkosic sediments, being deposited in a humid climate, it is unlikely that fine-grained sediments were unavailable for deposition (Odom, 1975).

The paucity of shales in fluvial deposits has often been considered as evidence for braided stream sedimentation. However, overbank deposits occur high in the vertical section and are most vulnerable to erosion (Friend, 1978; Jackson, 1978; Miall, 1980). Migrating mobile channel systems would be ideally suited to erode these uppermost sediments. Erosion or preservation of overbank deposits may also reflect rates of subsidence within the basin. Rapid subsidence will favor burial of entire channel sequences and overlaying shales preserved intact. However, during periods of slow subsidence, upper channel and overbank deposits are often eroded off (Miall, 1980). In summary, erosion on the upper alluvial plain, and bypass of fine-grained sediment through the system were responsible for the lack of siltstones in the Winthrop Sandstone. The lack of abundant erosion surfaces suggest the later as being the dominant process. This implies that the Winthrop was deposited by a bed-load dominated fluvial system.

Splay Deposits

During flooding episodes, water and sediment are diverted into the adjacent flood basin, commonly across the concave channel bank. These tongues of sediment are called crevasse splays, and are generally less than a few meters thick. Splays are recognized as sandy deposits, often coarsening upward, which are coarser-grained than surrounding levee or flood basin sediments (Reineck and Singh, 1980).

Sedimentation units interpreted to represent crevasse splay deposits occur laterally adjacent to and overlying channel deposits (Appendix 3, interval 1077-1086). Splays are typically fine-grained to very fine-grained sandstones, and either coarsen up or show no size grading at all. In addition, they are often plant fossiliferous.

The occurrence of splays in sinuous streams is usually lateral to the concave channel bank (Walker, 1984). Although splay deposits could not be specifically related to the channel cutbank, their very presence is evidence of deposition in a sinuous fluvial system of some degree. Crevasse splays grade laterally into, and are interbedded with, overbank shales.

Organic Deposits

In the southern part of the basin, coal is exposed in a road cut along the Twisp River at the confluence with Myer Creek. Coal beds are 0.5 to three meters thick and are interbedded with fine-grained sandstones and shales (facies Sm & Fsc) which lack primary sedimentary structures (Figure 11). Outcrop is poor in this area, and small faults cut the Winthrop Section. Coal beds lack lateral continuity, and contain abundant woody plant material and pyritic sulphur. Presumably these strata were deposited in a poorly drained flood basin which was periodically invaded by crevasse splays. Alternatively, coal could have been formed in a

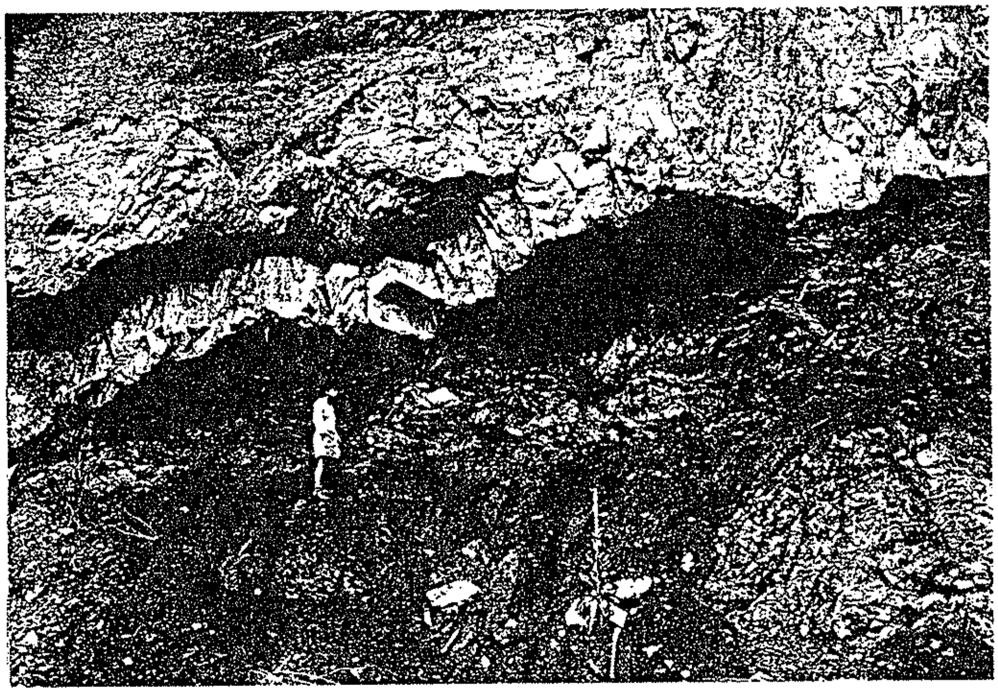


Figure 11. Coal beds exposed in a road cut 11.3 km west of Twisp. Coal is interbedded with fine-grained sandstones and shales (facies Sm and Fsc).

paralic setting. However, unsuitable outcrop, and the lack of fossil data, characteristic sedimentary structures or beds of chert conglomerate make any interpretation speculative. Without such knowledge, it is difficult to discriminate between coal deposits of a fluvial flood plain with those of a paralic environment.

MARINE DEPOSITS

Introduction

The underlying Slate Peak Member of the Virginian Ridge is interpreted to be entirely of marine origin (Trexler, 1985). The Triassic-Jurassic Hozameen Group, presently exposed in the Cascades to the west of the Hozameen Fault, is considered the probable source terrane for the chert clasts in the Virginian Ridge (Tennyson and Cole, 1978). Thick beds of chert pebble conglomerate most certainly have a western provenance, yet clearly defined crossbeds within these facies, exposed in the "transition zone" at the type section, indicate an eastern source. Trexler (1984) interprets these beds of matrix supported chert pebble conglomerates, exposed in the eastern basin, to have resulted from turbidites debouching into a shallow, restricted marine basin of low relief. At the type section, these sediments were evidently reworked by westward directed currents prior to lithification.

In the lower 350 meters of the type section (Appendix 3), lithic arkoses typical of the Winthrop are interbedded with black shales and chert pebble conglomerates characteristic of the Virginian Ridge. These relationships pose a problem in that it is unclear how much, if any, of the arkosic rocks in the transition zone were deposited under marine conditions. Thick beds of chert pebble conglomerate were certainly deposited in a marine environment, and there is no known potential source of chert to the east. In addition, these very coarse sediments present in the eastern basin could not have been deposited by fluvial processes operating from the western margin. None of the arkosic rocks show evidence suggesting deposition in fluvial channels or subaerial exposure, yet evidence of reworking by waves is also lacking.

Paralic Deposits

All of the rocks in the Winthrop Sandstone which occur beneath the uppermost occurrence of chert pebble conglomerate are inferred to have been deposited in a restricted shallow marine basin. Four lines of evidence suggest this interpretation: 1) position beneath chert pebble conglomerates of definite marine origin; 2) very thinly laminated sandstones where individual laminae are laterally continuous; 3) symmetrical, straight crested ripples; and 4) coarsening upward sediment cycles, possibly representing prograding ramps or paralic shores. Marine fossils, or evidence for wave or tide working is notably absent. However, future work on the micropaleoentology of the lower Winthrop may provide more information on the nature of marine-fluvial transition.

The strongest evidence for marine sedimentation in the Winthrop is the interbedding of chert pebble conglomerates of definite marine origin (Trexler, 1984). The simplest and most direct interpretation is that all strata beneath these conglomerate beds are also marine. This is upheld by the lack of pointbar deposits or evidence of subaerial exposure (rooting) within these strata. In addition, major Cretaceous transgressions were preceding most rapidly during the Albian and Cenomanian (McKerrow, 1981), thus promoting the maintenance of marine conditions in the Methow Basin.

At the North Devils section and in the lower part of the type section, and especially at the Slate Peak section, fine-grained facies are often thinly laminated, where individual laminae are continuous along bedding planes for several meters. This stratigraphy is not characteristic of fluvial overbank deposits in which sedimentation is more localized and conforms to variations in topography.

At the Slate Peak section there are excellent bedding plane exposures of rippled surfaces. These are symmetrical, straight crested ripples with minor bifurcations where individual crests are often continuous for several meters. Such ripples are considered typical of those formed by wave action (Tucker, 1982).

In the transition zone at the type section (Appendix 3, interval 107-136), coarsening upward cycles are interpreted to represent prograding ramps or paralic shoreline. As stated above, there is no evidence that these sedimentation units are crevasse splays, or associated with fluvial deposits of any kind. The coarsening upward sandstone cycles are overlain by chert pebble conglomerates interpreted to represent turbidites with a western source (Trexler, 1984). Despite this stratigraphic relationship, coarsening upward cycles may represent prograding paralic shores because the middle Cretaceous was a time of rapid eustatic transgression (McKerrow, 1981). Alternatively, these sedimentation units may delineate sand bodies prograding across a marine ramp in the deeper portions of the basin.

Corollary to these interpretations is that the entire North Devils and Slate Peak sections are a product of marine deposition, as is the lower 350 meters of the type section.

In other words, the Whiteface Creek and Early Winters sections do not contain any chert pebble conglomerate above or within their stratigraphic section. This is in agreement with the relative position of these sections within the basin. Marine sedimentation within the Winthrop Sandstone is limited to the eastern side of the basin low in the section, and northern parts of the basin. These regional sedimentation patterns result from a westward prograding Winthrop Sandstone, deposited during and subsequent to the eastward and northward prograding fan delta system of the Virginian Ridge.

During the final stages of marine deposition (Cenomanian?), the area was a nonmarine-paralic basin receiving sediment from sources both east and west (Tennyson and Cole, 1978). The basin was evidently restricted by contemporaneous uplift in the Cascades; however within the Winthrop, there is little evidence indicating depths within the basin. Trexler (1984) calculated water depths of less than five meters towards the western margin and an average basin slope of one to two degrees based on the thickness of delta lobe conglomerates and submarine debris flows. If these figures are correct, basin infilling would have abruptly terminated marine sedimentation as the rising Cascades cut off access to the open ocean.

As indicated by Trexler (1984), the eastward derived quartzo-feldspathic, coarsening upward sandstone cycles present in the upper Virginian Ridge and the lower Winthrop may represent advancing prodelta lobes. In fact, the depositional system represented by the rocks in this study has often been refered to as the Winthrop fluvio-deltaic system (Tennyson and Cole, 1978). However, the Winthrop Sandstone lacks many features considered typical of deltaic deposits. In particular, large scale coarsening upward sequences on the order of many tens or hundreds of meters are not present. The lack of such features may be due to the shallow nature of the marine basin into which the Winthrop was prograding. Overall however, the Winthrop does show a bed thickening upward trend across the section, being characteristic of prograding sediment bodies in general. It is interesting to note that on a much larger scale, the entire Jurassic-Cretaceous Methow section could be interpreted as a large delta system.

LATERAL TRENDS

As previously mentioned, the Winthrop Sandstone shows a westward decrease in average grain size and sand:shale ratios. This observation is consistent with paleocurrent azimuths which show an east to west direction of stream transport. As indicated in Appendix 8, the Winthrop also shows a general depletion in lithic fragments in the westward direction. However, this conclusion is not immediately apparent because total lithic fragments in QFL modes include both chert derived from sources west of the basin, and intraclasts derived from within the basin (Appendix 8). Table 3 shows renormalized QFL modal data from the five measured sections obtained by excluding chert and intraclasts from the lithic pole to illustrate the westward depletion in unstable volcanic lithic fragments. As indicated above, the Early Winters Creek section contains abundant intercalated hypabyssal igneous rocks within its thickness. The anomalously high lithic content of sandstones from this section (Table 3) is interpreted to reflect local, syndepositional igneous activity.

SUMMARY OF ENVIRONMENTS OF DEPOSITION

The overall depositional system represented by the Winthrop Sandstone is a prograding paralic system, grading upward into a mobile channel, bed-load dominated fluvial system of low sinuosity. The facies resulting from these environmental conditions are graphically represented in the composite stratigraphic section in Figure 12. Figure 13 shows a hypothetical depositional reconstruction of the Methow Basin during middle and Upper Cretaceous time.

Table 3. Sand/shale ratios and average QFL modes for each of the five measured sections. QFL modal data has been renormalized by excluding chert and intraclasts from the lithic pole to illustrate the westward depletion in volcanic lithic fragments. Note the anomalously high lithic content of the Early Winters Creek section, reflecting local syndepositional igneous activity.

	Section		Sand/Shale	QFL
W				
|	Slate Pk.	-	7/1	$Q_{35}F_{62}L_{3}$
|	N. Devils	-	6/1	$Q_{34}F_{66}L_{0}$
|	E. Winters	-	19/1	$Q_{31}F_{44}L_{25}$
|	Whiteface	-	28/1	$Q_{37}F_{58}L_{5}$
|	Type	-	23/1	$Q_{33}F_{41}L_{26}$
E				

All of the rocks beneath the uppermost occurrence of chert pebble conglomerate were deposited under marine conditions. Orogeny in the Cascades created an inland sea which was abruptly terminated by basin infilling and continued uplift. Marine sedimentation in the Winthrop is represented by the North Devils and Slate Peak sections, along with the lower 350 meters of the type section.

The majority of the Winthrop Sandstone is the result of continental fluvial sedimentation. The Winthrop is characterized by a lack of incised channel geometry, but visible channel margins are at a low angle and composed of sandstone. These unstable banks facilitated extensive lateral migration whereby creating a multi-lateral channel architecture. Many of the laterally extensive channel deposits are also stacked vertically in a multi-story fashion. Channel deposits contain a wide variety of internal structures. Pointbar sequences are present, but complete sequences are rarely preserved. Overall, greater than 90% of the fluvial portion of the Winthrop Sandstone resulted from channel sedimentation. Interchannel deposits include overbank shales, crevasse splays and coal. The paucity of overbank deposits is the result of erosion on the upper alluvial plain, and transport of these sediments through the depositional system. The lack of abundant erosion surfaces suggests the later as being the dominant

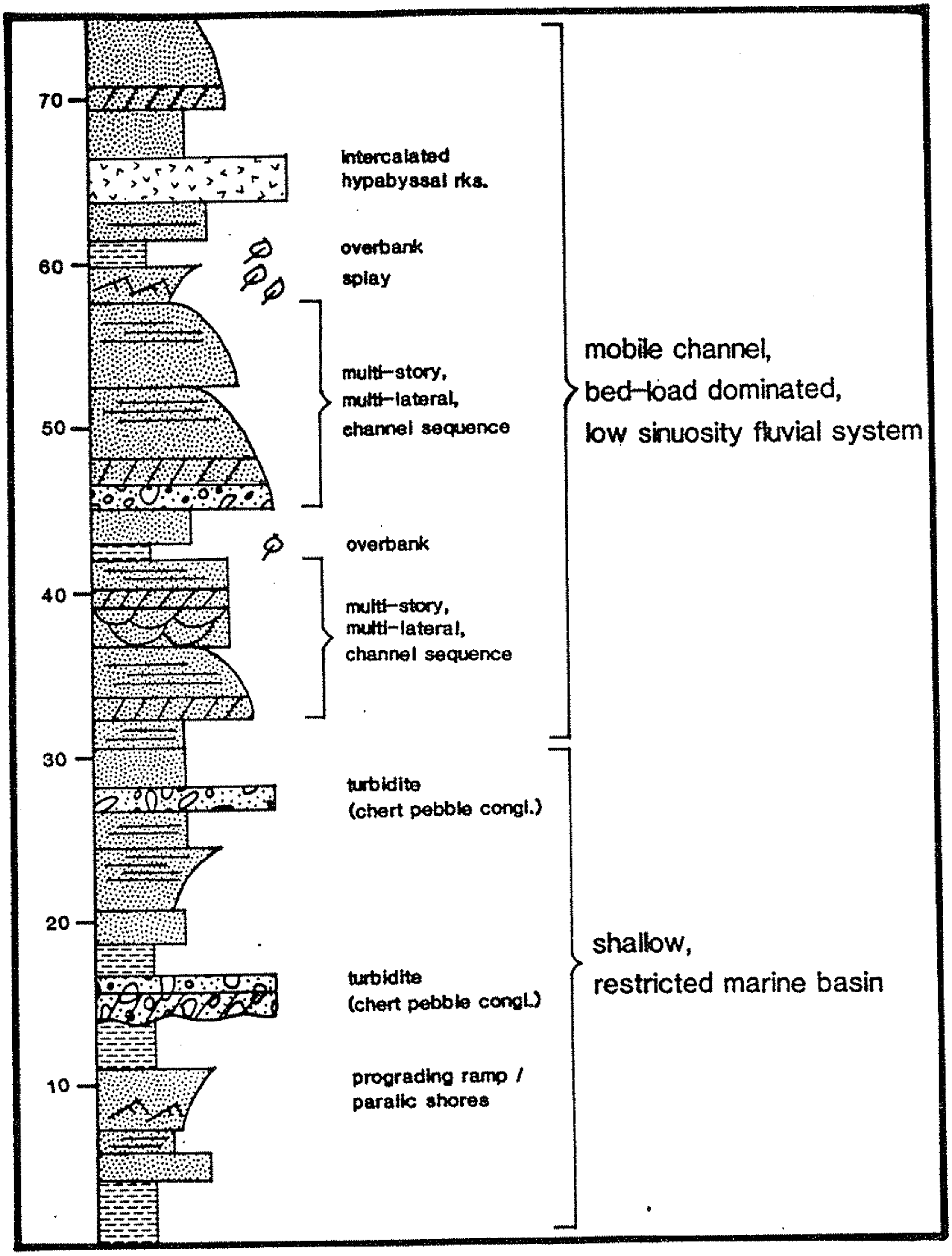


Figure 12. Composite stratigraphic section of the Winthrop Sandstone showing the marine-fluvial transition. For explanation of symbols, see Appendix 2.

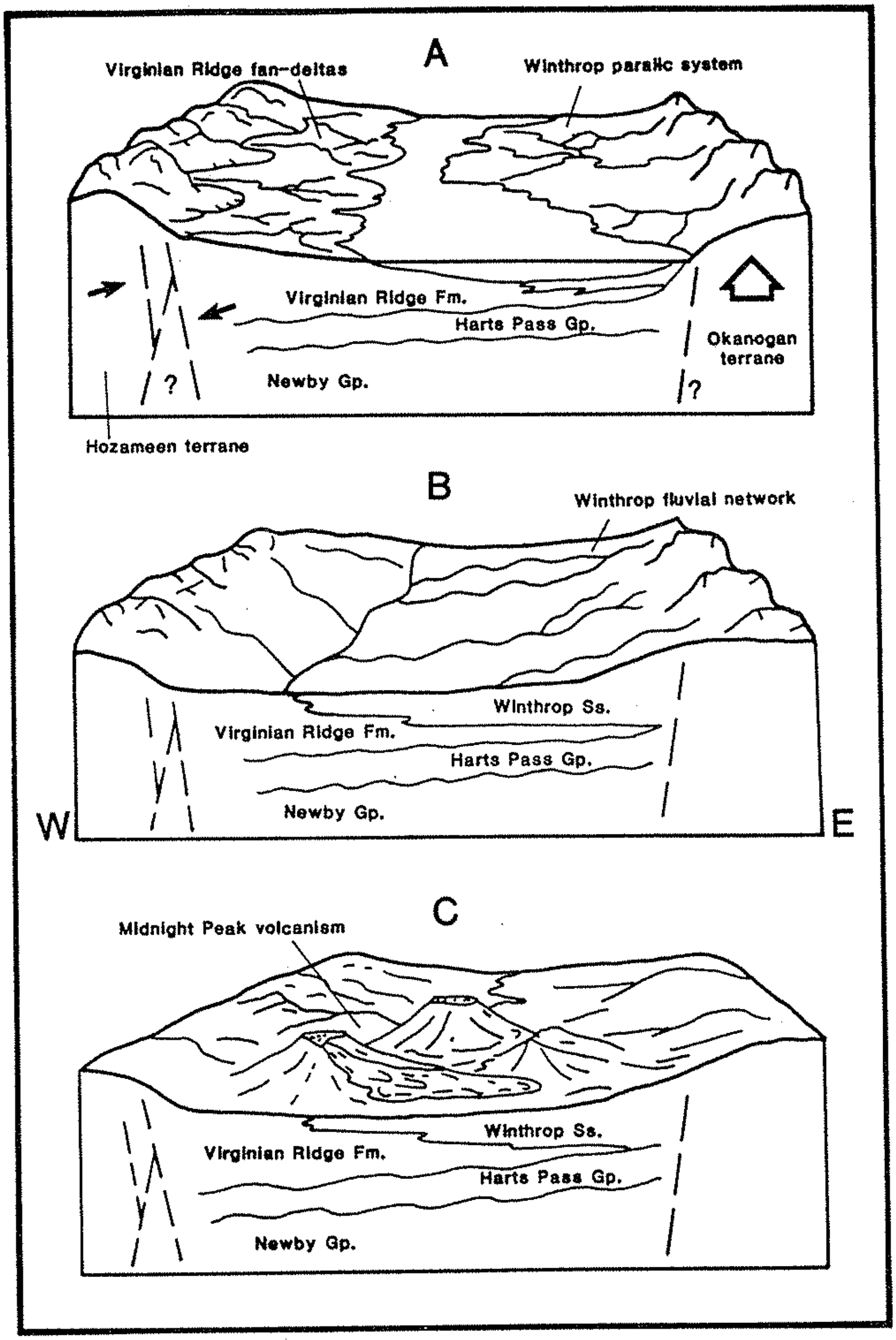


Figure 13. Stages of development of the later Cretaceous Methow Basin: A) early Cenomanian (?); B) Cenomanian-Turonian (?); C) Turonian-Campanian (?) (after Trexler, 1984).

process. This implies that the Winthrop fluvial system was bed-load dominated.

MODERN ANALOGS

There are a number of modern sedimentary basins which exibit geographic or tectonic similarities to the middle Cretaceous Methow Basin. Although the Persian Gulf is presently host to an arid climate characterized by in situ carbonate deposition, this shallow, restricted marine sea shares tectonic similarities to the Methow Basin. As the Arabian Plate moves northeast into the Eurasian Plate, the Persian Gulf is closing in a manor analogous to that experienced by the Methow Basin as shown in time block A of Figure 13. Streams flow west and southwest out of the Zagros Mountains into the Persian Gulf.

In Alaska, the tectonic setting of Cook Inlet and the adjacent Kenai Peninsula and Kodiak Island is very similar to the middle Cretaceous Methow Basin. The Kenai Peninsula and Kodiak Island consist dominantly of Jurassic to Upper Cretaceous melange, flysch and ophiolitic rocks abducted and accreted to the continent during Tertiary time (Biekman, 1980). Many of these rocks are altered to greenschist facies, and active volcanoes occur inboard of these land masses. The Cook Inlet is therefore analogous to the restricted marine Methow Basin shown in time block A of Figure 13. Although the rivers presently draining into the inlet carry sediment considerably coarser-grained than that found in the Winthrop Sandstone, sedimentation in both of these basins is characterized by deposition of detritus eroded from previously accreted highlands. The Kenai Peninsula and Kodiak Island are analogous to the Cascades during Cretaceous time and the volcanism occurring within the basin, such as at Augustine Island, is comparable to Midnight Peak volcanism (time block C, Figure 13).

Other modern analogs include the Puget Sound and the Strait of Georgia which are being closed by the accretionary bodies of the Olympic Peninsula and Vancouver Island. These areas present a similar geographic and tectonic setting to those illustrated in time block A of Figure 13.

Modern streams resulting in similar stratification types to those observed in the Winthrop Sandstone include the Amite River in Louisiana and the Colorado River of Texas. These rivers have been classified as coarse-grained, bed-load meandering streams (McGowen and Garner, 1970). Their stratigraphy is characterized by the lack of upper pointbar and overbank deposits resulting from channel instability and erosion on the alluvial plain (McGowen and Garner, 1970). In addition, fining upward sequences are commonly not observed in these rivers.

DISCUSSION

The Winthrop Sandstone displays characteristics of both braided and meandering stream deposits, but there is little direct evidence for channel morphology. Features such as exumed meander belts, mudstone plugs and epsilon surfaces are lacking, and no measurements of channel sinuosity could be made. As noted in the introduction, it is becoming increasingly apparent that streams of vastly different morphologies can produce similar stratigraphy, and in the continuum of channel types, there can be an infinite variety of deposits. For these reasons, the descriptive terms braided or meandering were not adopted in this study. Instead, the three fold architectural classification of Friend (1983), where channels are described as being either fixed, mobile or sheet, proved to be descriptive and useful. In addition, this classification scheme focuses on the nature of the sediments themselves, and removes any connotation of the stream pattern which deposited them. The Winthrop is best understood as being the product of deposition in a mobile channel fluvial system. However, for the purpose of comparison with other deposits, it will be useful to discuss certain characteristics of the Winthrop which are typical of either braided or meandering rivers.

The most striking characteristic of the Winthrop which would be considered typical of braided stream deposition is the distinct lack of claystone and siltstone. Although erosion on the alluvial plain removed an unknown amount of overbank shales, the low angle sandy channel banks actually inhibited the process of overbank deposition. Such streams are often characterized by a high width/depth ratio (Schumm, 1981), and channels widen during flooding episodes to accommodate the additional discharge. Wide channels bounded by noncohesive banks tend to migrate across large areas and produce a multi-lateral or blanket like sandstone geometry. In addition, although the Winthrop is relatively consistent in nature throughout its thickness, it lacks a regular progression, or a high degree of internal order in sedimentation units of facies types. Each of these characteristics are considered typical of many braided stream deposits.

Features characteristic of meandering stream sedimentation include pointbar deposits and crevasse splays which respectively form on the inside and outside of meander loops. Although similar stratification types can form in braided streams, these deposits constitute the only evidence for a sinuous fluvial system. For these reasons, the Winthrop Sandstone is inferred to have been deposited by a mobile channel, bed-load dominated fluvial system of low sinuosity.

Paleocurrent patterns are not clearly indicative of channel morphology. The combine paleocurrent rose in Figure 9 shows a 225° spread of data points with a vector magnitude of 60%. While such a wide variance may be more typical of meandering streams, Miall (1974) has indicated that gross paleocurrent measurements are of little value, and the relationship is more complex than once thought. Unless directional variation shows a clear cut relationship between paleocurrents and channel type, a multitude of measurements taken around the channel, from good three dimensional outcrop exposures, are needed to make a correct interpretation (Miall, 1974; Collinson, 1978). In addition, while the presence of epsilon cross stratification may be characteristic of deposition by sinuous streams, the lack of these features does not indicate otherwise (Jackson, 1978). Many meandering streams do not form epsilon surfaces because they lack steep convex banks for them to form on (Jackson, 1978).

PALEODRAINAGE PATTERNS

Dominant paleocurrent azimuths in the Winthrop Sandstone vary from northwest to southwest with an overall vector mean of 275^{o} (Figure 9). It appears that these variations represent local differences in stream direction, and do not reflect regional paleodrainage patterns.

The extent to which regional structural trends affected drainage patterns in the middle Cretaceous is unknown, however, several factors suggest that tectonism was active in the Methow at this time. These include: 1) intercalated hypabyssal rocks in the Winthrop and Virginian Ridge; 2) the regional Albian unconformity; 3) local angular unconformities with the overlaying volcanoclastics of the Ventura Member of the Midnight Peak Formation; 4) concurrent radiometric dates from the Cathedral Batholith (97 my) and Park Granite Stock (Hawkins, 1968; Engels and others, 1976); and 5) the developing arc-trench system to the west.

Alluvial basins tend to parallel regional structural trends, and drainage patterns are typically oriented either parallel or transverse to this grain (Miall, 1981). If the major northwest-southeast trending folds and faults observed in the Methow today were active during the middle Cretaceous, then paleocurrent patterns indicate a drainage network roughly perpendicular to this trend. However, detailed reconstruction of paleodrainage patterns is not possible given the data gathered in this study. For example, it is unclear whether the east to west flowing drainage network emptied into trunk streams with a more north-south orientation (Figure 13). The distribution of paleocurrent directions from the five measured sections (Figure 9) suggest this, but more data is needed to substantiate this conclusion. The most direct interpretation which can be made is that paleostream flow was generally east to west, and lateral variations in vector means across the basin reflect local changes in stream direction.

The present outcrop extent of the Winthrop Sandstone, approximately 56 km in a northwest-southeast direction and 16 km in a northeast-southwest direction, combined with the blanket like sand geometry, suggests deposition in a prograding coastal margin followed by fluvial sedimentation in a high density drainage network. Flow expansion, commonly fault controlled, is common on the upstream end of alluvial basins where streams may fan out into a distributary system (Miall, 1981). Although there is much controversy surrounding the history of the Pasayten Fault, there are indications that its activity spans the Upper Cretaceous (Davis and others, 1978; Menzer, 1983). Regardless of which faults uplifted the Okanogan Terrane during this time, it is clear that the Methow Basin area was topographically low, and these eastern bounding faults may have created a fall line at the basin margin. During the middle Cretaceous, streams draining the Okanogan highlands experienced a decrease in gradient whereby abruptly depositing the sandy bedload. Initially, uplift in the Okanogan was likely greater than erosion rates, and basin subsidence rates exceeded aggradation creating a progradational response. However, the rapid westward thinning of the Winthrop indicates uplift and erosion rates in the source area, and subsidence and aggradation rates in the basin were about the same creating depositional equilibrium (Miall, 1981).

The uncertainty surrounding the details of the paleodrainage patterns makes locating the ultimate depositional site impossible. During the initial stages of paralic sedimentation, the restricted shallow marine basin was the final repository for much of the eastward derived sediment. Since there is no evidence for internal drainage, basin infilling and uplift in the Cascades would have necessitated a river mouth in connection with the open ocean. The rivers of the middle Cretaceous would have been degradational while traversing the Cascades, and transporting much of the fine-grained sediment that is lacking in the Winthrop Sandstone.

Sedimentation rates in ancient successor basins are among the highest in nonmarine sedimentary environments, and vary from 0.1 to 0.5 m/1000 years (Miall, 1978b). According to these figures, the Winthrop Sandstone would have been deposited in four to 20 million years, assuming a maximum thickness of 2000 meters. However, rates of modern alluvial sedimentation are one to two orders of magnitude higher than those estimated for ancient fluvial sequences. This implies that sedimentation in the rock record is either highly episodic, or occurs much faster than our dating techniques can detect (Miall, 1978b).

In summary, it appears that lateral variations in paleocurrent vector means across the Methow Basin (210°-324°) represent local changes in stream direction and do not reflect regional paleodrainage patterns. The geometry of the Winthrop Sandstone suggests deposition in a prograding coastal margin followed by fluvial sedimentation in a high density drainage network. Initially, the restricted shallow marine basin was the final repository for much of the eastward derived sediment. Since there is no evidence for internal drainage, basin infilling and uplift in the Cascades would have necessitated a river mouth in connection with the open ocean.

PROVENANCE

The three main factors which control sandstone composition are tectonics and source terrane, climate, and depositional environment (Dickinson and Suczek, 1979). In the Winthrop Sandstone, tectonics and source lithology probably imposed the strongest influence on its composition. Dickinson and others (1983), has created ternary diagrams that relate modal composition data to fields that are characteristic of different provenance terranes as controlled by plate tectonics. Figure 14 shows framework composition of the Winthrop Sandstone plotted on such a diagram. Note that compositional poles in Figure 14 are modified to fit the provenance structure of Dickinson and others (1983), and are different from those of Folk (1974), (Figure 5).

As shown in Figure 14, nearly all modal points plot in either the basement uplift or magmatic arc provenance fields. The magmatic arc provenance is further subdivided into undissected, transitional, and dissected arcs, and the Winthrop modes fall predominantly into the latter two of these three categories. Transitional and dissected magmatic arcs are those in which erosional unroofing has removed much of the volcanic cover to expose the underlying intrusive core. Sandstones derived from these sources typically plot

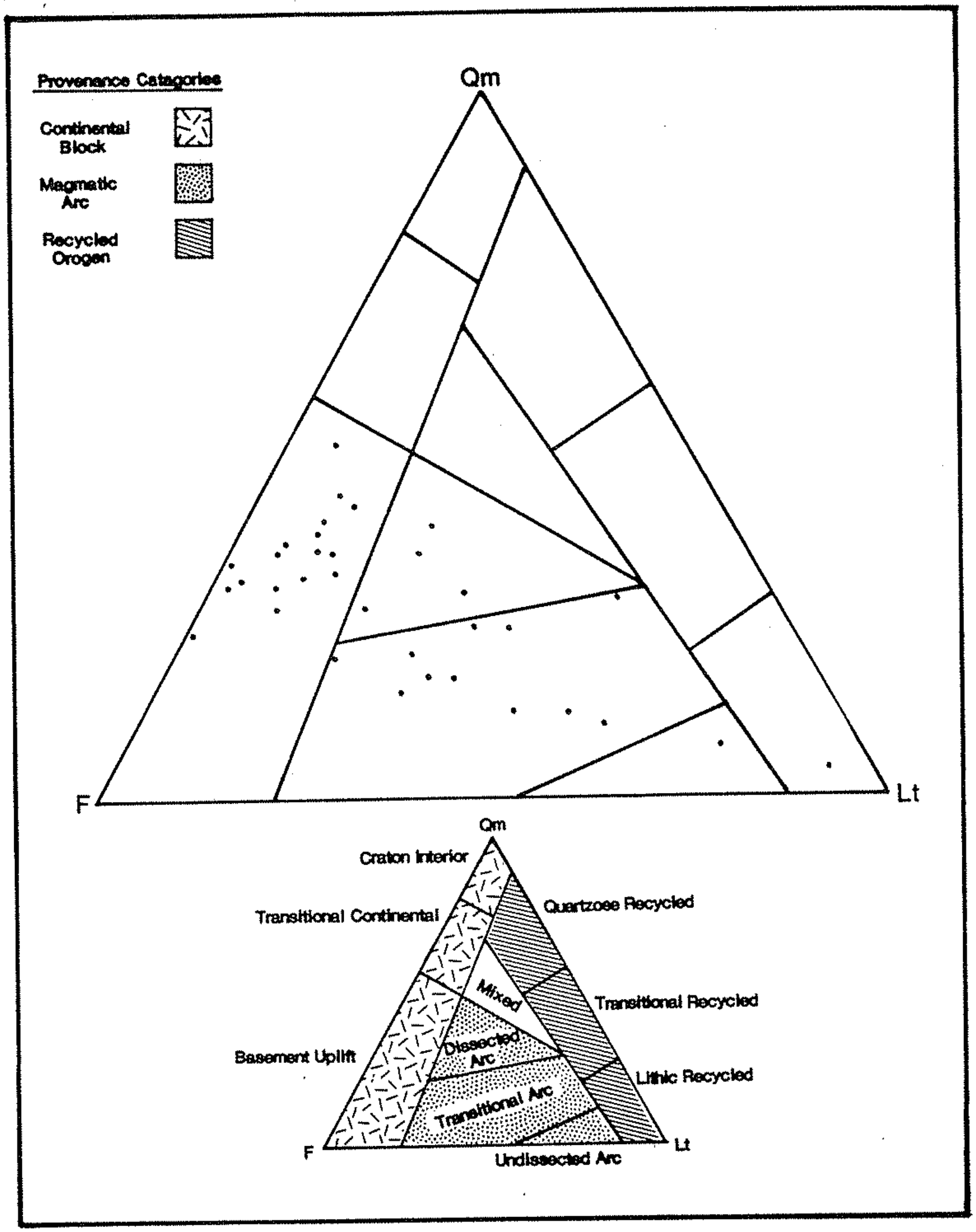


Figure 14. Compositional modes of 35 sandstone samples plotted on the tectonic-provenance classification of Dickinson and others (1983).

in the lower center of ternary diagrams. This provenance type is transitional with the uplifted continental block, where exposure of basement rocks produces clastic debris of arkosic composition. In summary, the composition of the Winthrop Sandstone (overall mode $Q_{32}F_{48}L_{20}$) indicates a dominant plutonic source, with contributions from surrounding and overlaying volcanic cover of intermediate composition.

On a more detailed scale of observation, specific grain types, notably quartz, may be indicative of provenance. Most of the quartz grains (83%) in the Winthrop are monocrystalline, which is characteristic of a plutonic source (Blatt and Christie, 1963). Polycrystalline quartz is most abundant in low rank metamorphics, and averages 29% and 13% of high rank ortho-metamorphics and plutonic rocks respectively (Basu and others, 1975). The subordinate affect of volcanic source rocks is also evidenced by the distinct lack of non-undulose quartz grains (Blatt and Christie, 1963). Quartz grains with undulose extinction containing abundant microlite inclusions which lack embayed outlines are most common in the Winthrop, and are atypical of volcanic quartz (Scholle, 1979). However, these data may have been influenced by diagenesis because "mechanical compaction suffered by sandstones with little matrix may give rise to a significant increase in the undulosity of monocrystalline quartz" (Arribas and others, 1985).

Rocks typical of a magmatic arc complex include diorite, quartz diorite, quartz monzonite, andesite, dacite, and basalt (Galloway, 1974). This is significant in that these rock types contain abundant plagioclase, which is the most common detrital grain in the Winthrop and constitutes nearly 100% of all feldspar grains. In addition, each of these rock types, and others containing abundant plagioclase, are exposed in the Okanogan Terrane east of the Methow Basin.

Westward directed paleocurrent data in the Winthrop Sandstone suggest the Okanogan Terrane as a probable source area (Cole, 1973). The Okanogan highlands are interpreted to represent a Late Triassic to Early Jurassic volcanic-plutonic arc complex with later magmatic events occurring through the Paleogene (Fox and others, 1977; Menzer, 1983). The Summit-Frazer Trondhjemite Gneiss is believed to be the pre-Late Mississippian basement in the area (Menzer, 1983). Although the oldest age date from this unit is 108 Ma (Engels and others, 1976), wide spread anatexis and remobilization from Mesozoic orogeny account for this discrepancy (Menzer, 1983). The Summit-Frazer is presently exposed across large areas east of the Pasayten Fault. Main phase rocks are mostly trondhjemites, with modal compositions of $P_{76}Q_{22}K_2$. Oligoclase is the most common plagioclase mineral (Menzer, 1983). The aerial extent of, and abundant sodic plagioclase contained within these trondhjemite gneiss' suggest them to be prime candidates for possible source rocks of the Winthrop Sandstone. The Summit-Frazer is equivalent, at least in part, to the Chewack River Gneiss Complex (Hawkins, 1968), the unamed leucocratic gneiss of Hibbard (1971), and the Gneissic Trondhjemite Of Tiffany Mountain (Rinehart, 1981).

Eugeosynclinal sedimentary and volcanic rocks were later deposited on top of the pre-Late Mississippian protolith (Menzer, 1983). These rocks vary in age from Late Mississippian to Early Jurassic and include: 1)the Hozameen Group (?) and Leecher Metamorphics in the Methow; 2) the Salmon Creek Schist and Spanish Camp Gneiss Complex just east of the Pasayten Fault; 3) the Anarchist Group and the Metamorphic Complex of Conconully farther to the east; 4) the Cache Creek and Nicola Groups in British Columbia; and 5) the Hozameen Group and Chilliwack Series to the west of the Methow (Hibbard, 1971; Rinehart and Fox, 1976; Menzer, 1983).

These geosynclinal and underlying basement rocks were strongly metamorphosed during Late Triassic-Early Jurassic orogeny. This episode gave rise to a host of deep seated mafic and intermediate intrusives favorable as source rock for the Winthrop Sandstone (Hibbard, 1971). Alteration envelopes surrounding these plutons were likely sources for the minor amounts of metamorphic rock fragments in the Winthrop. A partial list of these intrusive bodies, and names assigned by different workers, is given in Table 4.

During Jurassic time, volcanic cover evidently mantled the crystalline rocks of the Okanogan arc as evidenced by the lithic composition the the Newby Group (Tennyson and Cole, 1978). Continued erosion exposed the plutonic core giving rise to the arkosic sedimentation of the Harts Pass Group. Rejuvenated uplift, possibly in connection with the intrusion of the Horseshoe Magma Series and/or initial mobilization of the Okanogan Gneiss Dome (Hibbard, 1971; Fox and others, 1977), prompted another episode of erosion in the Okanogan highlands reflected in the arkosic sedimentation of the Winthrop Sandstone.

In summary, westward directed paleocurrent azimuths within the Winthrop Sandstone suggests the Okanogan Terrane, exposed east of the Methow Basin, as a probable source area. Framework composition of the Winthrop indicates a dominant plutonic source. Good candidates for source rocks of the Winthrop Sandstone include the Summit-Frazer Trondhjemite Gneiss, and many of the mafic and intermediate plutons of Late Triassic to Early Jurassic age. A list of these units is given in Table 4.

Table 4. Potential source rocks for the Winthrop Sandstone presently exposed in the Okanogan highlands.

Unit	Age	Dominant Composition
Summit-Frazer Trondhjemite Gneiss (Menzer, 1983).	pre-Late Mississippian	trondhjemite
Chopaka Intrusive Complex (Hibbard, 1971).	190.5 Ma	gabbro
Toats Coulee Magma Series (Hibbard, 1971).	Early Jurassic	tonalite quartz diorite
Loomis Pluton (Rinehart and Fox, 1972).	194 Ma	quartz diorite
Sinlahekin Tonalite (Hibbard, 1971).	Early Jurassic	tonalite
Sarsapkin Tonalite (Hibbard, 1971).	Early Jurassic	tonalite
Douglas Mountain Tonalite Porphyry (Hibbard, 1971).	Early Jurassic	tonalite
Toats Coulee Pluton (Rinehart and Fox, 1972).	170 Ma	granodiorite
Similkameen Composite Pluton (Fox et al., 1977).	166-190 Ma	granodiorite quartz diorite
Reed Creek Quartz Diorite Gneiss (Menzer, 1983).	Late Triassic Early Jurassic	quartz diorite
Leader Mountain Granodiorite Gneiss (Menzer, 1983).	Late Triassic Early Jurassic	granodiorite
Windy Hill Quartz Diorite (Menzer, 1983).	Late Triassic Early Jurassic	quartz diorite

PALEOCLIMATE

INTRODUCTION

Most paleogeographic reconstructions of the middle Cretaceous (Albian & Cenomanian) place the Methow Basin at approximately 55° N latitude along the west coast of North America (McKerrow, 1981; Parrish and others, 1982). At present this area is characterized by a seasonally cool temperate climate; however, the Cretaceous was a time of very low equatorial to polar thermal gradient (Batten, 1984). Middle Cretaceous climates in the temperate-polar latitudes were considerably warmer than present, and flora and fauna characteristic of lower latitudes were pushed far to the north (Barron and others, 1981). In addition, there is no evidence for Cretaceous glacial activity anywhere on the globe (Barron and others, 1981).

In the Winthrop Sandstone, direct or indirect evidence of paleoclimate is based on petrographic data and floral paleontology. However, these criteria yield conflicting interpretations about climatic conditions at the time of deposition.

FLORAL PALEONTOLOGY

Plant remains can be found throughout the finer-grained facies of the Winthrop Sandstone; however, the crevasse splays located between intervals 1080-1103 m in the type section (Appendix 3) produced the highest quality specimens. David Crabtree (written communication, 1986) from the University of Montana identified 15 specific genera from these beds. A complete list of these megafossil floras, along with those reported by Barksdale (1975), are given in Appendix 9.

The number of species presently identified in the Winthrop Sandstone (Appendix 9) is so restricted that quantitative evaluations of mean annual temperature, range of temperature, and other parameters amenable to leaf margin analysis are not possible (Crabtree, personal communication, 1986). In addition, since the flora are representative of a riparian community, the collection yields little if any information about precipitation. All that is directly evident is that the flora represents a community with both decidous and evergreen elements. Such a composition is typical of a broad range of recent "mesothermal" communities in several climatic regimes.

However, in the contex of other known floras geographically and chronologically proximal to the Winthrop, a more complete climatic reconstruction is possible. The majority of the taxa found in the Winthrop are common from Northern Rocky Mountain megafossil floras of late Albian age. Studies from many of these "Upper Blairmore" floral assemblages have yielded interpreted paleoclimates ranging from humid subtropical to warm temperate. Palynofloral studies in strata of Albian age also support this conclusion (Scott, 1973).

The contention that the Methow Basin was host to a warm, humid climate during the middle Cretaceous is also upheld by paleoecologists working on a global scale (Parrish and others, 1982; Batten, 1984). These workers have constructed paleoclimate maps based on worldwide correlation of plant fossils, and evaporite and coal belts. Their conclusions are consistent with those indicated above.

PETROGRAPHIC DATA

The three main factors which control sandstone composition are source terrane, climate and depositional environment (Dickinson and Suczek, 1979). Optimum conditions for the preservation of climatic signature on sandstone composition are: 1) source rock and tectonic setting remaining constant throughout deposition; 2) coarse-grained crystalline source rock; 3) short transport distances; 4) deposition in a nonmarine environment; 5) shallow burial diagenesis; and 6) first cycle sedimentation (Suttner and Dutta, 1986). In the Winthrop, each of these conditions appear to have been met; however, consideration of modal composition data seemingly leads to erroneous conclusions on climatic conditions.

The Winthrop Sandstone is characterized by the abundance of chemically unstable plagioclase feldspar. Plagioclase grains are typically sensitive to climatic control as they undergo rapid disintegration and alteration in the weathering environment. Suttner and Dutta (1986) has proposed a quantitative method of paleoclimate interpretation based on logarithmic plots of feldspar and rock fragments verses quartz. Using the petrographic data of the Winthrop Sandstone in conjunction with this methodology, indicates deposition occurred in a semi-arid climate. Such an interpretation is in clear contradiction with those conclusions based on floral remains of middle Cretaceous age. Apparently source terrane, rich in plagioclase feldspar, exerted the controlling effect on the composition of the Winthrop Sandstone. The only climatic signature apparent in the Winthrop framework is the distinct lack of calcium rich plagioclase, which degrades more rapidly than sodic varieties.

SUMMARY OF PALEOCLIMATE

Although a paleoclimatic reconstruction based on floral remains within the Winthrop is not possible, studies from other late Albian floras in the Northern Rocky Mountain region indicate a humid subtropical to warm temperate climate at that time. This conclusion is also supported by paleoecologists working on a worldwide scale, where the middle Cretaceous is seen as a time of pronounced global warming. However, the abundance of plagioclase in the Winthrop Sandstone suggests climatic conditions approaching semi-arid. Apparently source area, containing abundant feldspar, exerted the controlling affect on the composition of the Winthrop Sandstone and overshadowed any climatic signature.

AGE AND CORRELATION

The Winthrop Sandstone is temporally and lithologically correlative with the Pasayten Group in Manning Park, and the Kingsvale Group in the Tyaughton Basin, British Columbia (Barksdale, 1975; Kleinspehn, 1984). Flora in the Winthrop is very similar to that reported by Coates (1974) in the Pasayten Group, and all taxa collected from these units indicates an Albian age. New collections from the Winthrop during this study have not refined its known age range.

Although plant fossils within the Winthrop indicate a late Albian age, other evidence demonstrates it is younger. Marine fauna collected from the underlying Slate Peak Member of the Virginian Ridge are of late Albian to Cenomanian age. However, it appears that any relative dating techniques based on sediment thickness of the Winthrop are invalid. This study has shown that the Winthrop may actually be less than half the thickness reported by Barksdale (1975). This implies the Winthrop was deposited in a much shorter time span than previously thought.

The controversy surrounding the age of the Winthrop remains obscure, but best evidence shows deposition probably initiated during early Cenomanian time. Further work on the paleontology of the Virginian Ridge and Winthrop, along with radiometric dating of their intercalated hypabyssal rocks and the overlying Midnight Peak will no doubt shed more light on this question.

SUMMARY

The Upper Cretaceous Winthrop Sandstone consists of three general lithofacies which, in order of increasing abundance, are conglomerate facies, fine-grained facies and sandstone facies. Respectively, these three general lithofacies comprise 2%, 5% and 93% of all section measured.

Overall compositional mode of the sandstone lithofacies is $Q_{32}F_{48}L_{20}$ which plots as a lithic arkose, although arkoses are the most common rock type. Plagioclase constitutes nearly 100% of all feldspar grains. The sandstones can be divided into six separate facies on the basis of sedimentary structures. These facies are: Sm, massive to crudely bedded sandstone; Sp, planar crossbedded sandstone; St, trough crossbedded sandstone; Se, crudely crossbedded sandstone; Sr, ripple laminated sandstone; and Sh, horizontally bedded and laminated sandstone.

The fine-grained facies consists of siltstones with minor amounts of claystone. Siltstone intervals average 0.5 m to one meter in thickness, although they vary from two centimeters to five meters thick. Fossilized plant debris is common, and in some intervals accounts for a significant portion of the framework element. Based on sedimentary structures, the fine-grained lithofacies is further subdivided into two facies: Fl, laminated siltstones with very small ripples; and, Fsc, massive to laminated siltstones.

Conglomerates are dominantly matrix supported with angular to subangular clasts ranging in size from 0.5 cm to ten centimeters. Clast lithologies consist of, in order of decreasing abundance: intraclasts, chert and volcanic lithic fragments. Chert pebble conglomerates are generally confined to the basal sections of the Winthrop, and are identical in nature to those of the underlying Virginian Ridge Formation. Based on sedimentary structures, conglomerate facies are: Gms, massive, matrix supported conglomerate; Gm, massive to crudely bedded, matrix supported conglomerate; Gp, planar crossbedded conglomerate; and, Gt, trough crossbedded conglomerate.

The Winthrop Sandstone is conformably underlain by the Virginian Ridge Formation, although the nature of the contact varies considerably. At the type section, the two units are gradational over approximately 350 meters of section while at Whiteface Creek, the contact is sharp. Farther to the northwest, at Slate Peak, lithologies typical of the Winthrop and Virginian Ridge are completely interbedded throughout the stratigraphic interval normally occupied by the Winthrop Sandstone.

The Winthrop is gradationally overlain by the volcanics and volcanoclastics of the Midnight Peak Formation; however, local unconformities do exist. In the upper intervals of the type section, red beds of the Ventura Member of the Midnight Peak Formation are interbedded with lithologies typical of the Winthrop Sandstone. This relationship indicates that the Boesel Fault truncated little, if any section off the top of the Winthrop at the type section. This suggests that the complete type section (1700 m) may represent the maximum thickness of the Winthrop Sandstone as compared to the 4,115 m thickness reported by Barksdale (1975).

Study of paleocurrent indicators within the Winthrop Sandstone shows a strong east to west direction of sediment transport. This east to west, proximal to distal, relationship is represented by variations in lithofacies both laterally across the basin and vertically through the section. The Winthrop shows a westward decrease in average grain size and sand:shale ratios. In addition, nonresistant volcanic lithic fragments are depleted to the west, but anomalous values at Early Winters Creek reflect local syndepositional igneous activity. Bedding thickness decreases towards the west as well as upward through the section.

The overall depositional system represented by the Winthrop Sandstone is a prograding paralic system, grading upward into a mobile channel, bed-load dominated fluvial system of low sinuosity. Critical arguments for this interpretation are: 1) facies relationships with the marine deposits of the Virginian Ridge Formation; 2) lack of marine fauna within the Winthrop; 3) presence of plant fossils; 4) evidence of subaerial exposure (rooting); 5) abundance of chemically unstable framework grains such as plagioclase and rock fragments; 6) lack of wave formed features; 7) inferred channel sequences, laterally extensive and generally less than ten meters thick; and 8) overall facies relationships.

Beds of chert pebble conglomerate in the lower Winthrop were deposited in a shallow, restricted marine basin (Trexler, 1984). All of the rocks beneath the uppermost occurrence of chert pebble conglomerate were deposited under marine conditions.

The majority of the Winthrop Sandstone is the result of continental fluvial sedimentation. The Winthrop is characterized by a lack of incised channel geometry, but visible channel margins are at a low angle and composed of sandstone. These unstable banks facilitated extensive lateral migration whereby creating a multi-lateral channel architecture. Many of the laterally extensive channel deposits are also stacked vertically in a multi-story fashion. Channel deposits contain a wide variety of internal structures. Pointbar sequences are present, but complete sequences are rarely preserved. Overall, greater than 90% of the fluvial portion of the Winthrop Sandstone resulted from channel sedimentation. Interchannel deposits include both overbank shales, crevasse splays and coal. The paucity of overbank deposits is the result of erosion on the upper alluvial plain, and transport of these sediments through the depositional system. The lack of abundant erosion surfaces suggests the later as being the dominant process. This implies that the Winthrop fluvial system was bed-load dominated.

Westward directed paleocurrent azimuths within the Winthrop Sandstone suggests the Okanogan Terrane, exposed east of the Methow Basin, as a probable source area. Framework composition of the Winthrop indicates a dominant plutonic source. Potential source rocks for the Winthrop Sandstone, presently exposed in the Okanogan highlands, are the Summit-Frazer Trondhjemite Gneiss and an assortment of mafic to intermediate plutons of Late Triassic to Early Jurassic age.

APPENDIX 1

LOCATION OF MEASURED SECTIONS

All measured sections lie on the Robinson Mountain (1:100,000) topographic sheet, Washington. Sections one through five correspond to location numbers given in Figure 1.

1- Type Section: Located 11.2 km northwest of Winthrop on state highway 20 (sec 13, 14, T35N, R20E; Mazama, Washington 1:62,500 sheet). Section was measured along the hillslope from southeast to northwest.

2- Whiteface Creek Section: Section begins in the saddle between McLeod Mountain and the unamed peak (7680 ft) 1.6 km to the southwest (no T&R grid; Mazama, Washington 1:62,500 sheet). The section was measured through the overturned beds along the hillslope of the easternmost tributary of Whiteface Creek.

3- Early Winters Creek Section: Measured along the steep hillslope overlooking the north bank of Early Winters Creek, approximately 3 km upstream from its confluence with the Methow River (no T&R grid; Mazama, Washington 1:62,500 sheet).

4- North Devils Peak Section: Located in the extreme southwest corner of the Mount Lago sheet, Washington (no T&R grid; 1:24,000), 1.2 km north of Devils Peak and 1.4 km east of Robinson Pass. This section is contained within the Pasayten Wilderness Area.

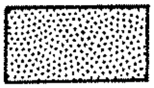
5- Slate Peak Section: Located just within the boundaries of the Pasayten Wilderness Area in the saddle between Slate Peak and Haystack Mountain (no T&R grid; Slate Peak, Washington 1:24,000 sheet).

APPENDIX 2

EXPLANATION OF SYMBOLS USED IN STRATIGRAPHIC SECTIONS

LITHOLOGIC UNITS

 - Conglomerate

 - Sandstone

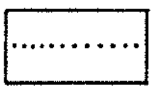
 - Siltstone

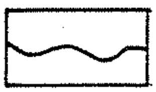
 - Intercalated Hypabyssal Rocks

 - Intrusive Rocks

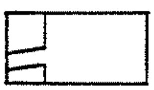
TYPE OF CONTACT

 - Sharp

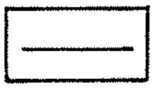
 - Gradational

 - Erosional

 - Covered Interval (shown to scale)

 - Covered Interval (not to scale)

TYPES OF SEDIMENTARY STRUCTURES

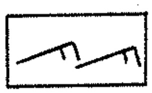
 - Horizontal Bedding

 - Laminations

 - Tabular Crossbeds

 - Trough Crossbeds

 - Scour and Fill

 - Ripples

ACCESSORY ELEMENTS

 - Plant fossils

 - Rooting

 - Rip up clasts

X - Tool marks

S - Scour marks

 - Load casts / soft sediment deformation

 - Convolute laminations

C - Chert

Ln - Lenticular bedding

Fl - Flaser bedding

Rb - Associated red beds (Ventura Mem.)

O - Nodules

GRAIN SIZE

Clay - 0.7 cm

Silt - 1.3 cm

VFS - 1.8 cm

FS - 2.0 cm

MS - 2.3 cm

CS - 2.5 cm

VCS - 2.8 cm

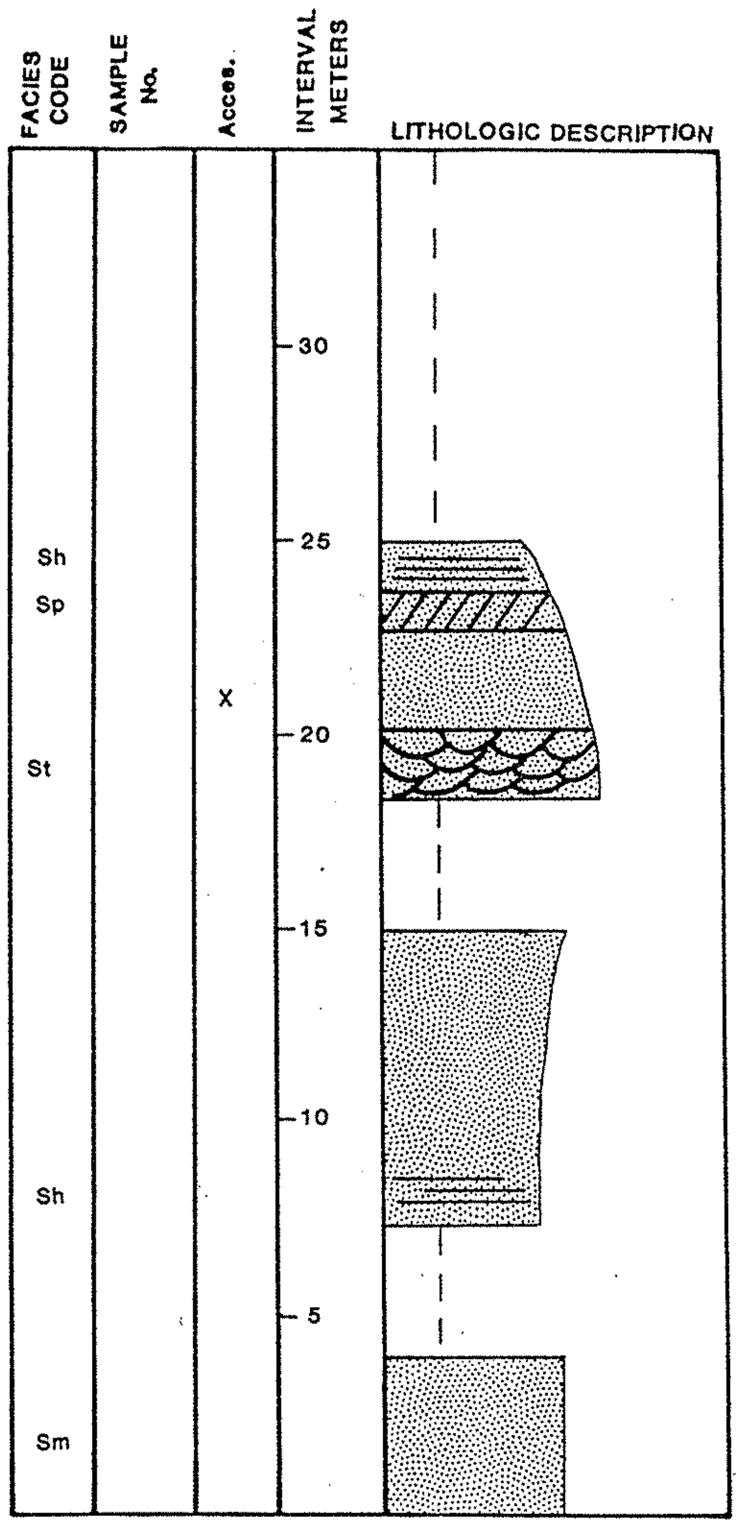
Gravel - 3.3 cm

(Measurements in reference to distance from baseline.)

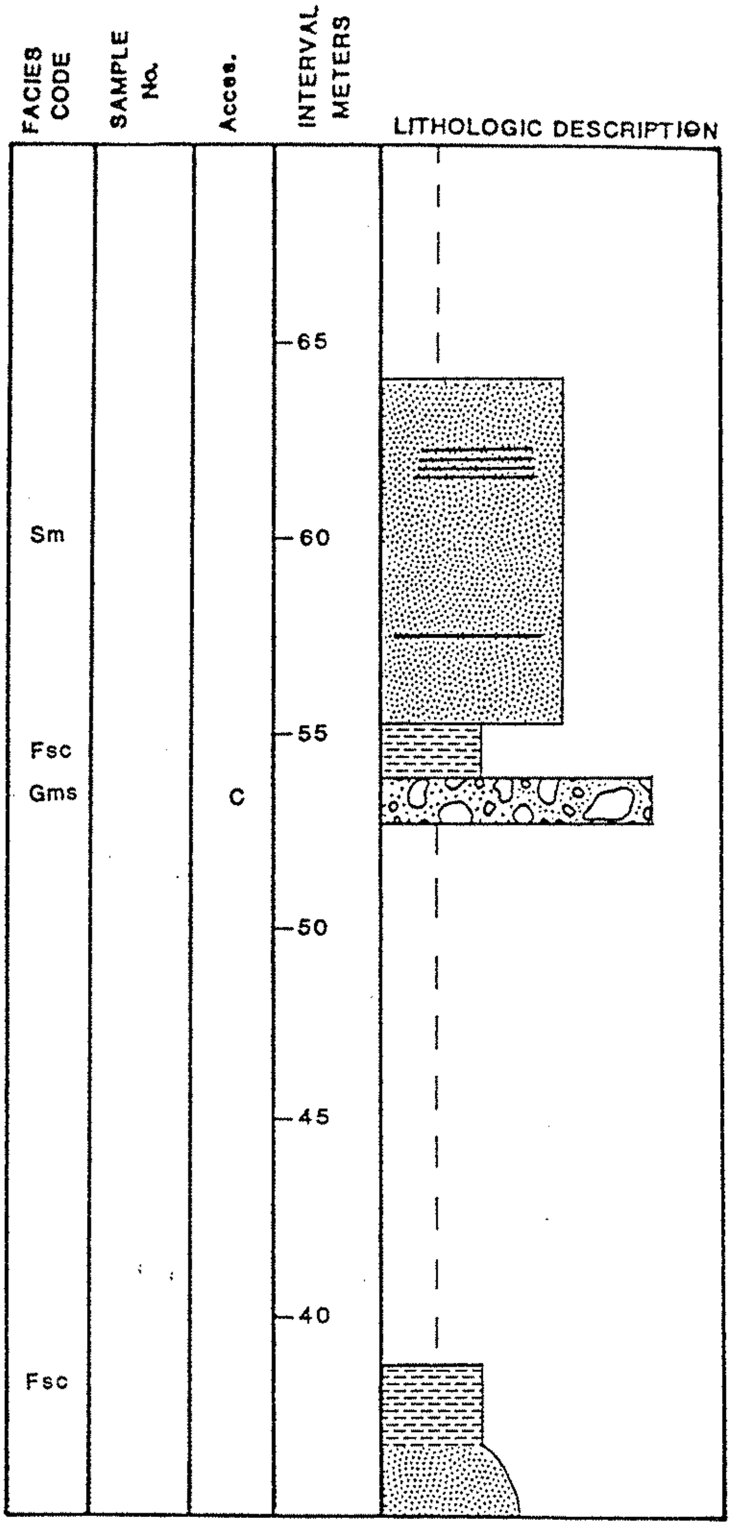
APPENDIX 3

TYPE SECTION

TYPE STRATIGRAPHIC SECTION

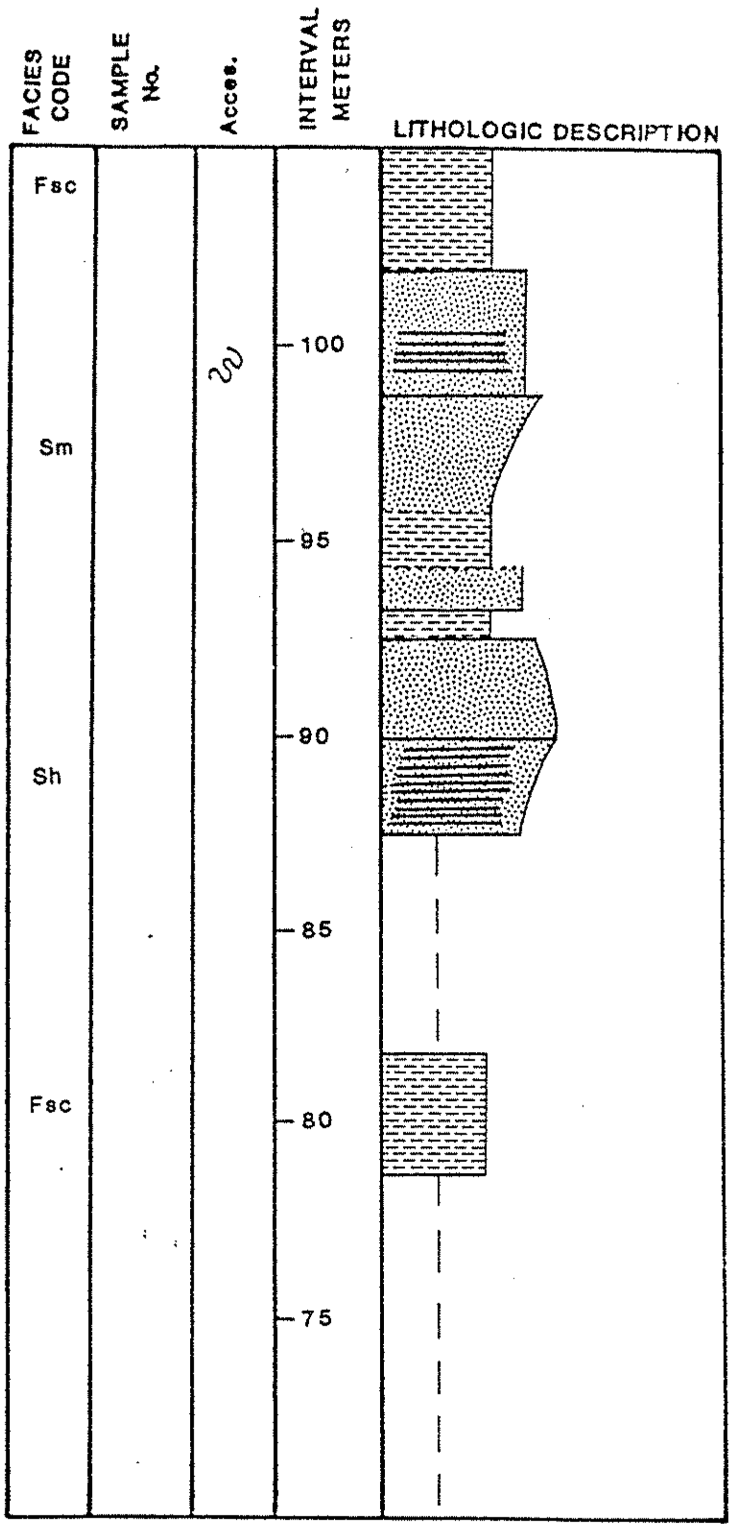


TYPE STRATIGRAPHIC SECTION
(CONTINUED)



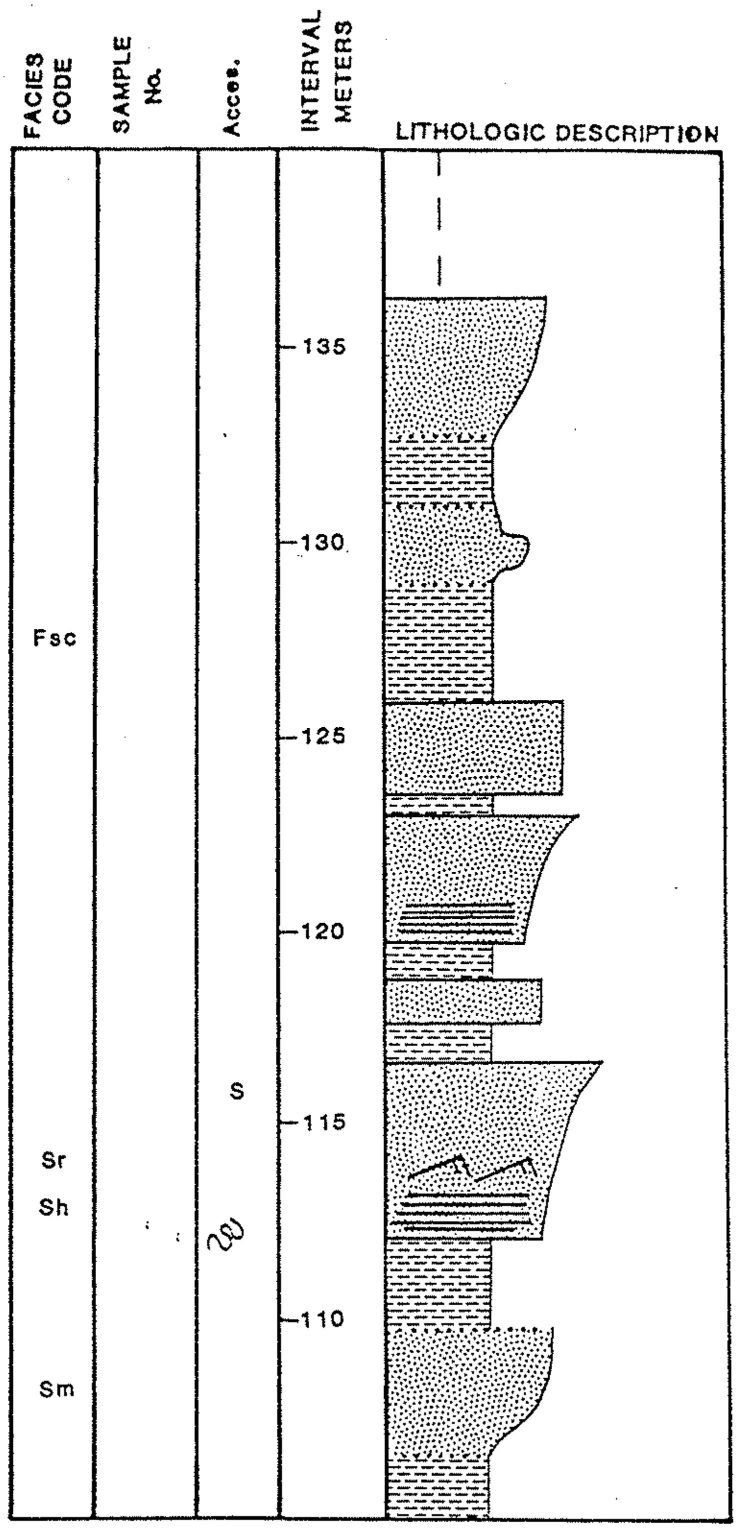
TYPE STRATIGRAPHIC SECTION

(CONTINUED)

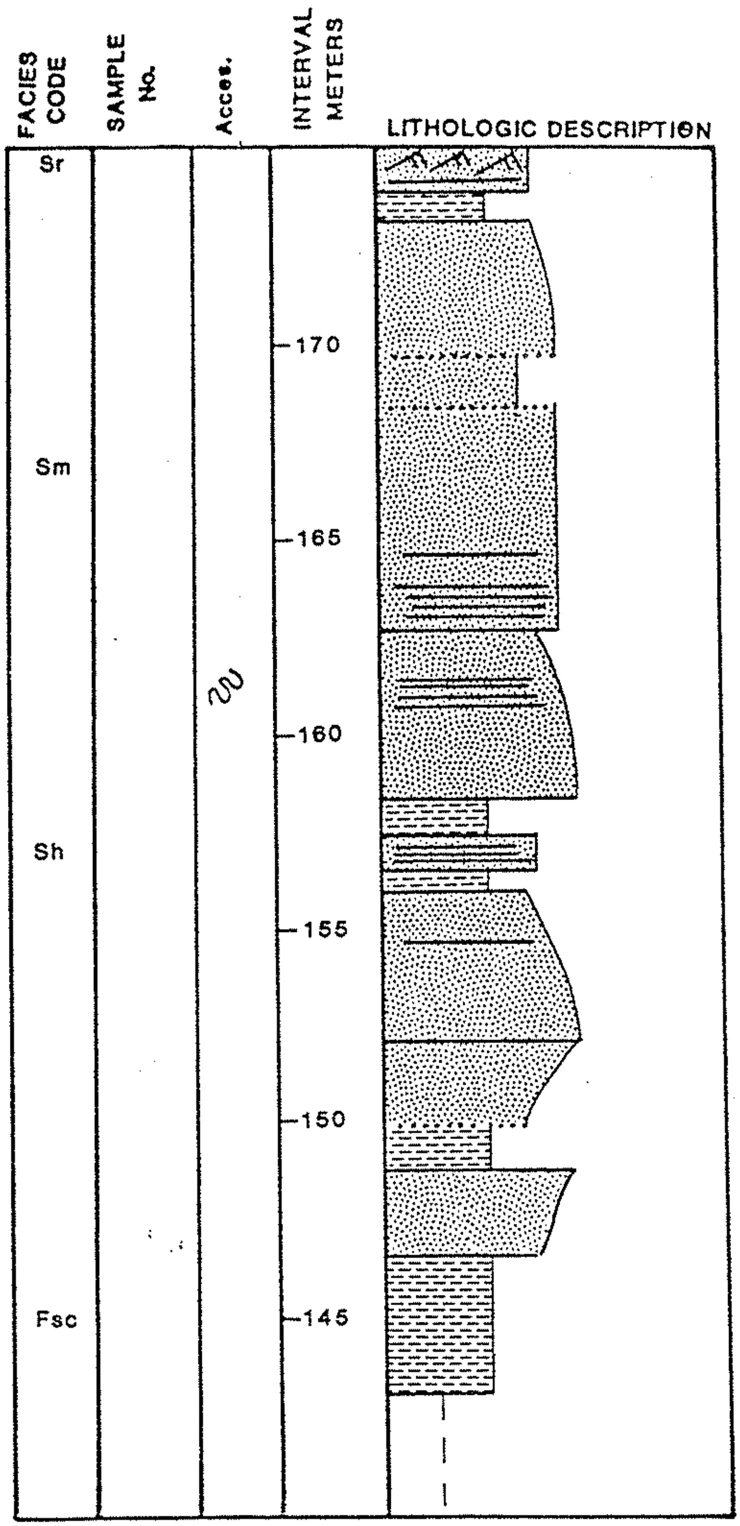


TYPE STRATIGRAPHIC SECTION

(CONTINUED)

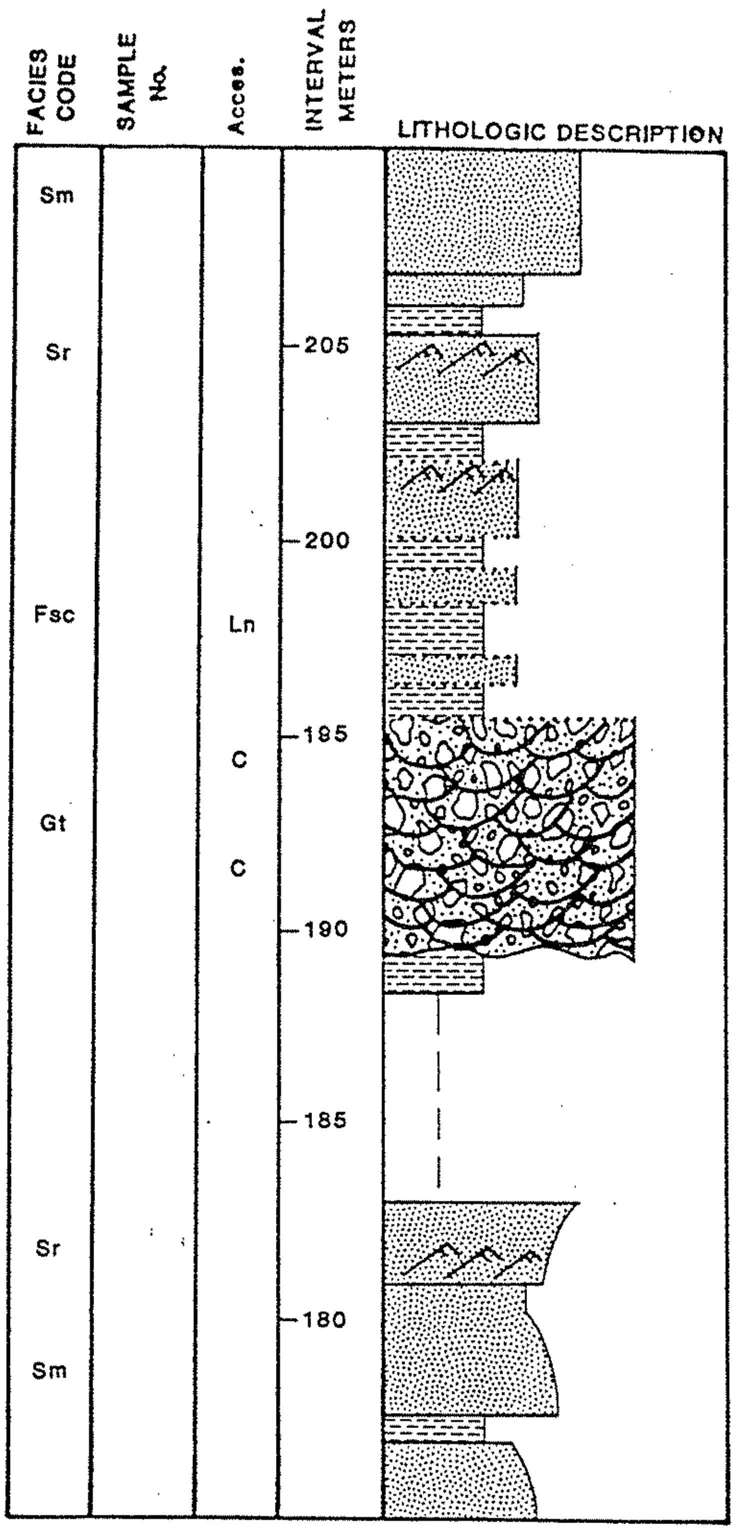


TYPE STRATIGRAPHIC SECTION
(CONTINUED)

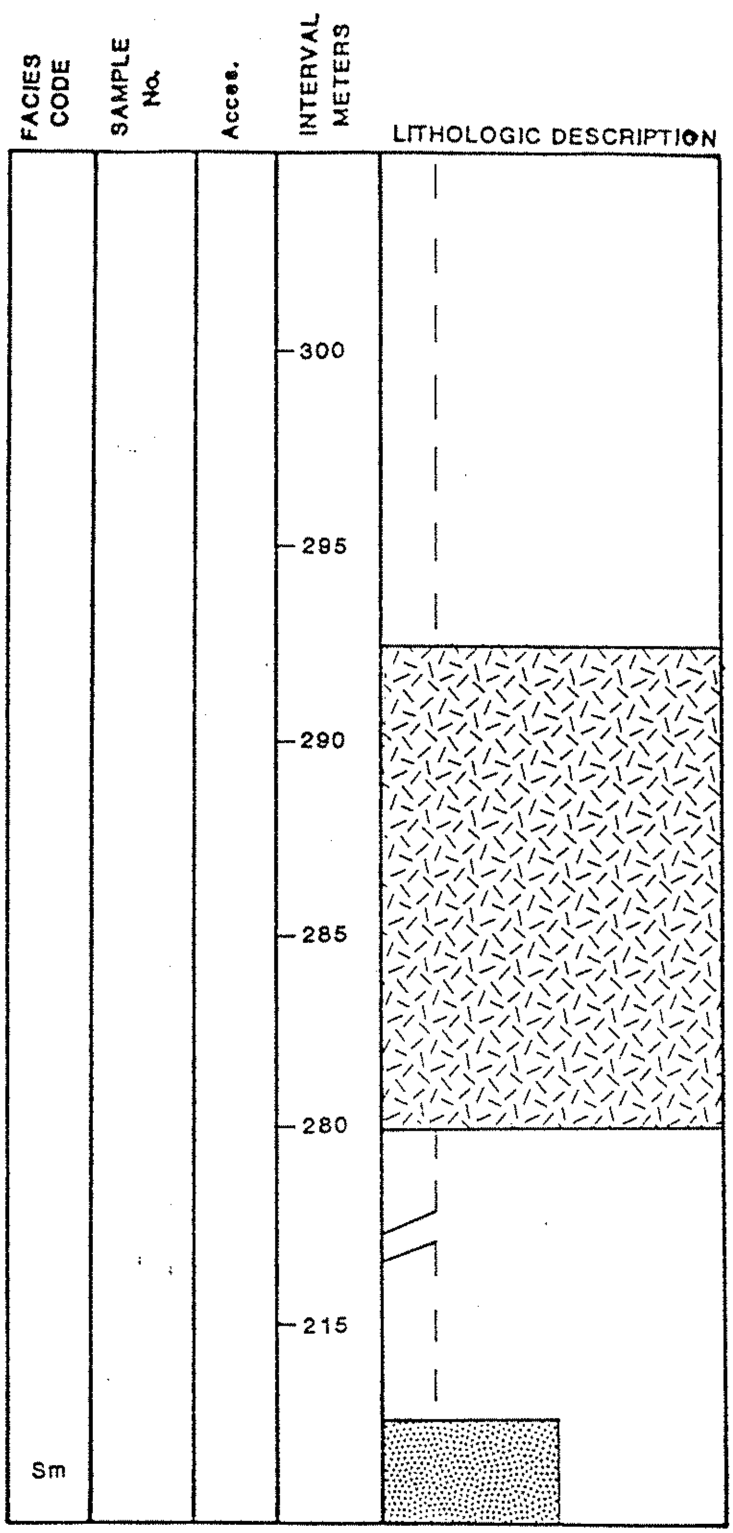


TYPE STRATIGRAPHIC SECTION

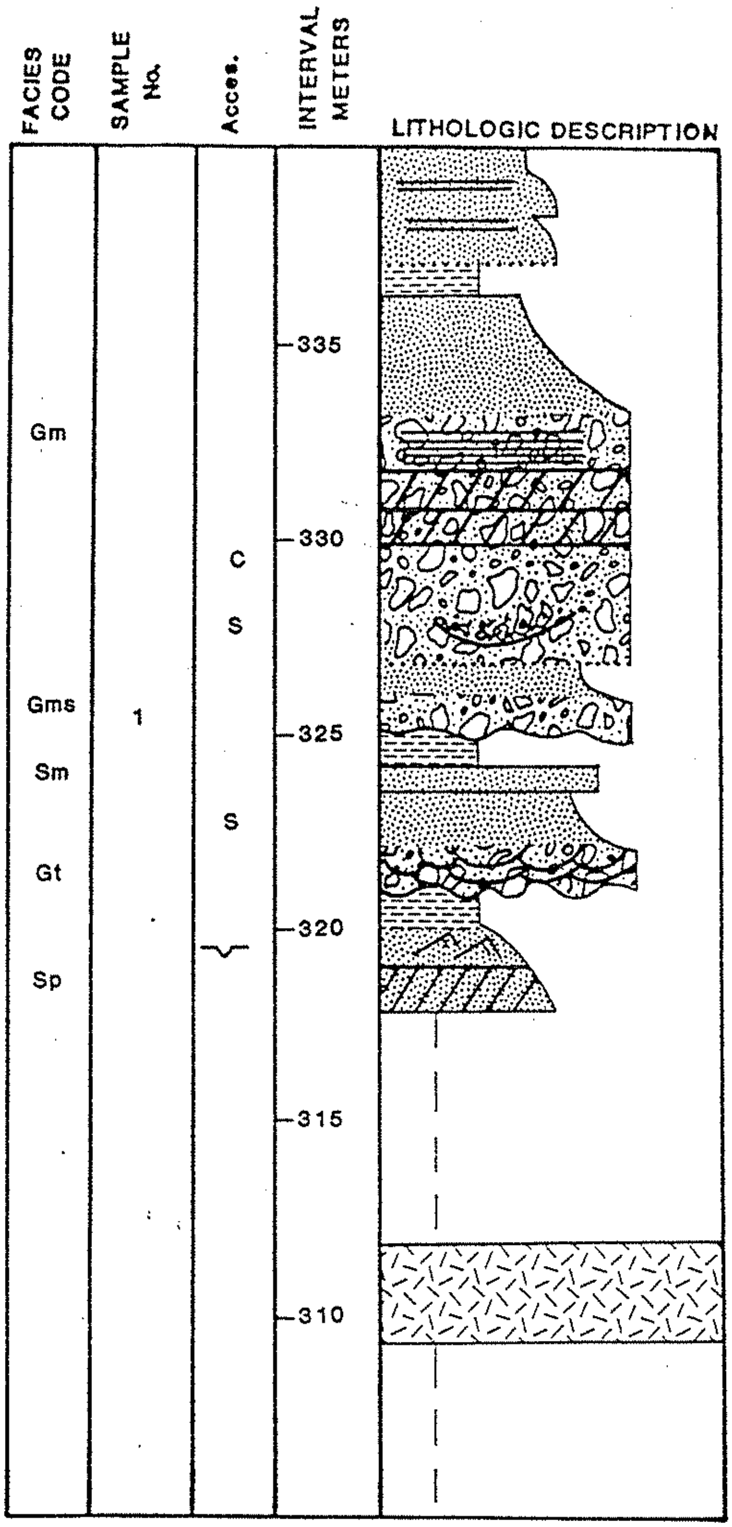
(CONTINUED)



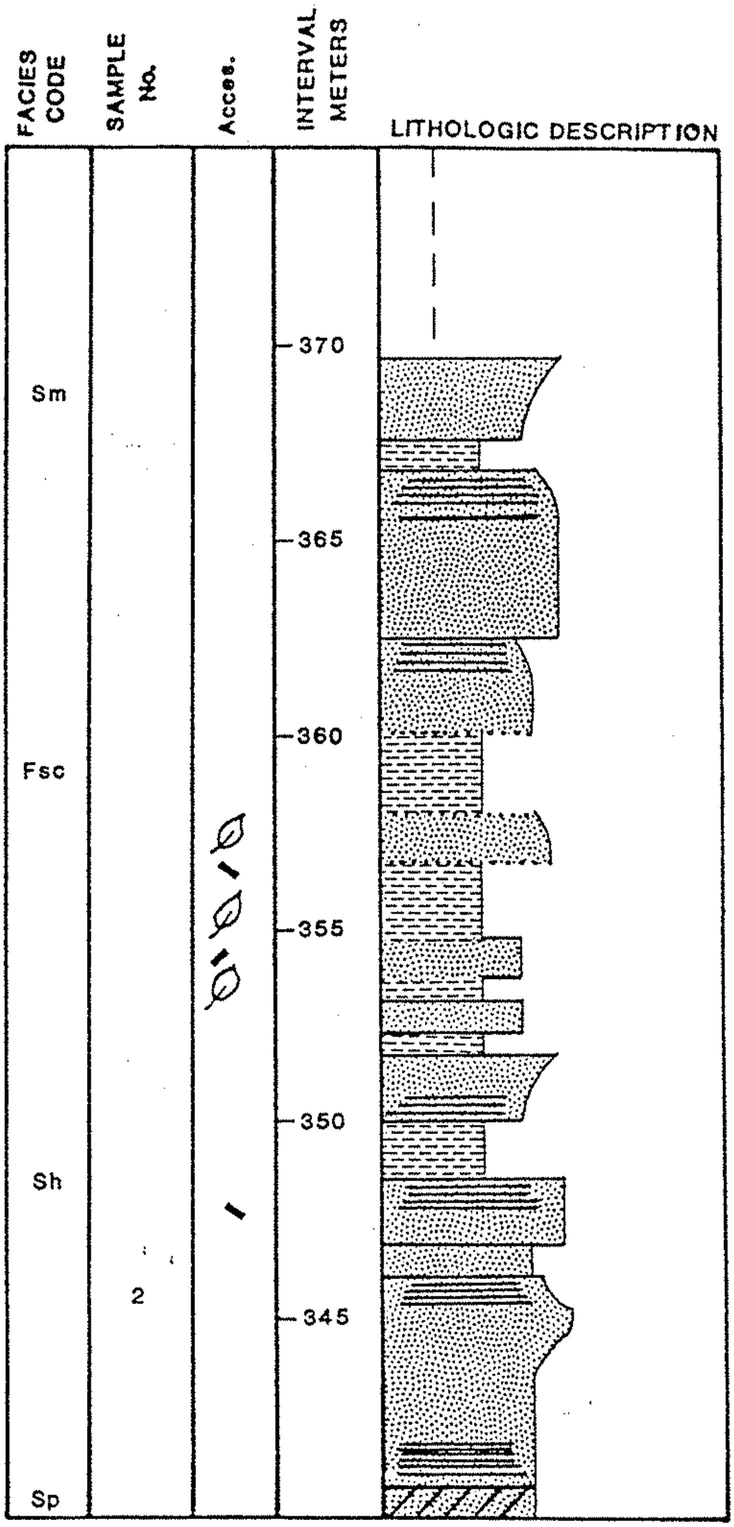
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



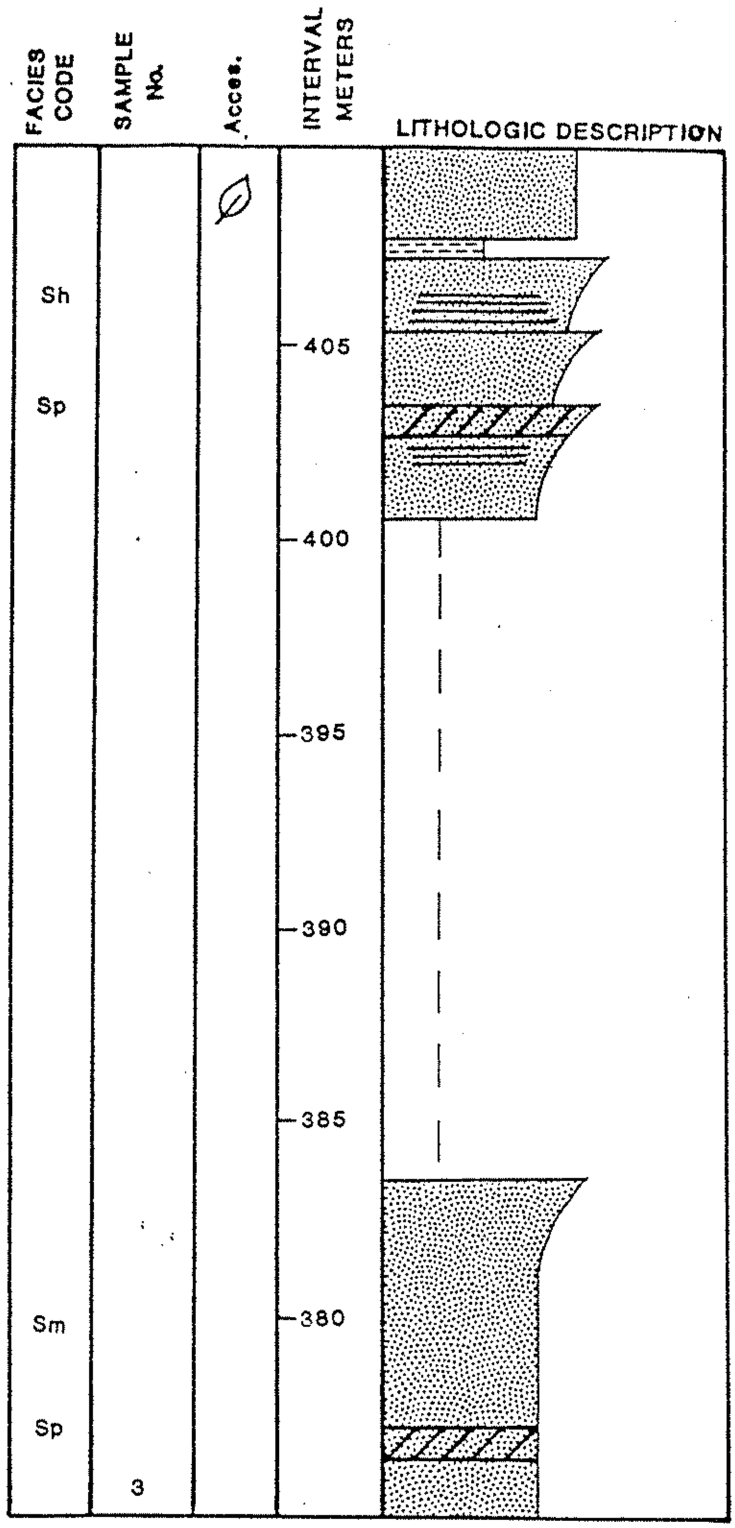
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



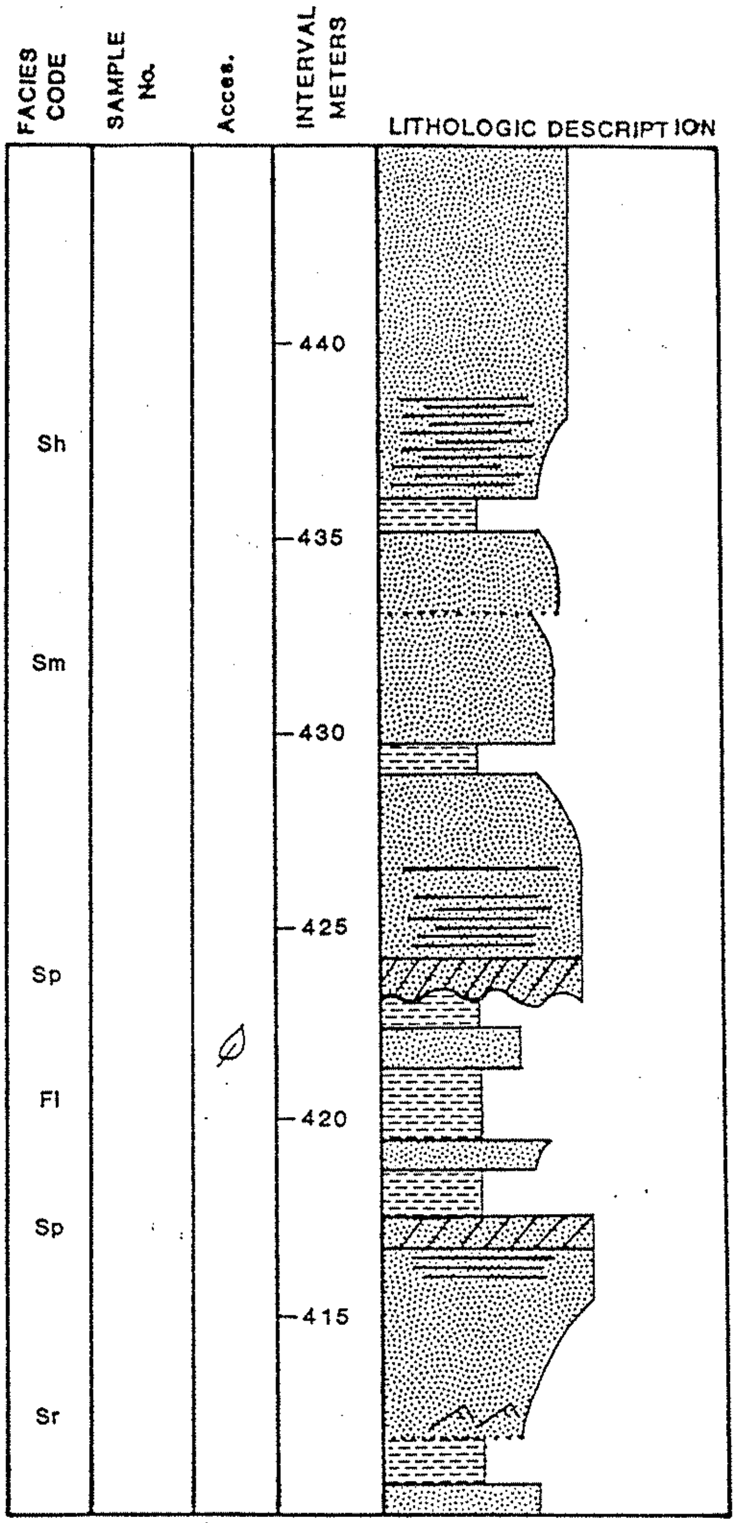
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



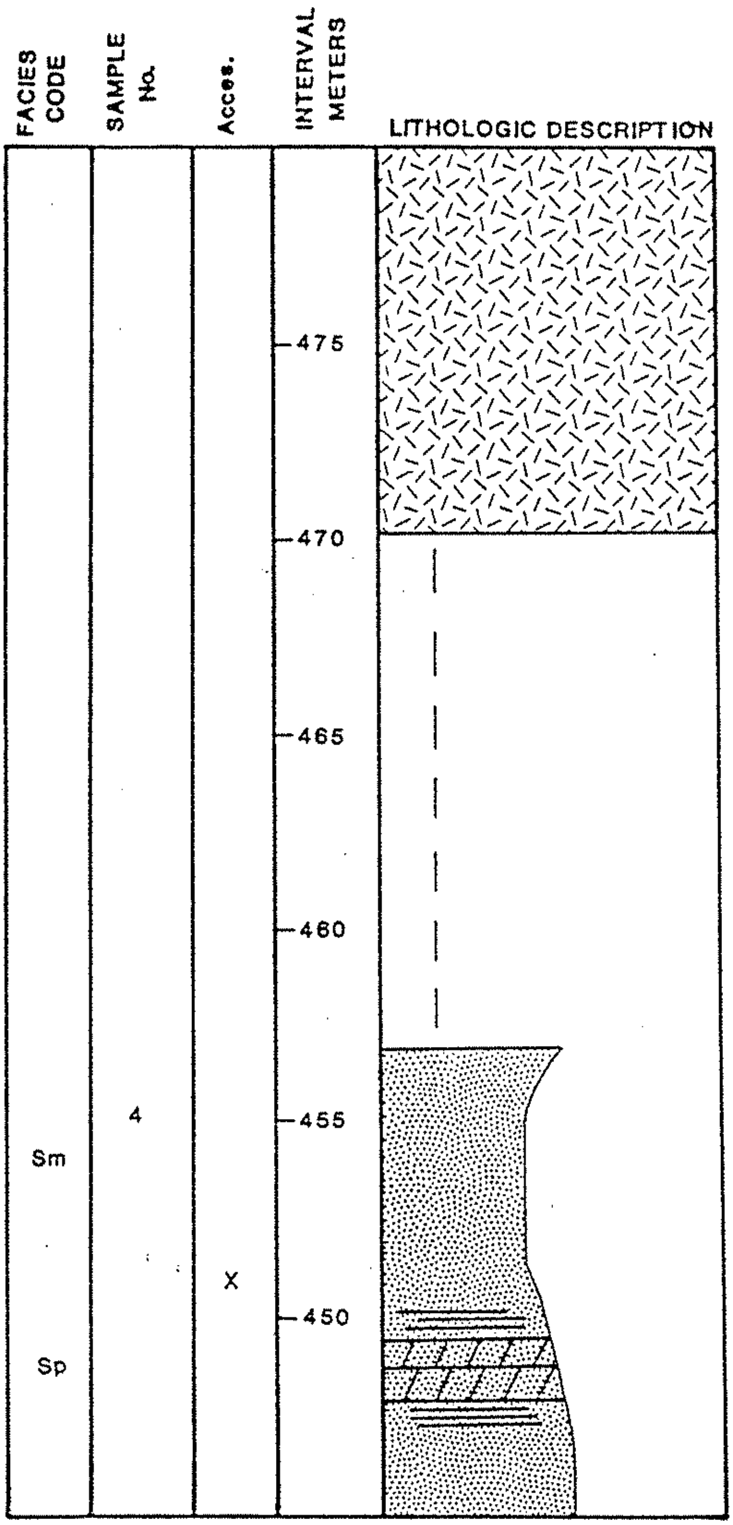
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



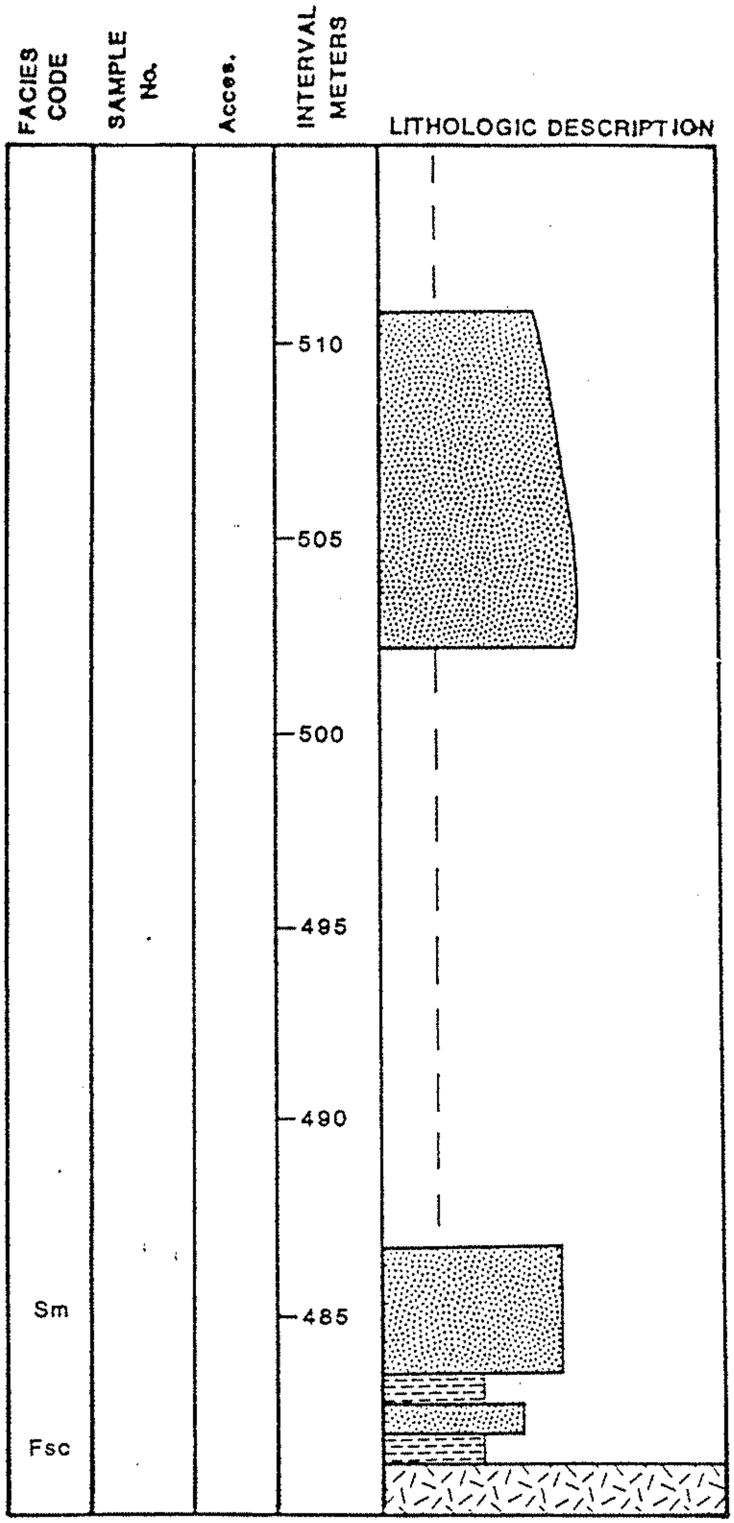
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



TYPE STRATIGRAPHIC SECTION
(CONTINUED)

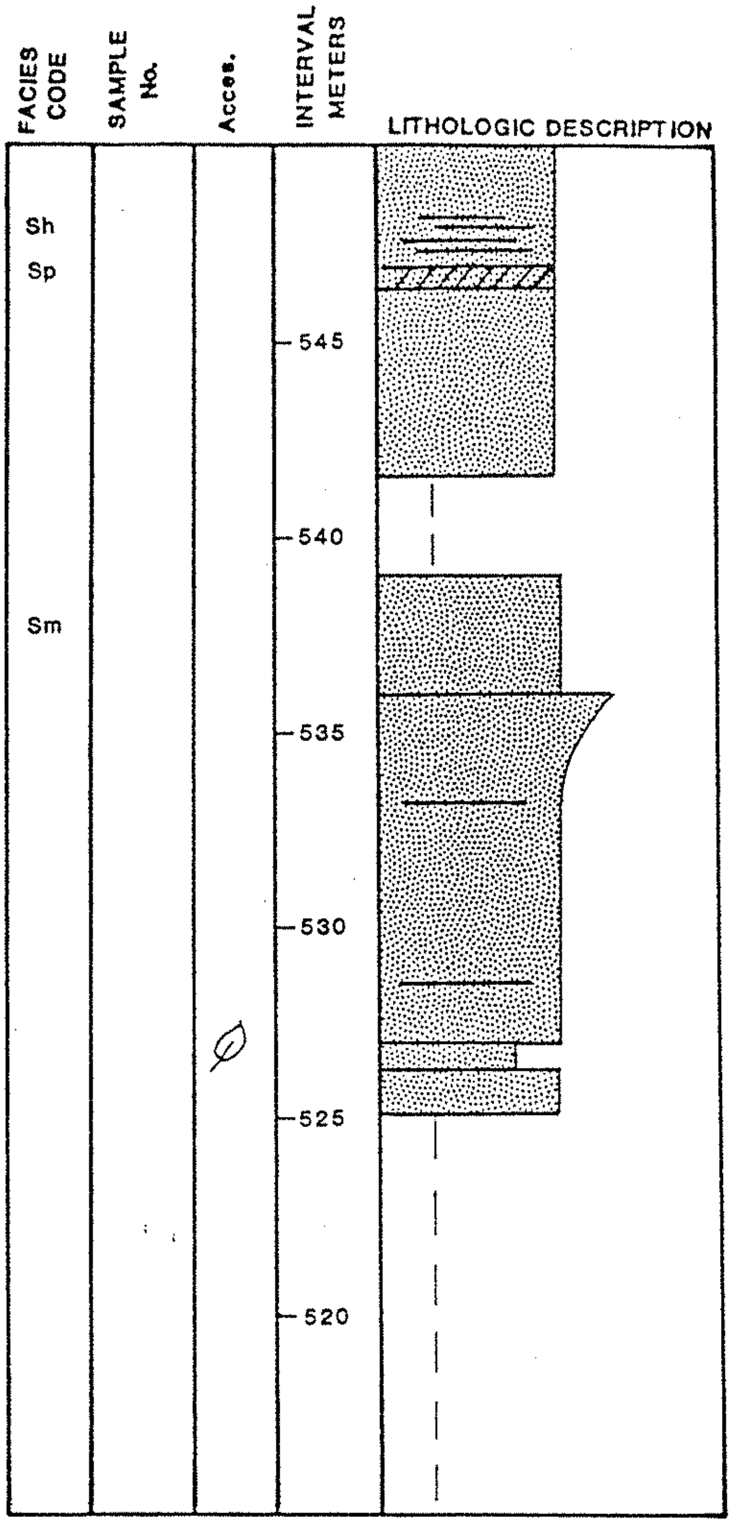


TYPE STRATIGRAPHIC SECTION
(CONTINUED)

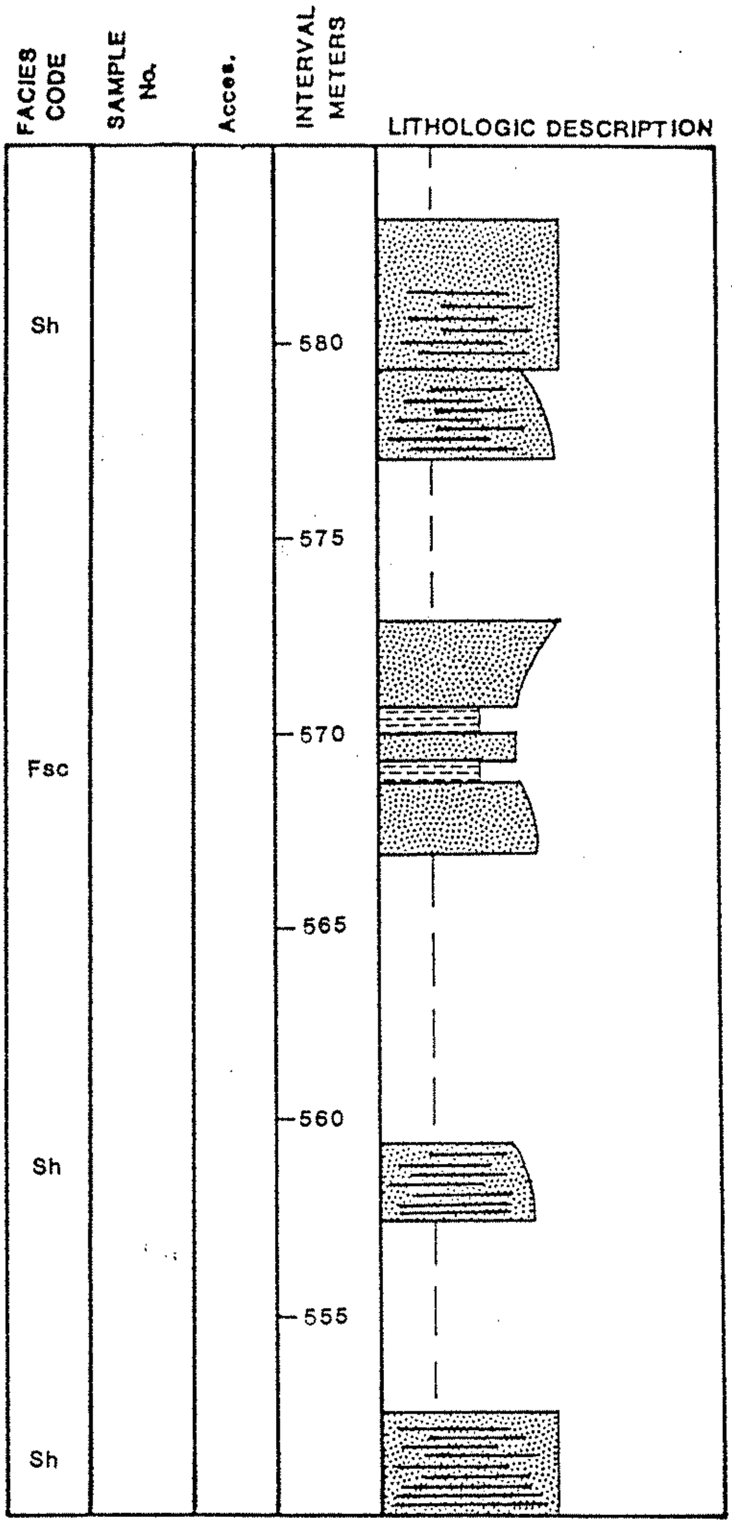


TYPE STRATIGRAPHIC SECTION

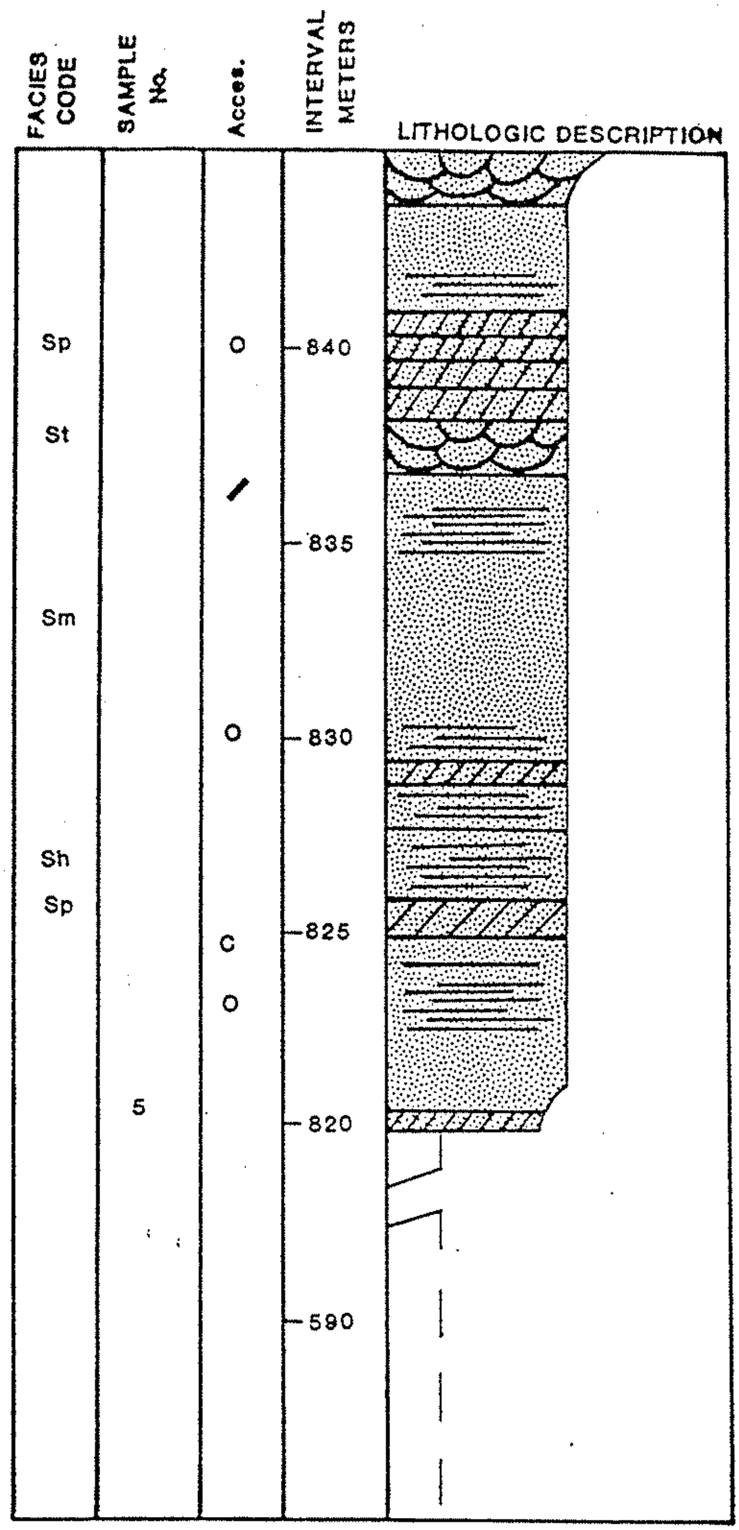
(CONTINUED)



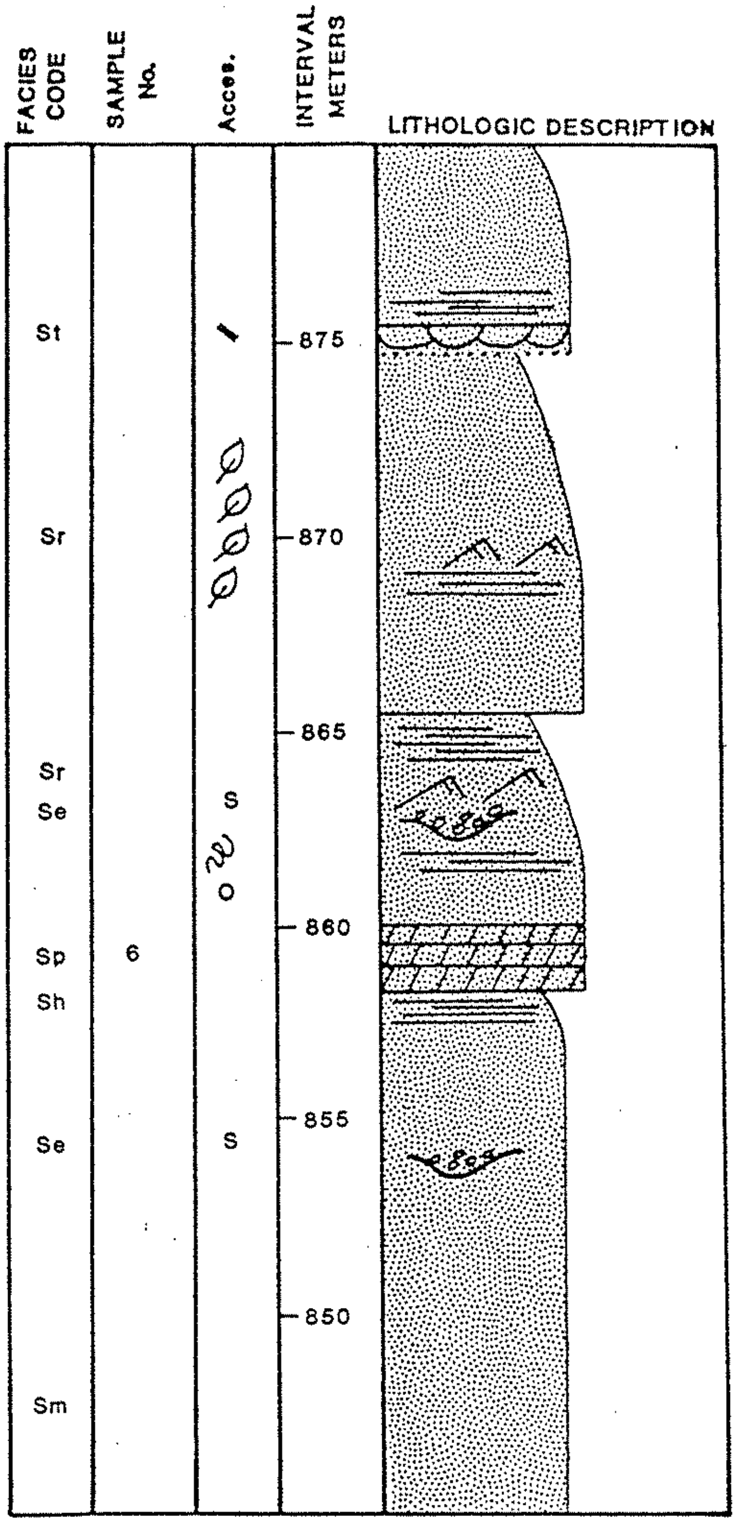
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



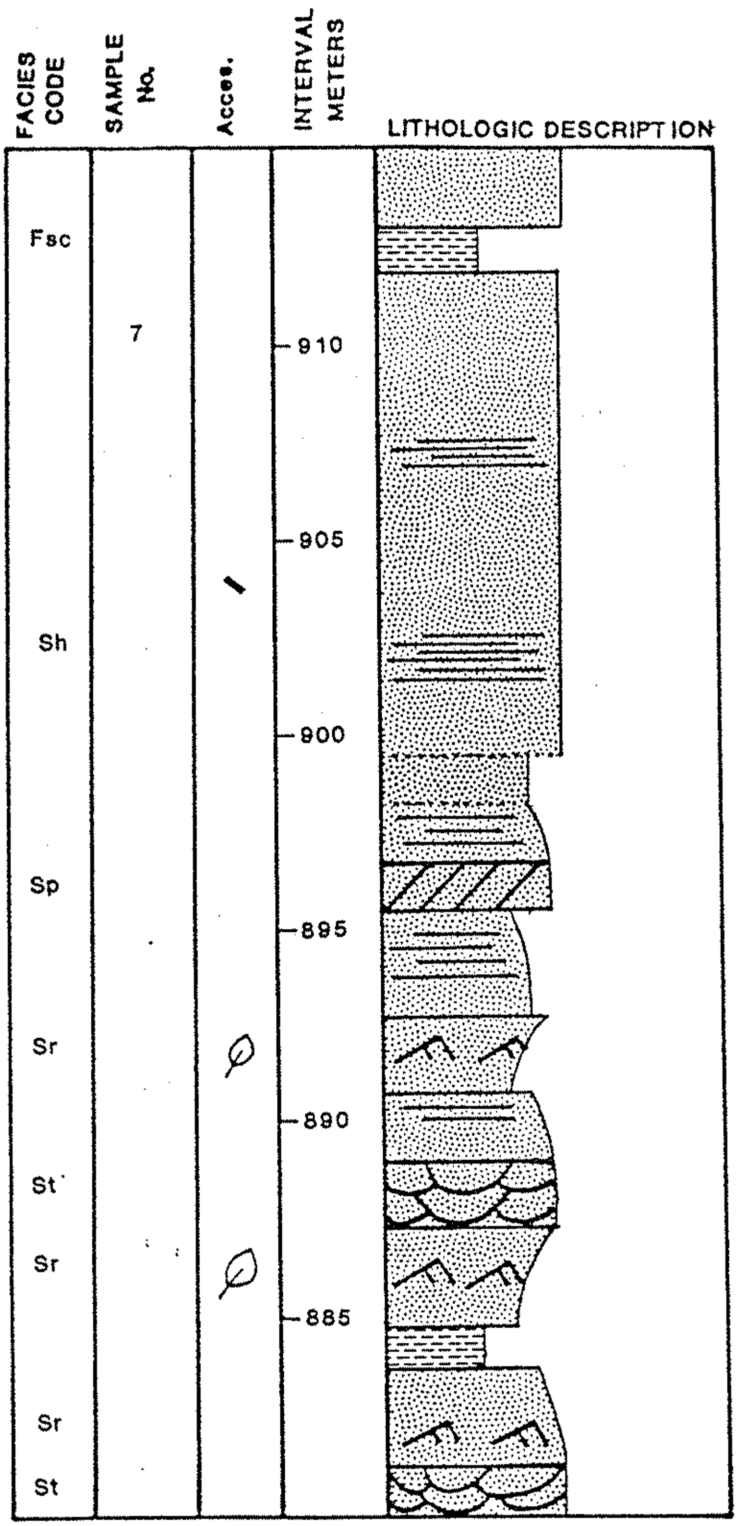
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



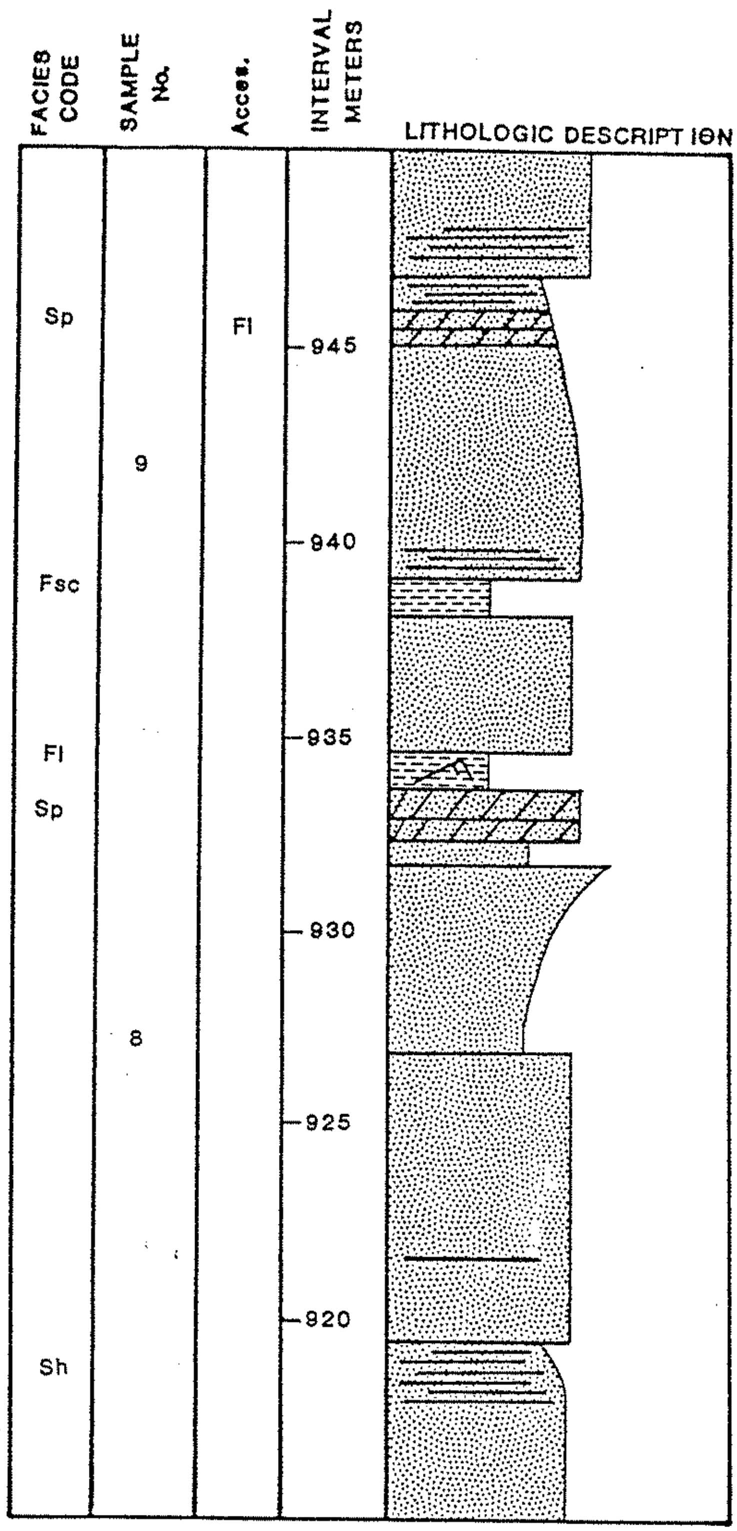
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



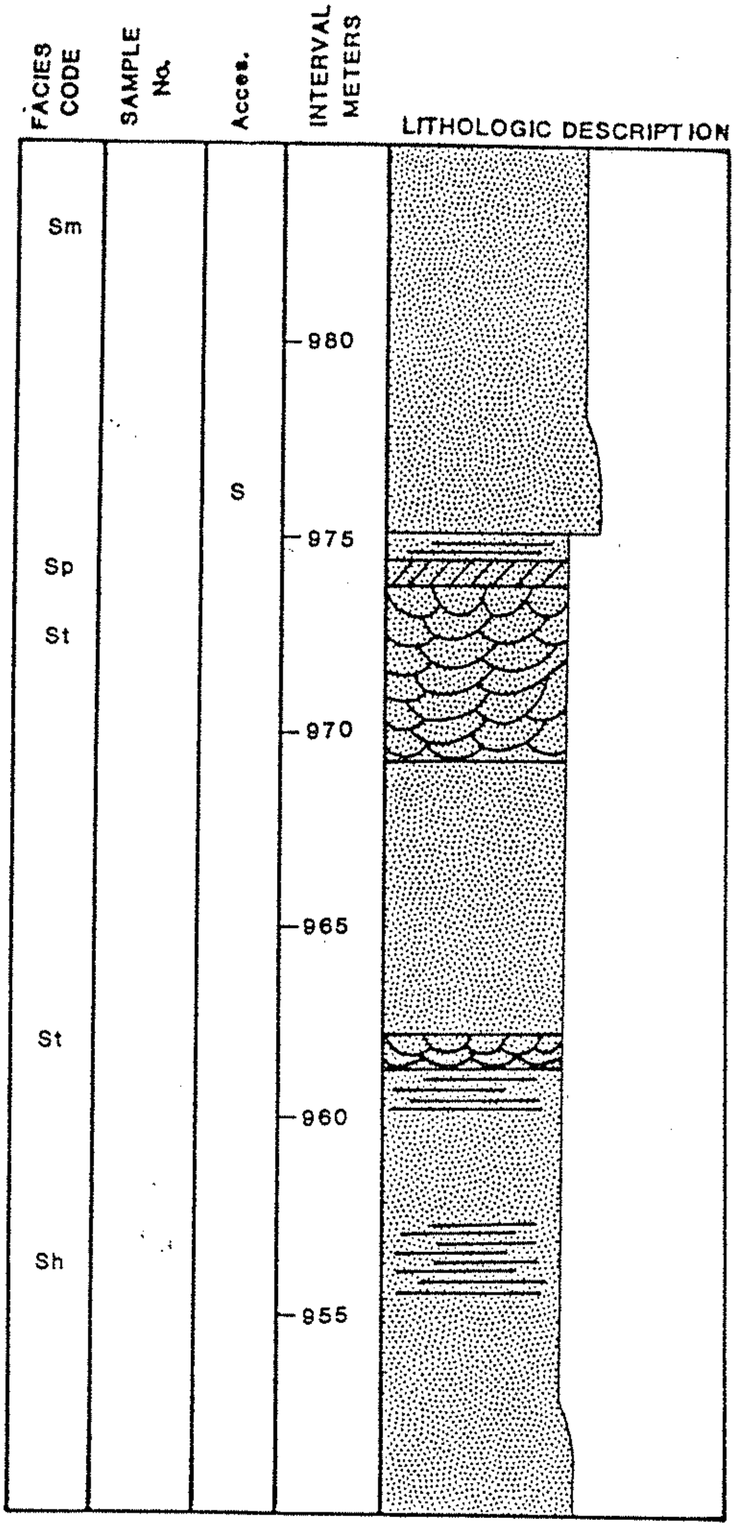
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



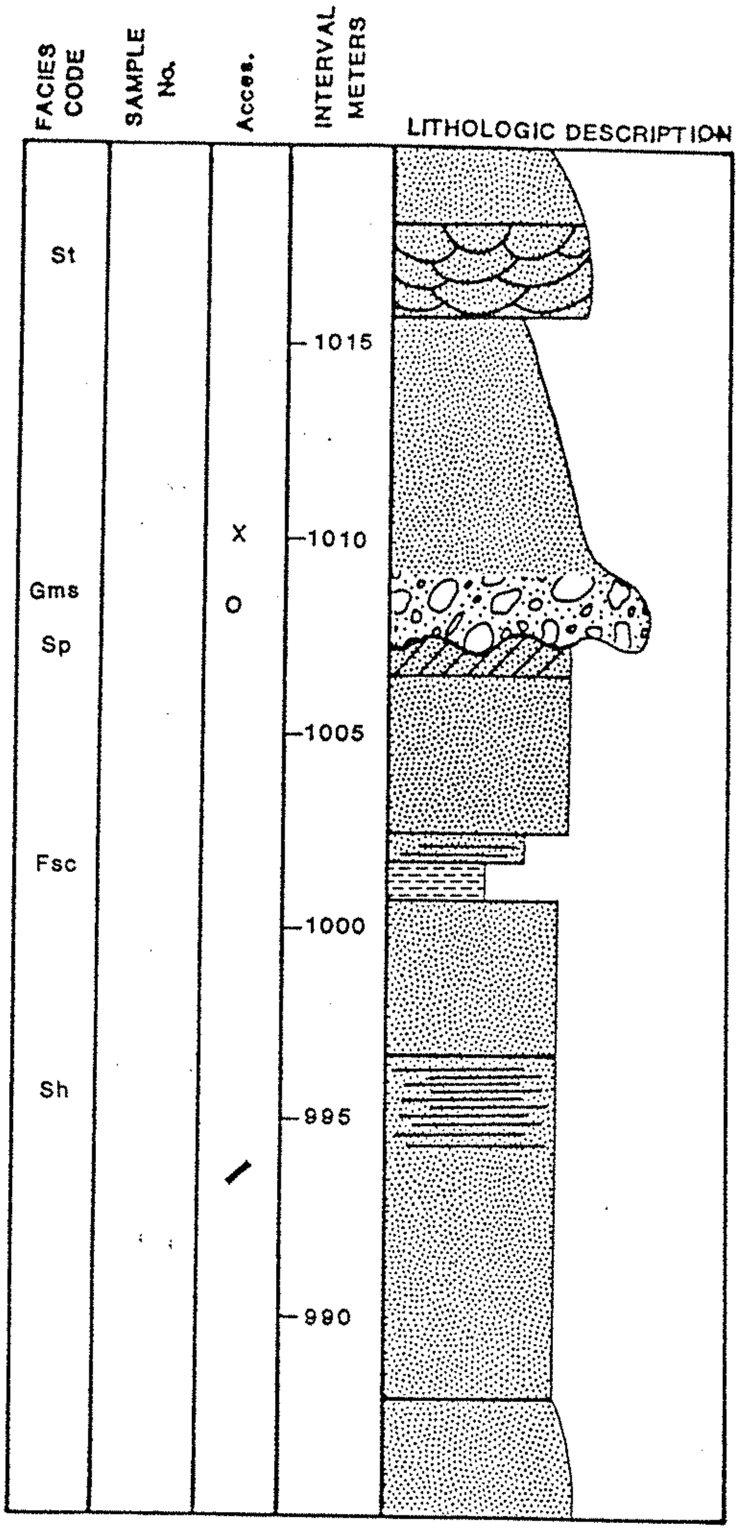
TYPE STRATIGRAPHIC SECTION (CONTINUED)



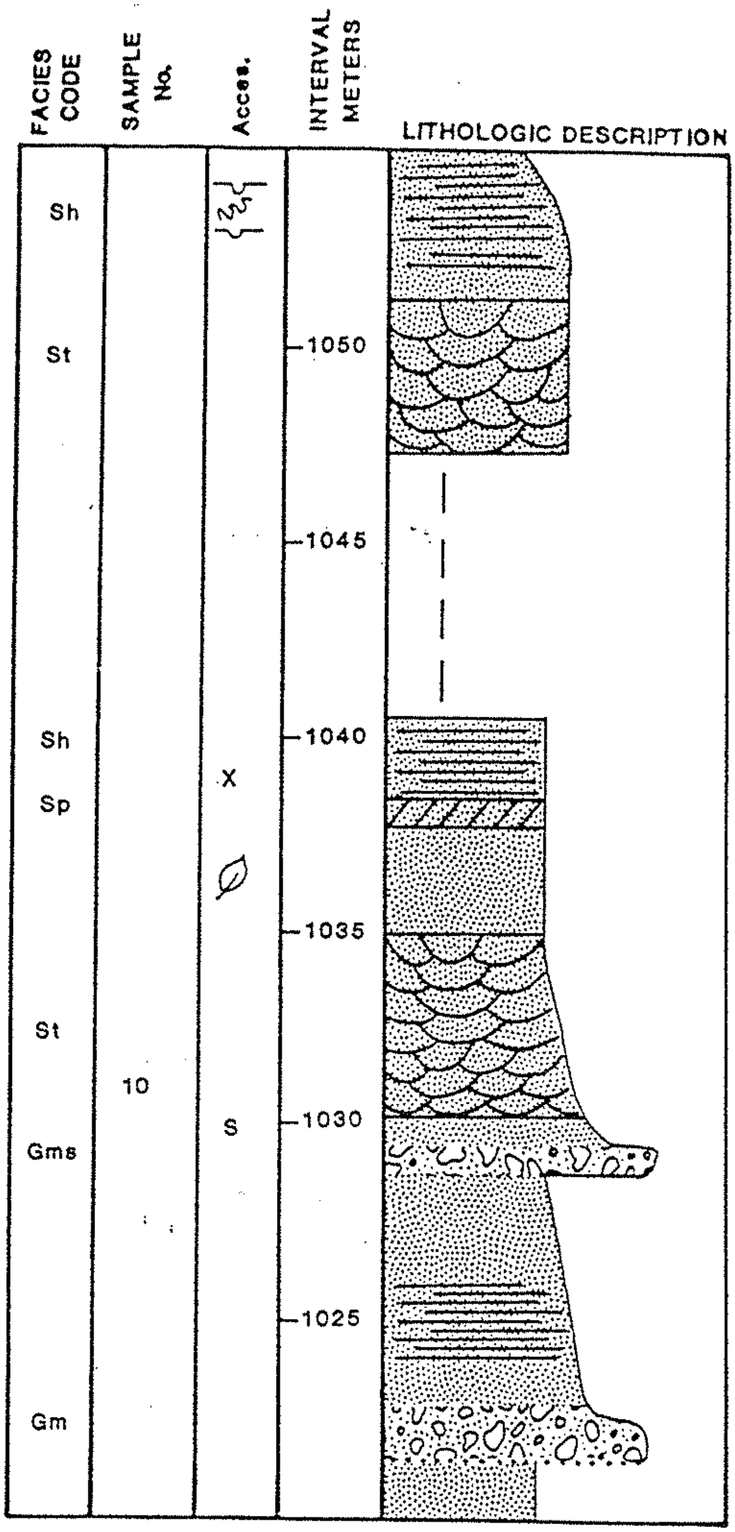
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



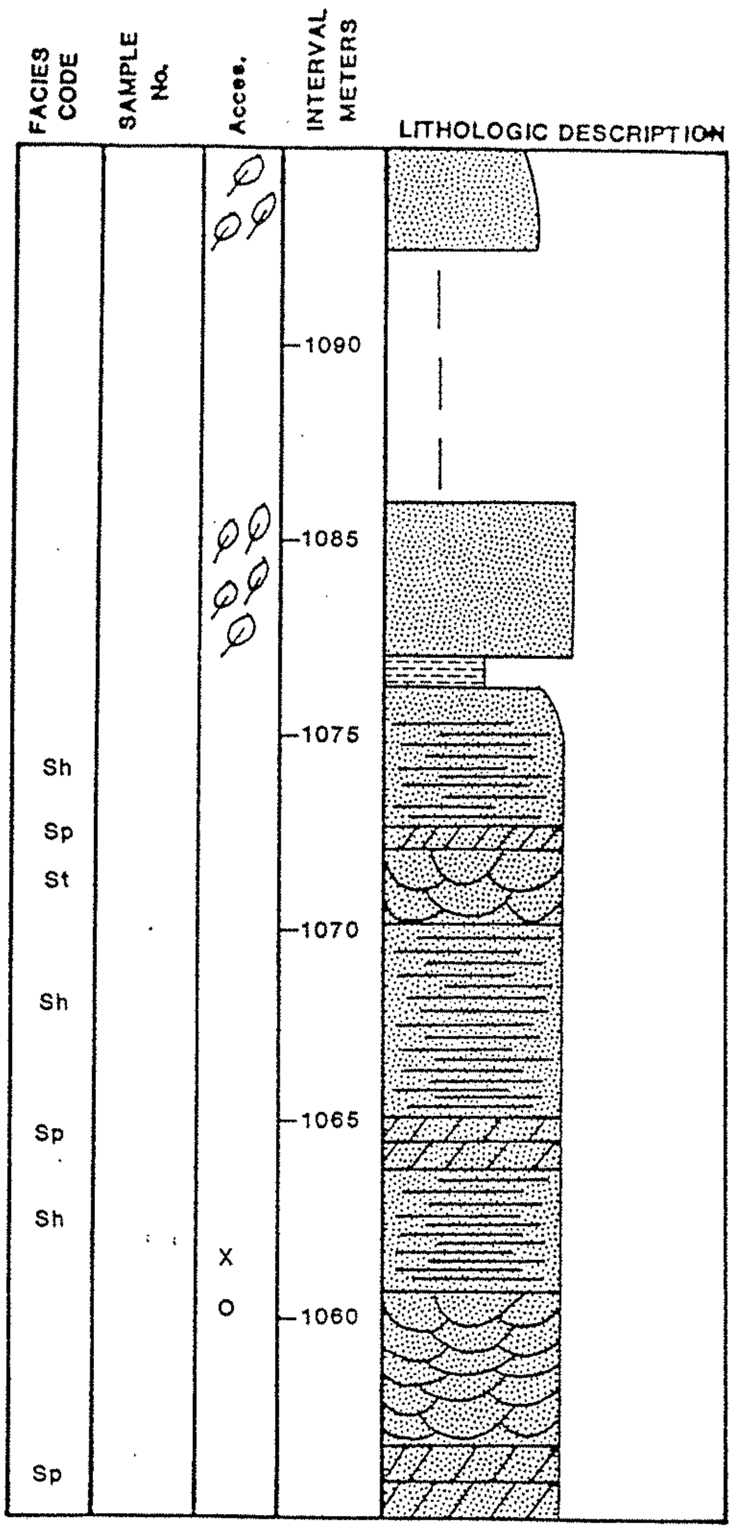
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



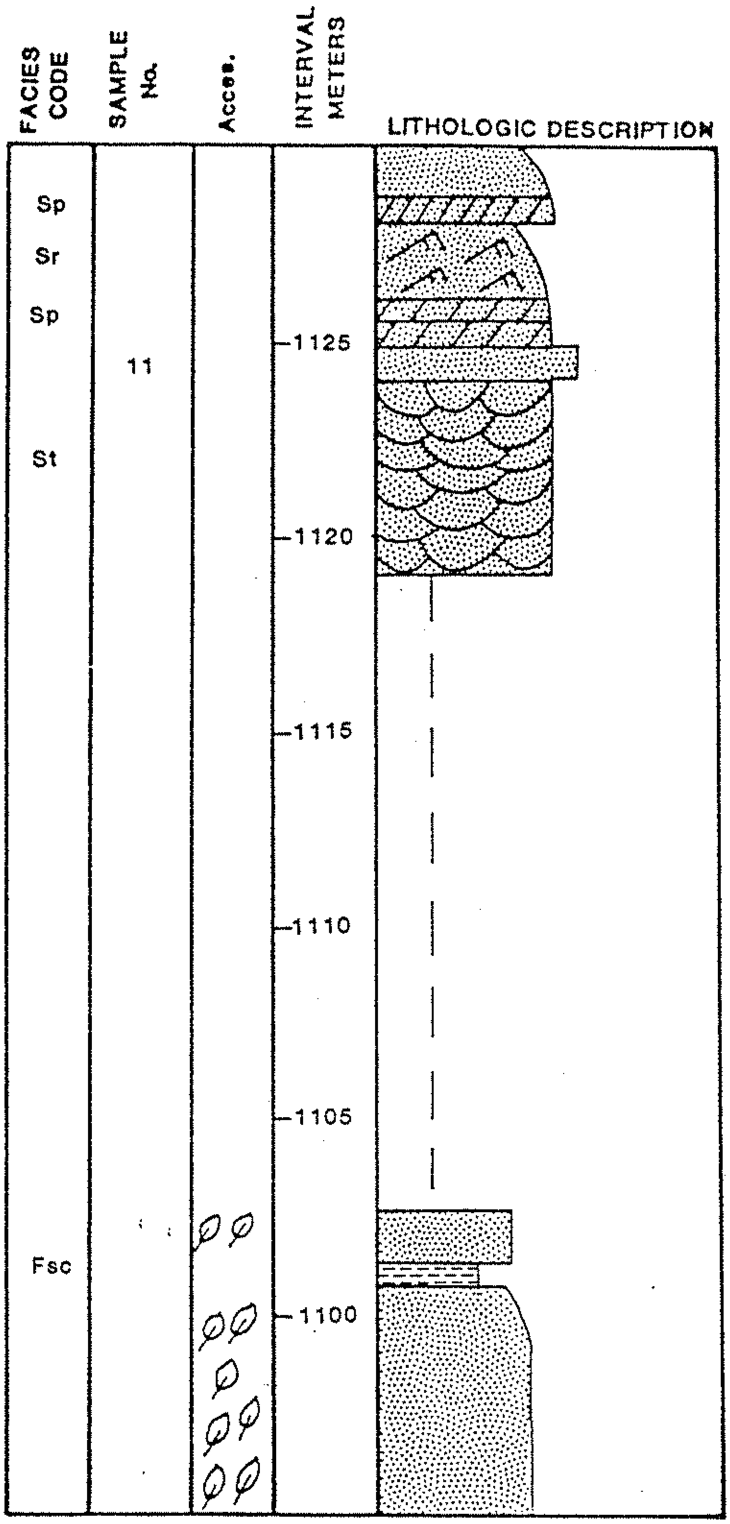
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



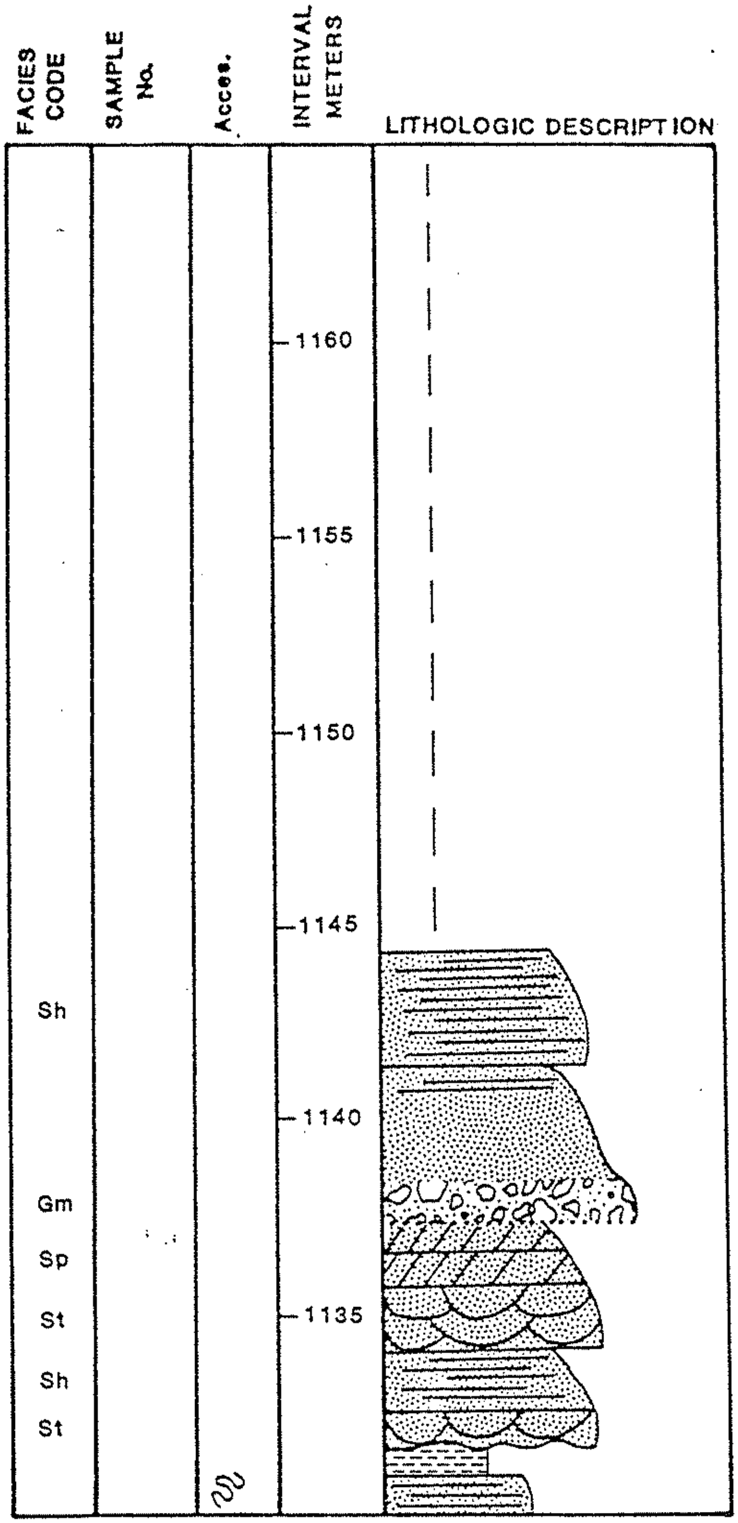
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



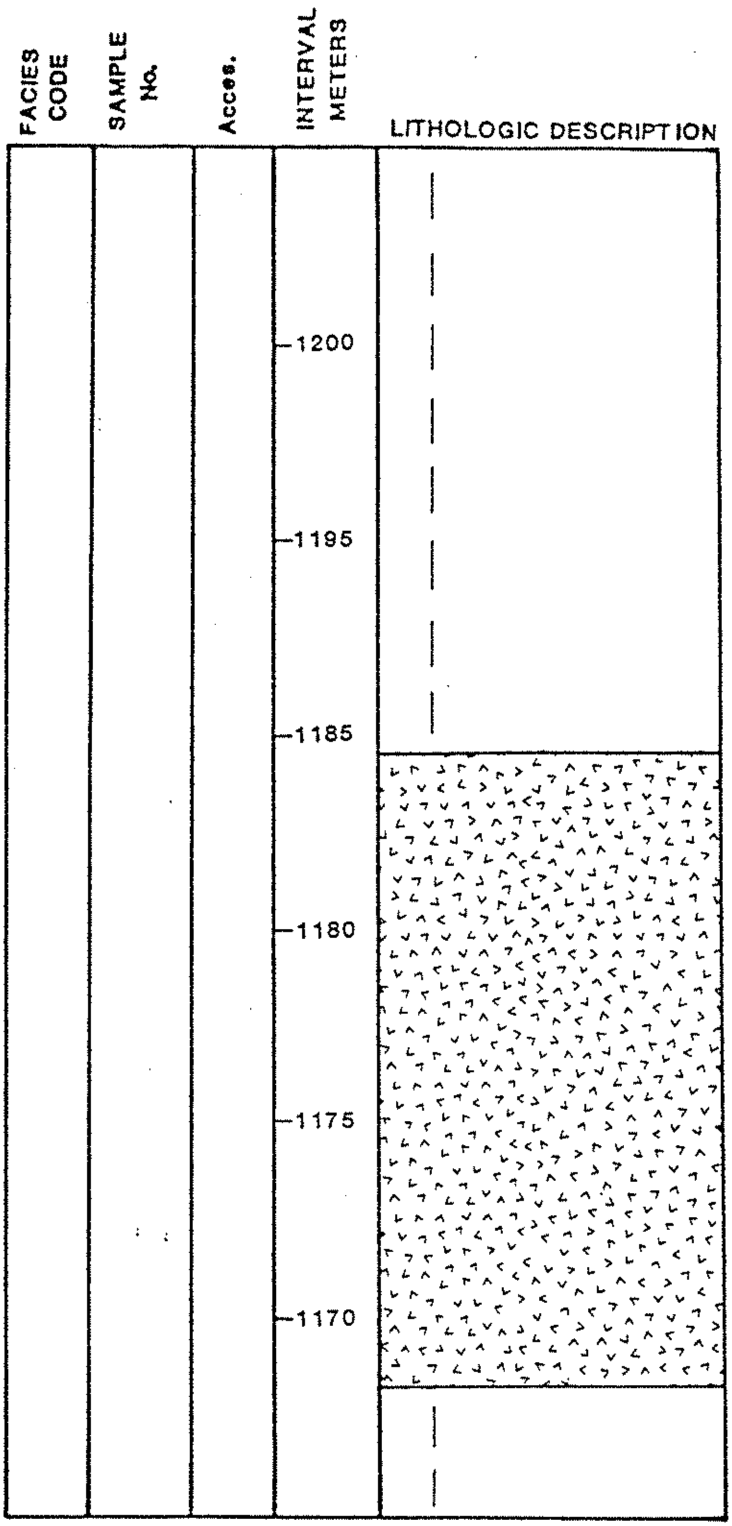
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



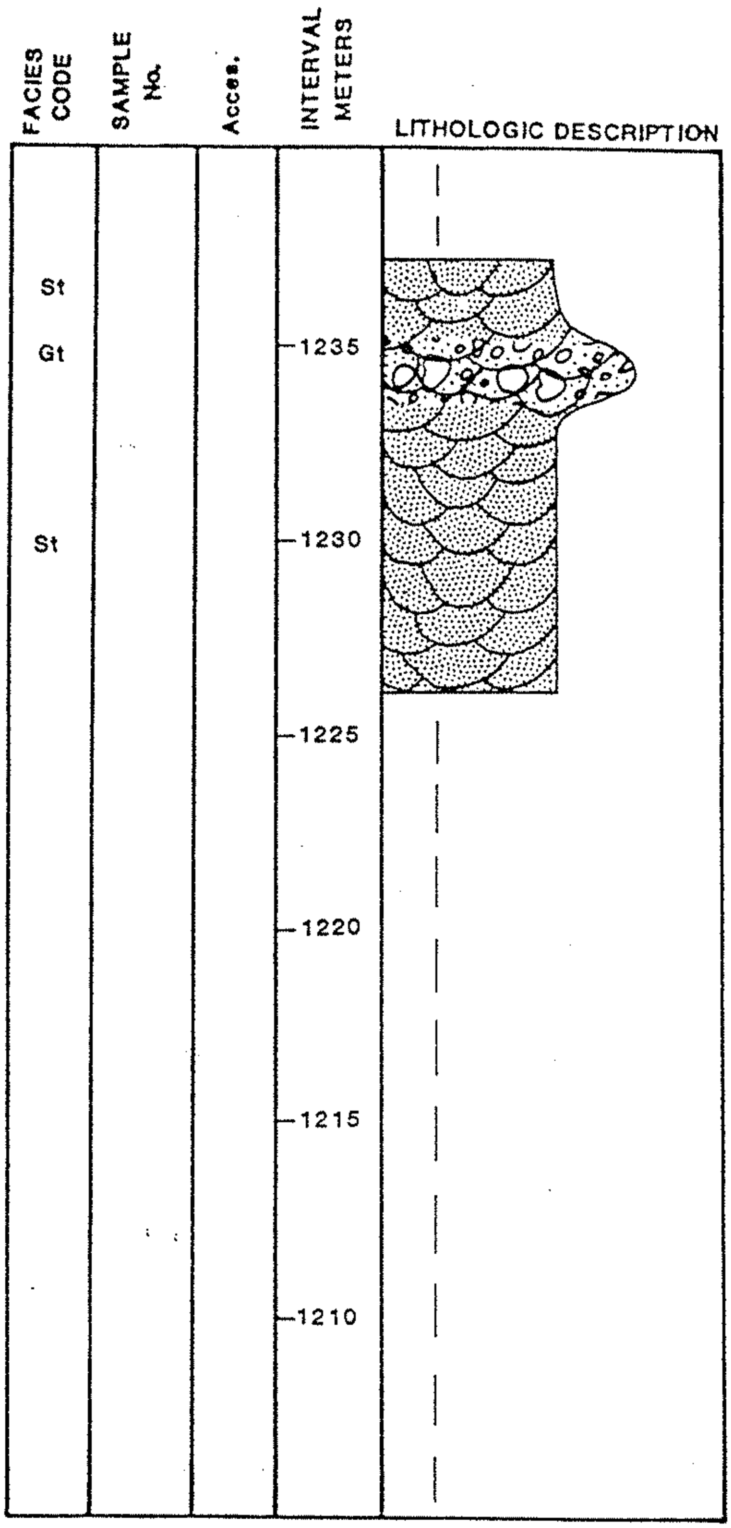
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



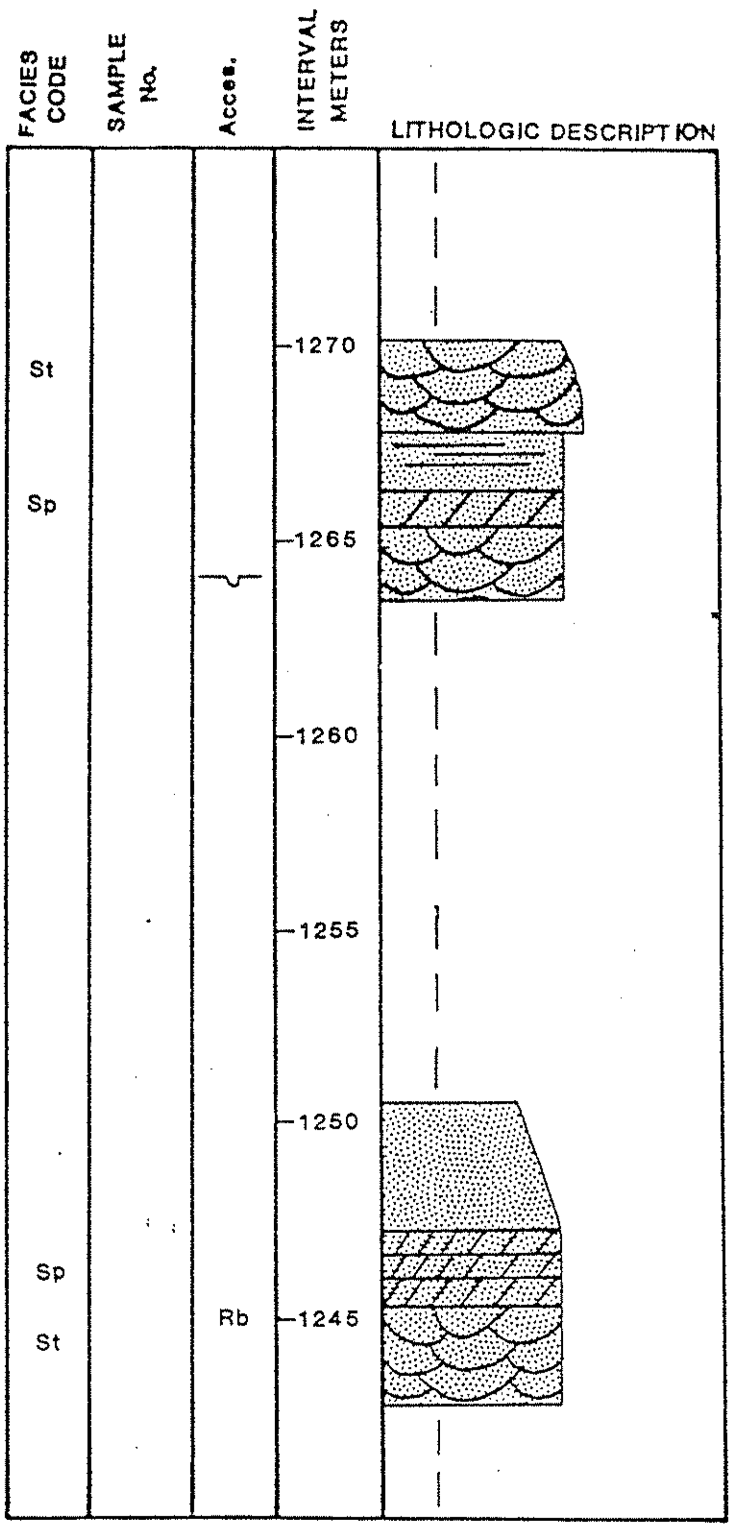
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



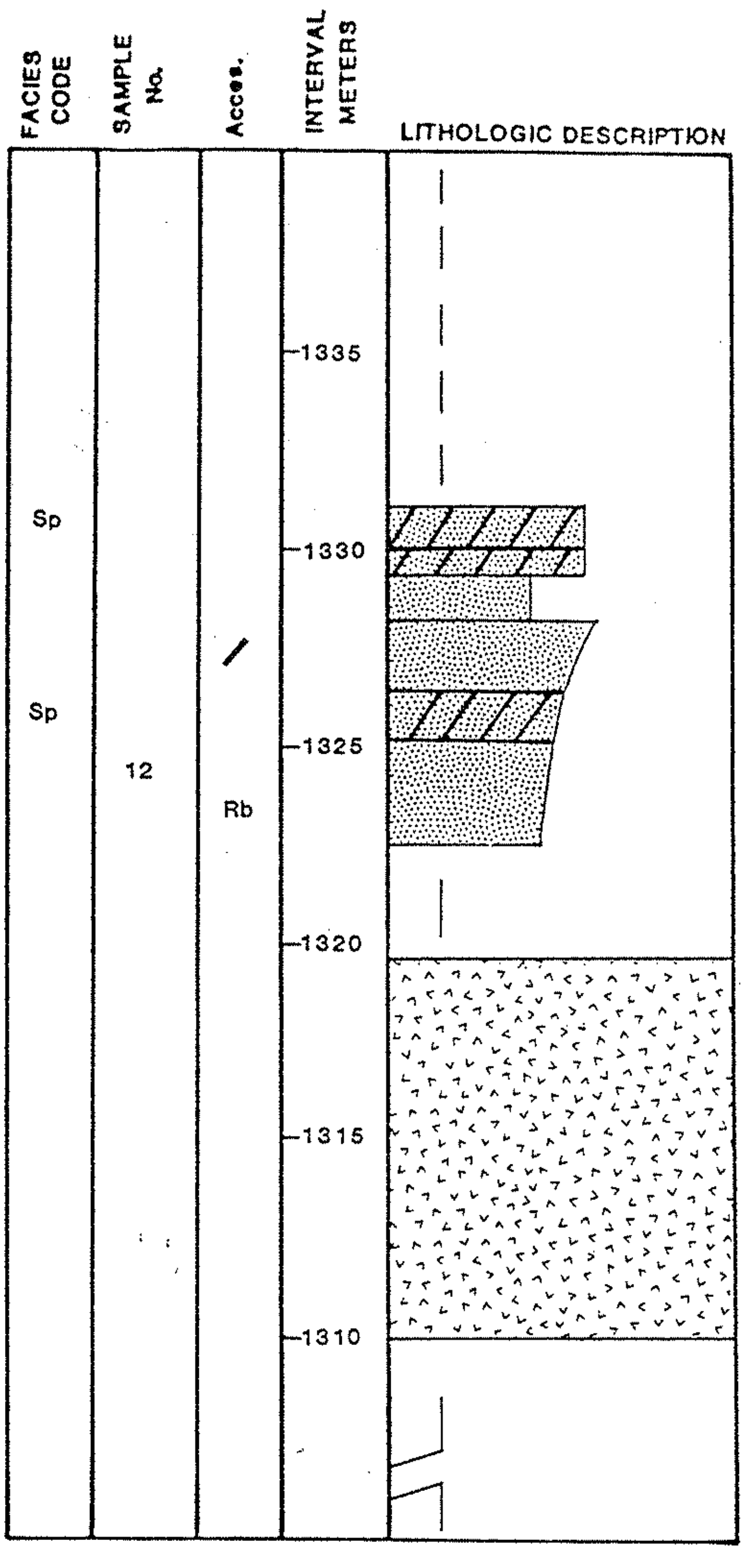
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



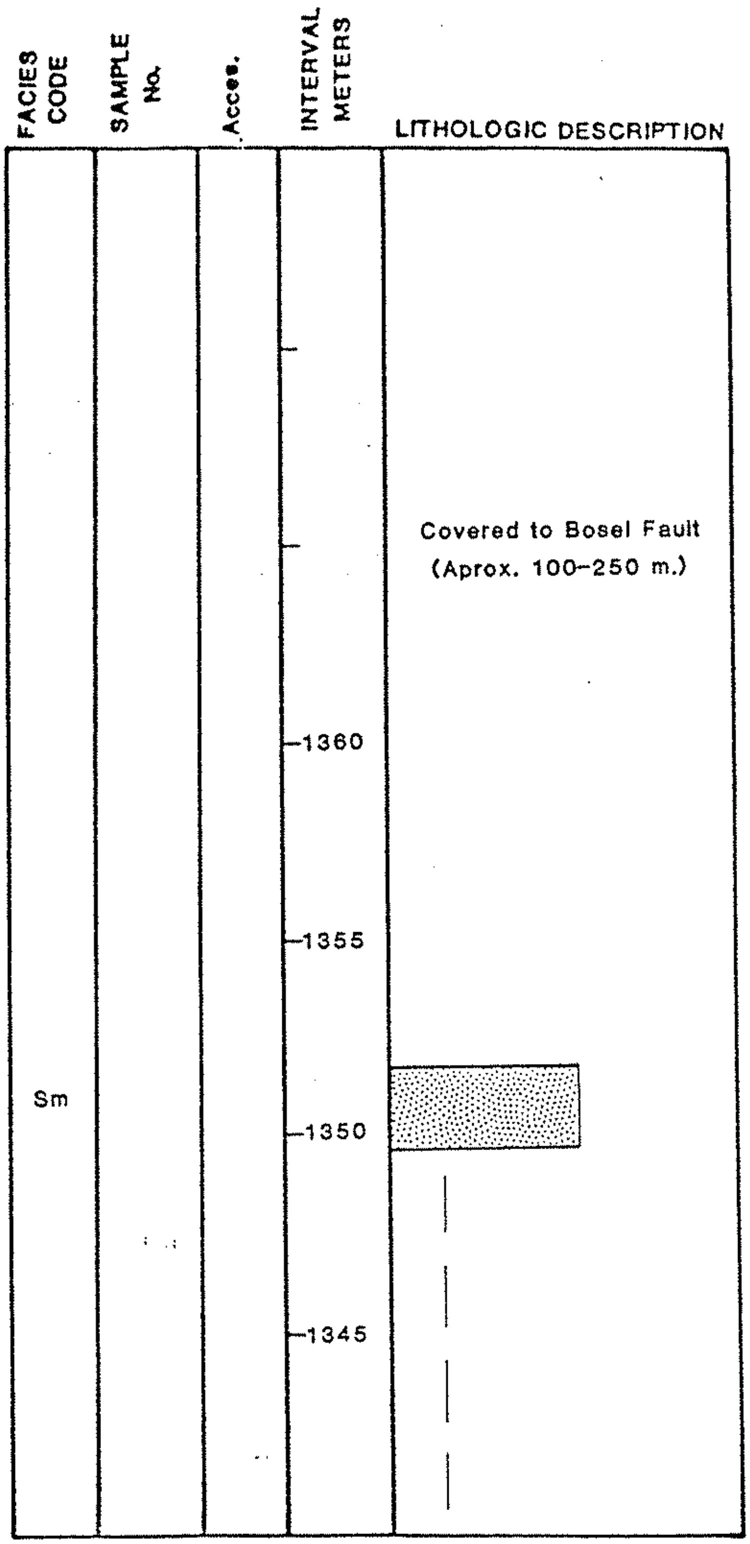
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



TYPE STRATIGRAPHIC SECTION
(CONTINUED)



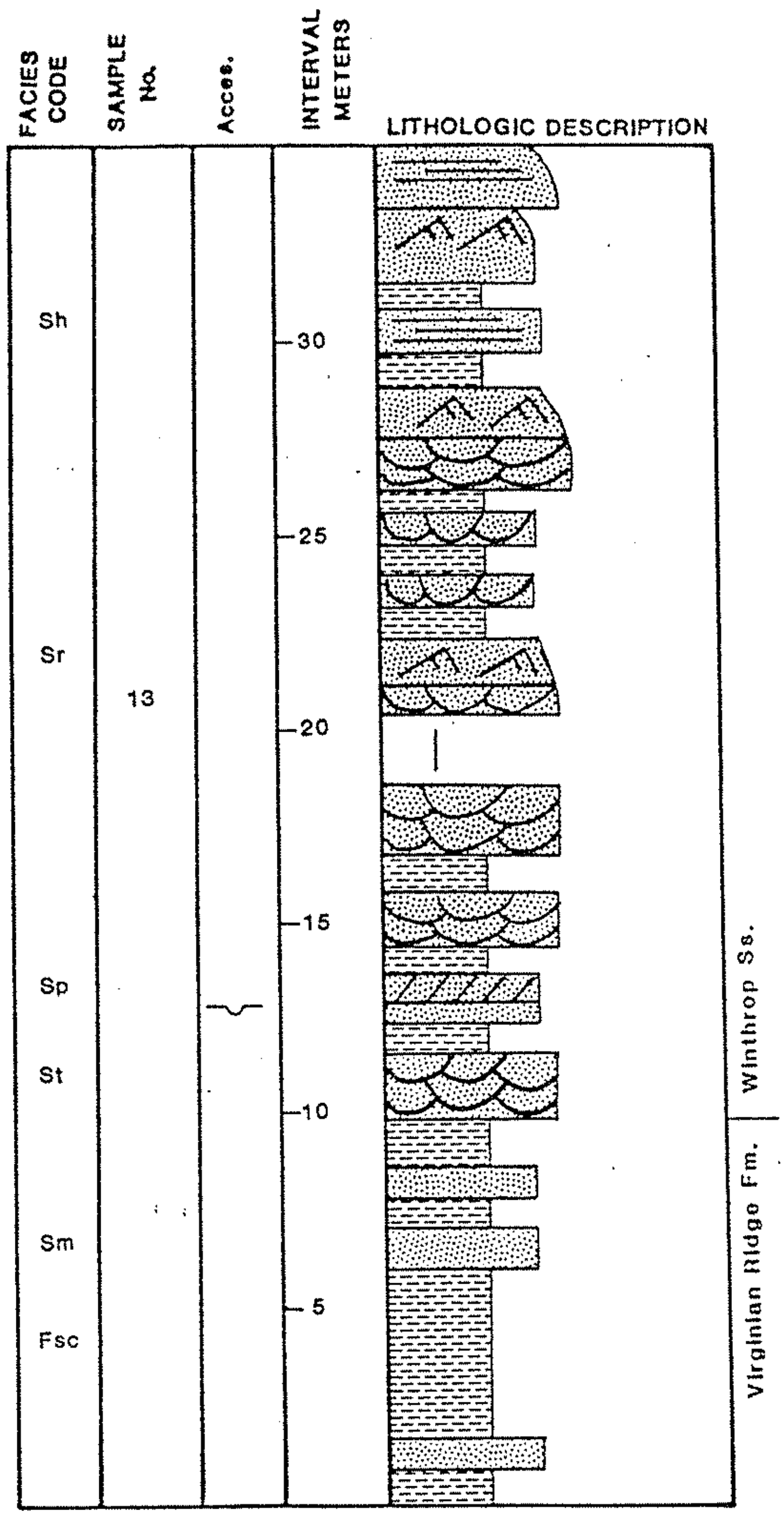
TYPE STRATIGRAPHIC SECTION
(CONTINUED)



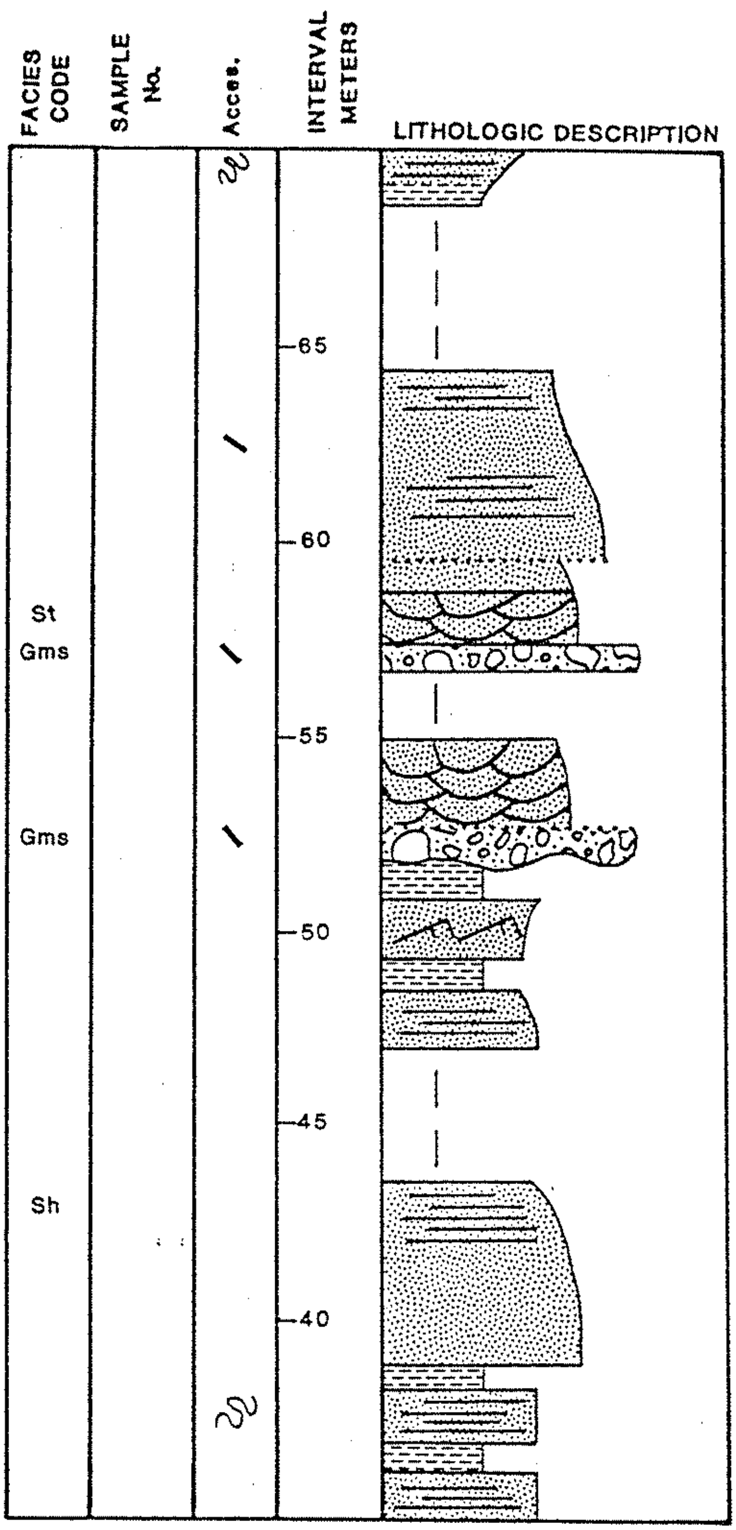
APPENDIX 4

WHITEFACE CREEK SECTION

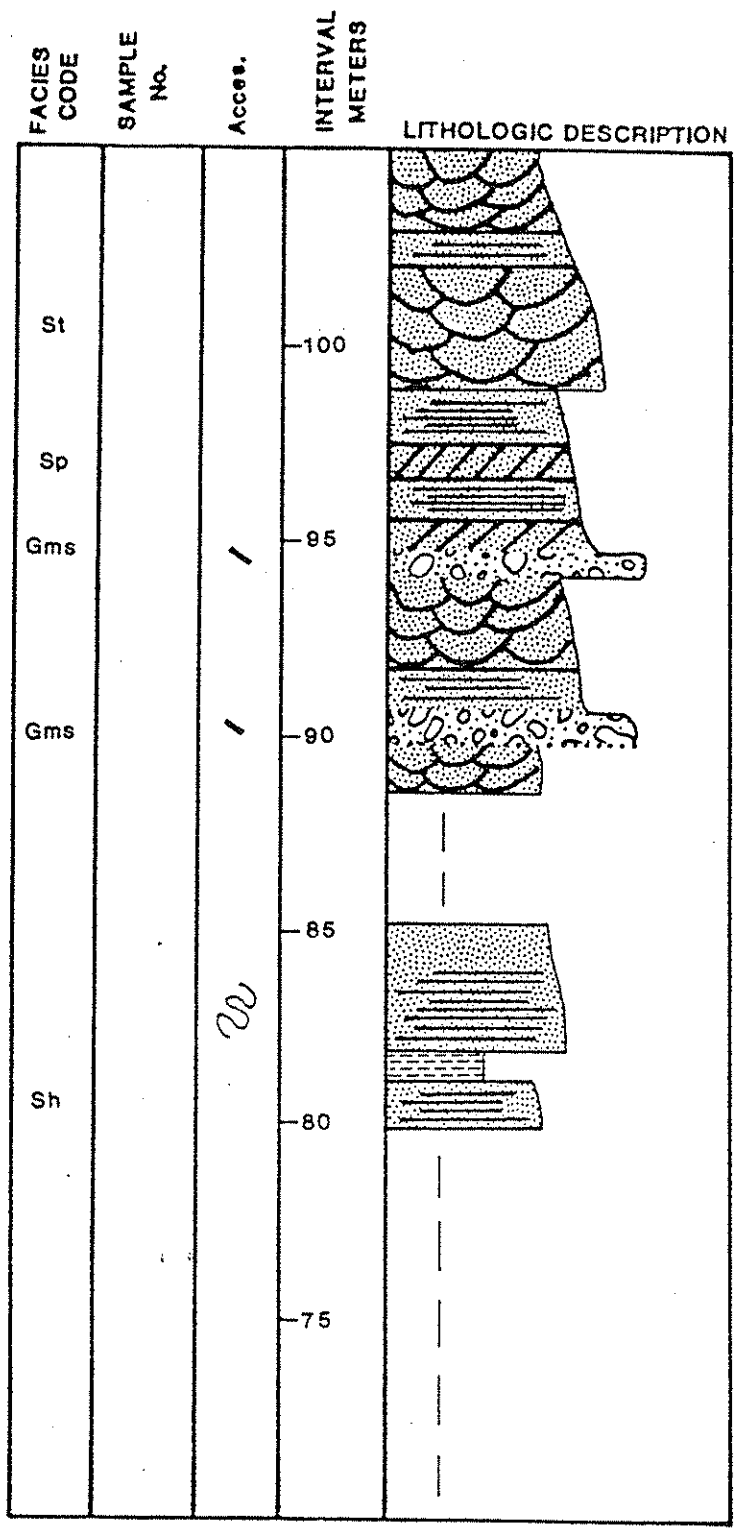
WHITEFACE CREEK STRATIGRAPHIC SECTION



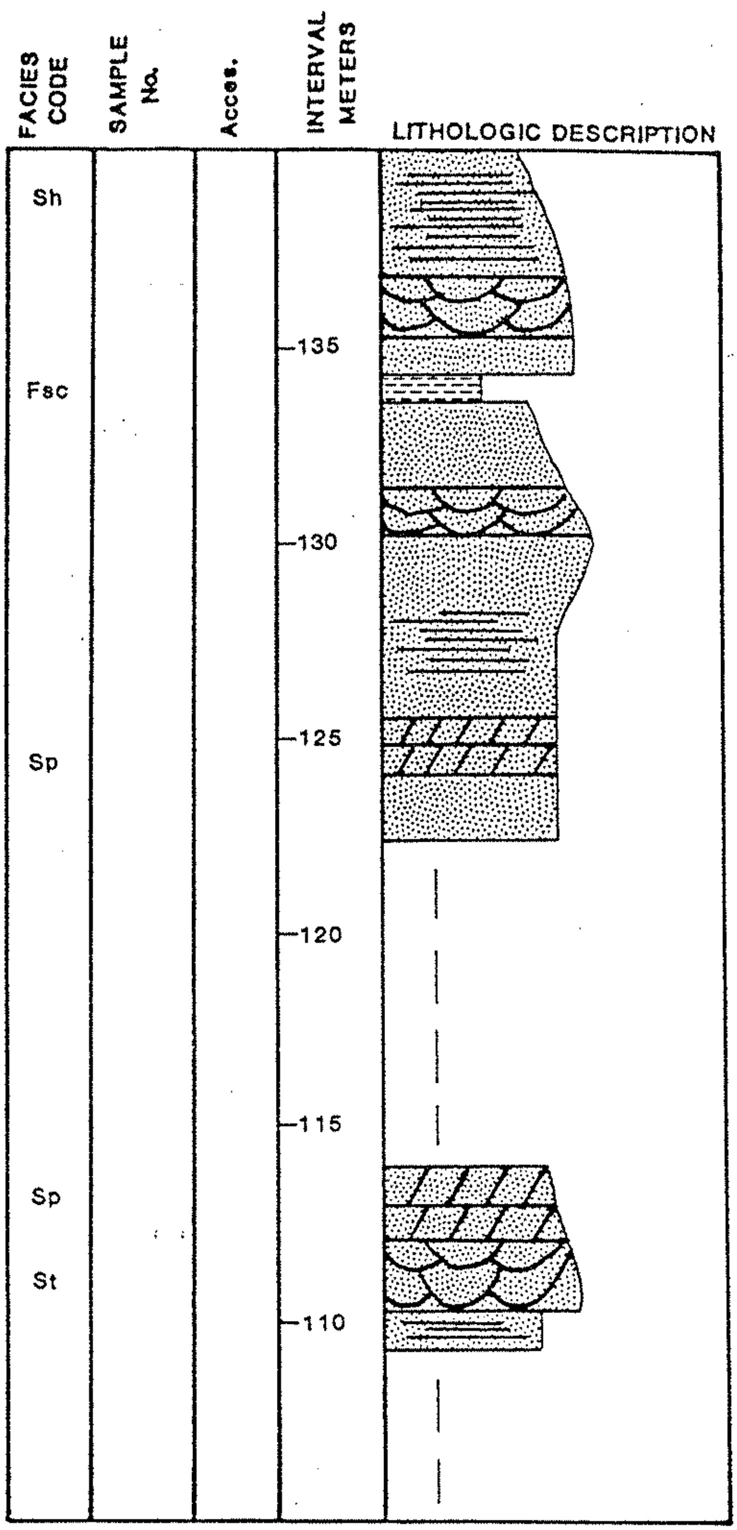
WHITEFACE CREEK STRATIGRAPHIC SECTION (CONTINUED)



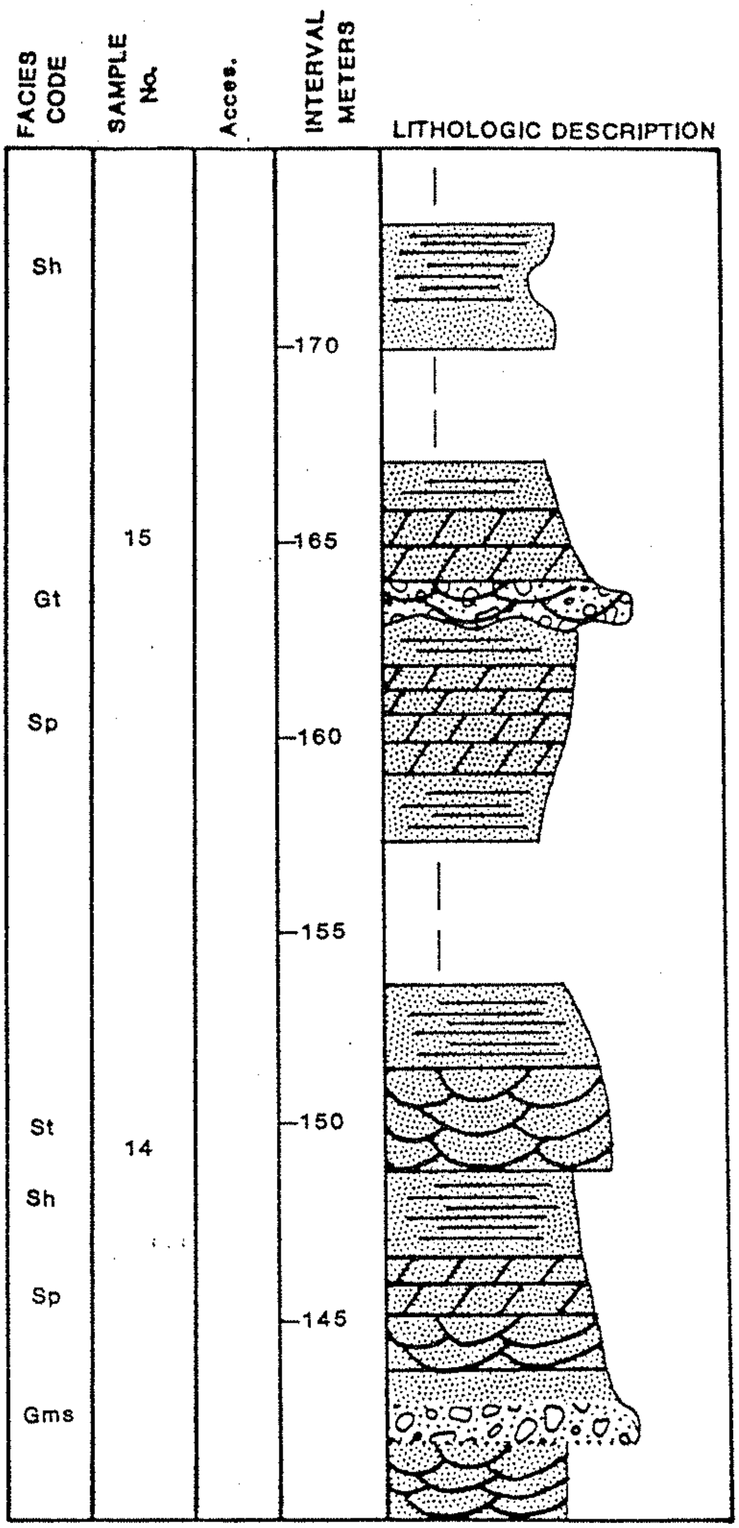
WHITEFACE CREEK STRATIGRAPHIC SECTION
(CONTINUED)



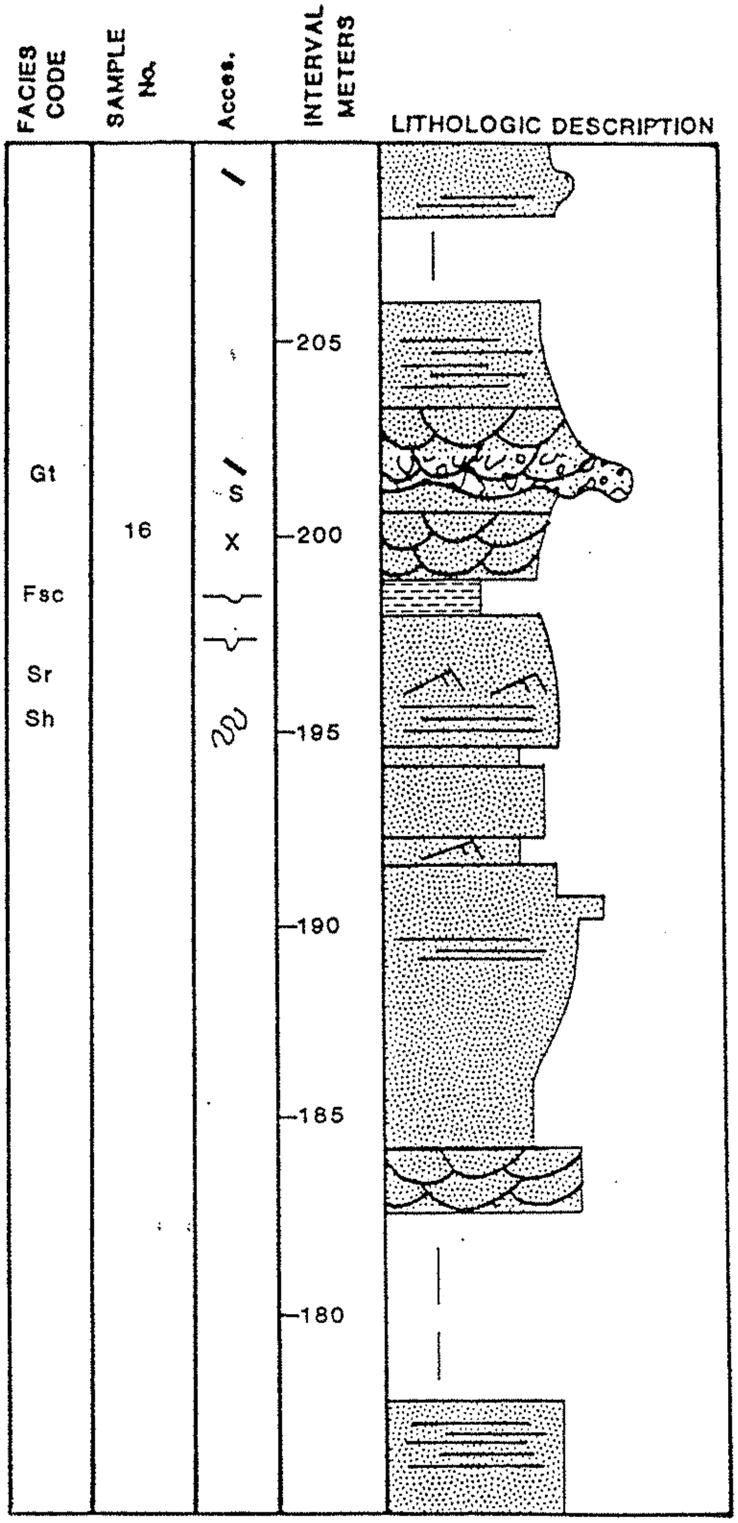
WHITEFACE CREEK STRATIGRAPHIC SECTION (CONTINUED)



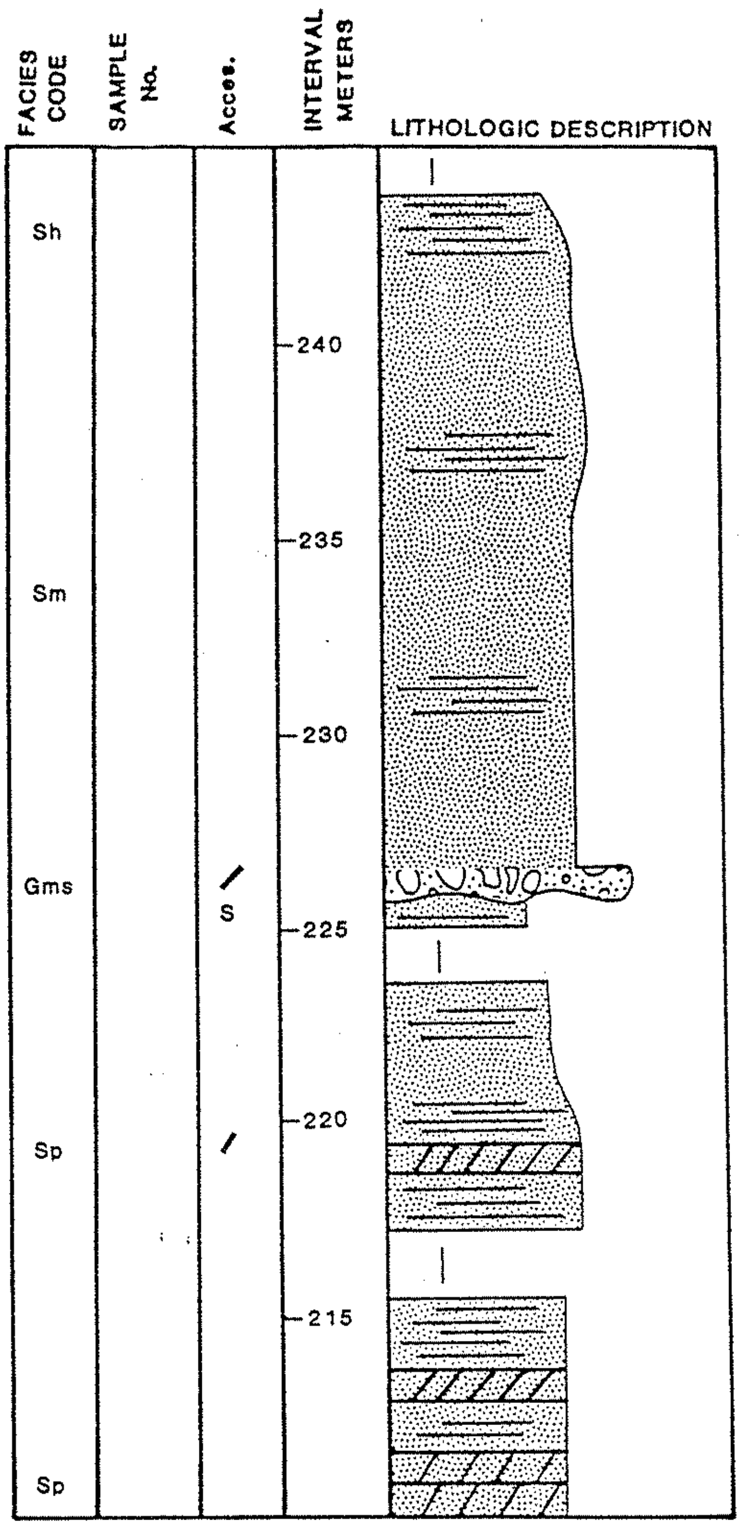
WHITEFACE CREEK STRATIGRAPHIC SECTION
(CONTINUED)



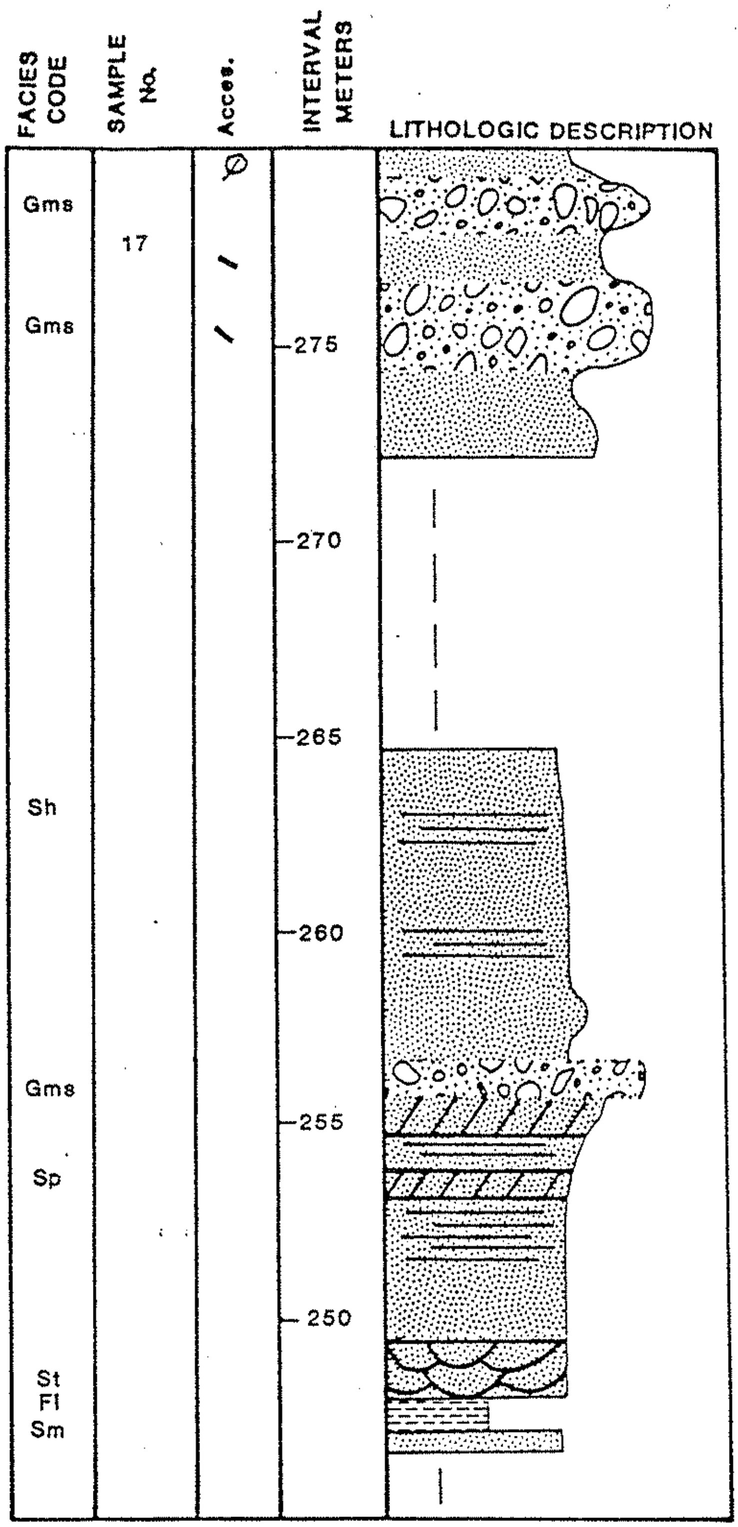
WHITEFACE CREEK STRATIGRAPHIC SECTION (CONTINUED)



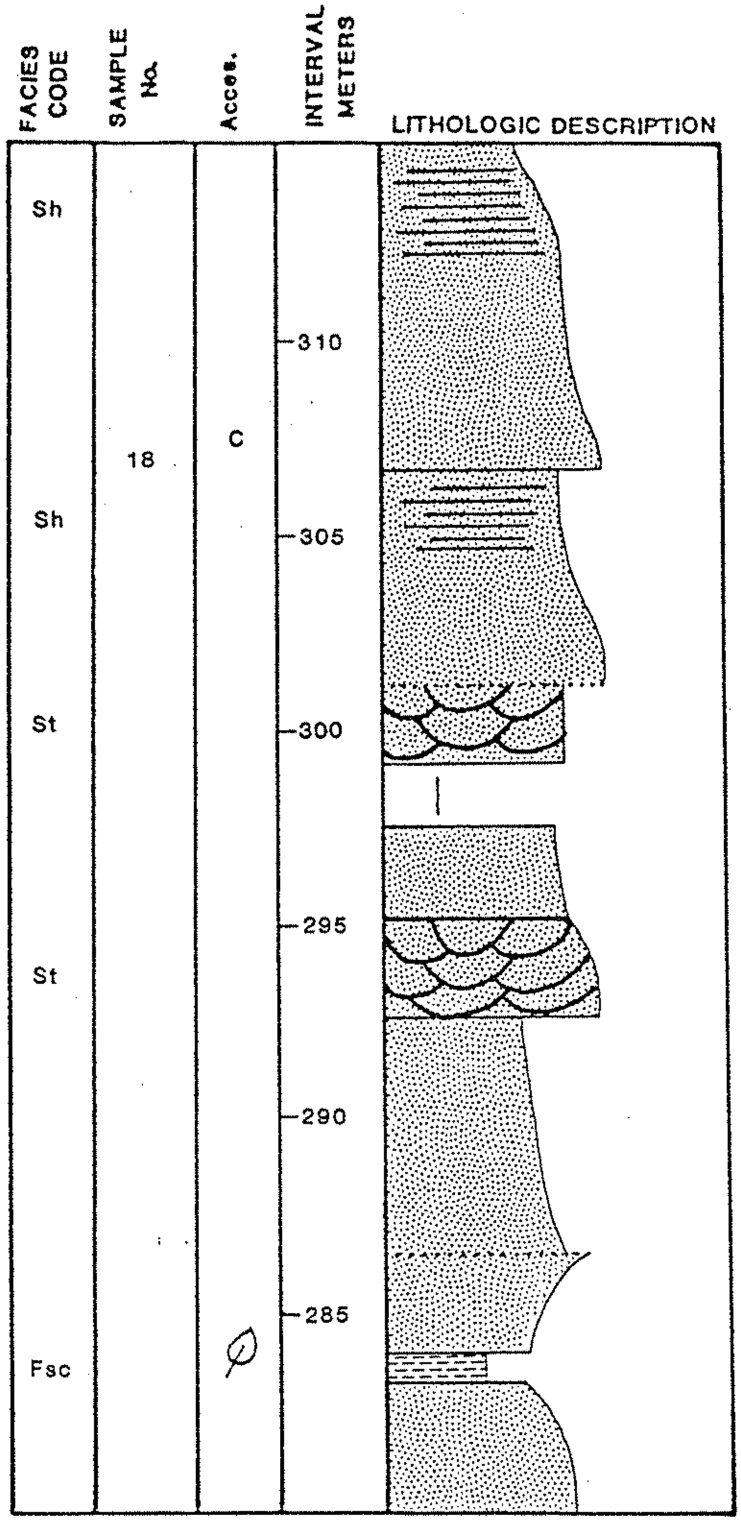
WHITEFACE CREEK STRATIGRAPHIC SECTION (CONTINUED)



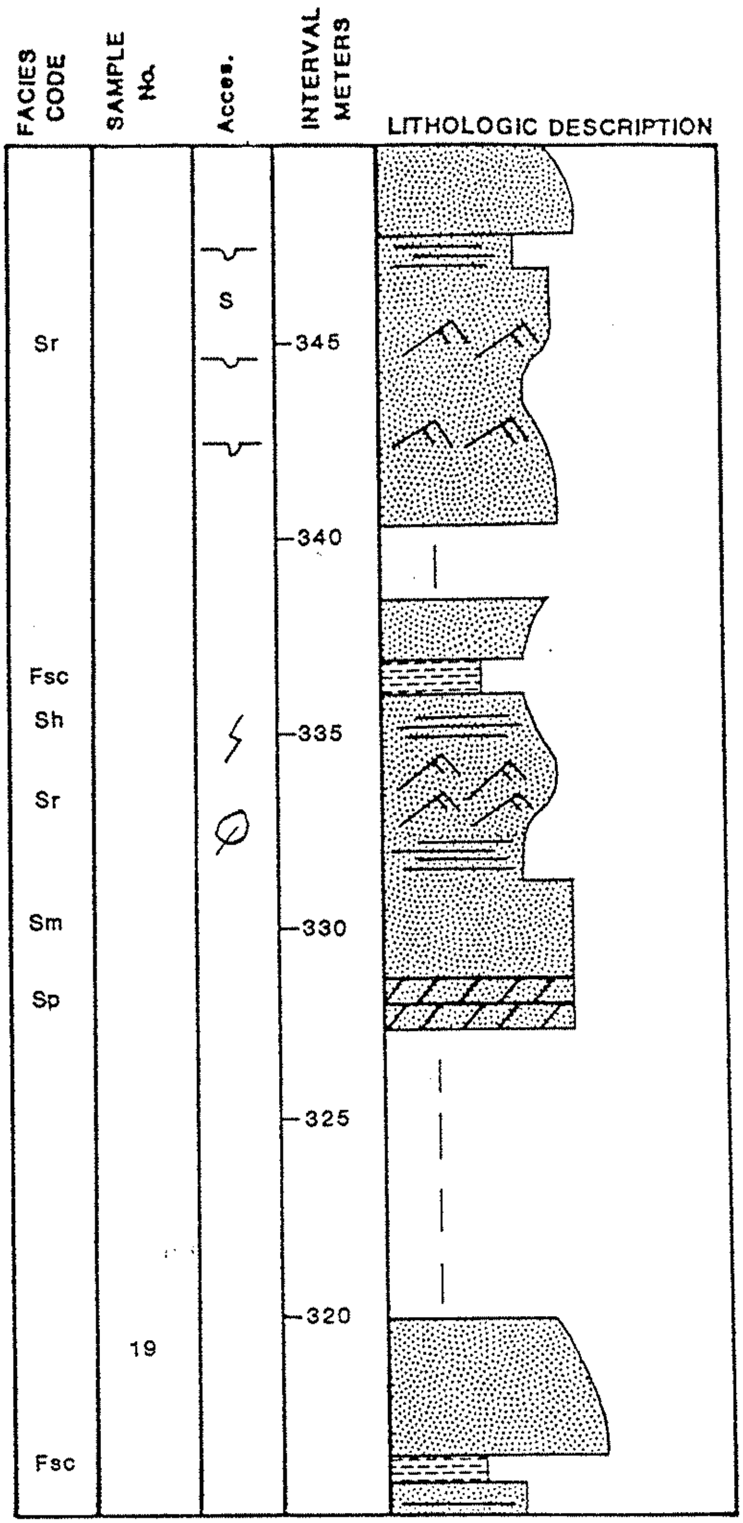
WHITEFACE CREEK STRATIGRAPHIC SECTION (CONTINUED)



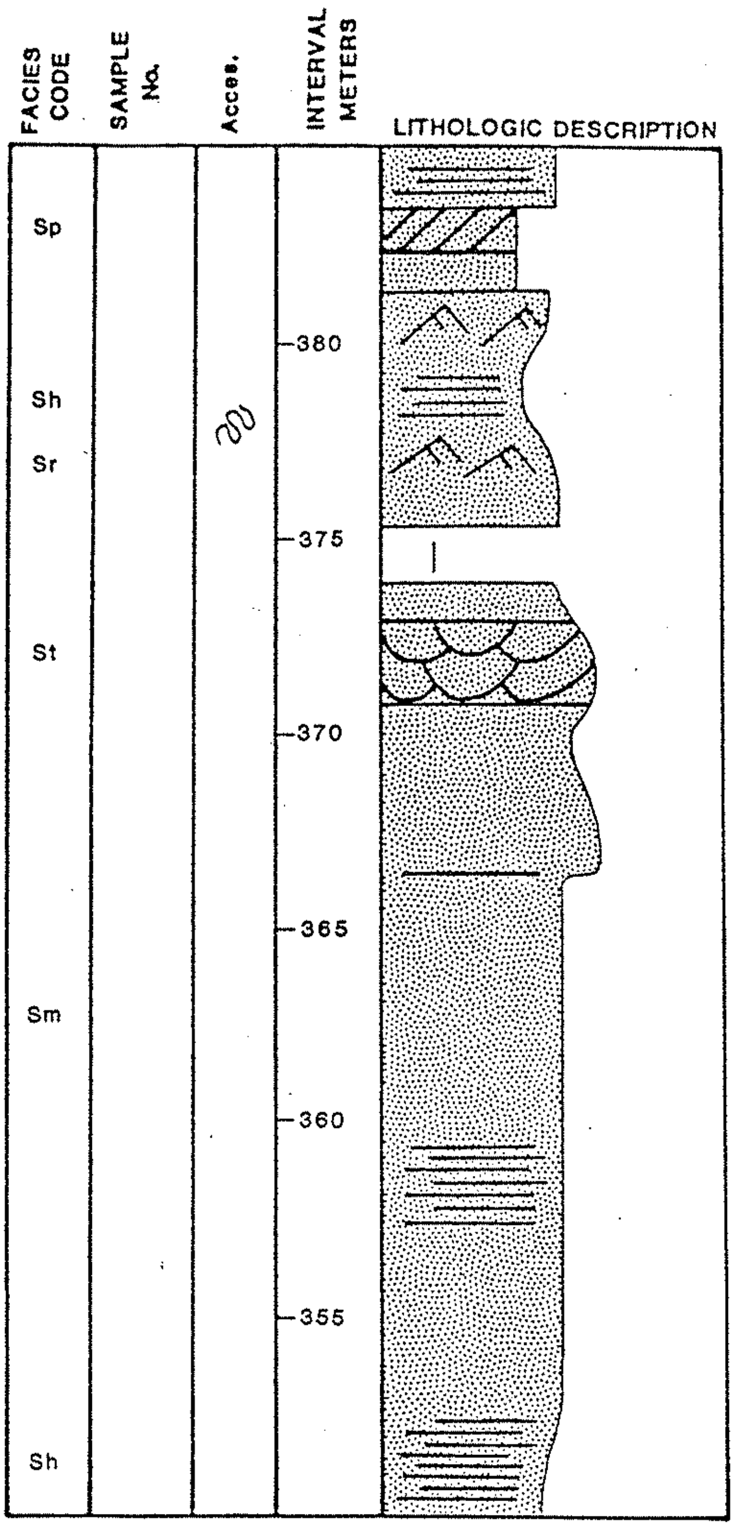
WHITEFACE CREEK STRATIGRAPHIC SECTION
(CONTINUED)



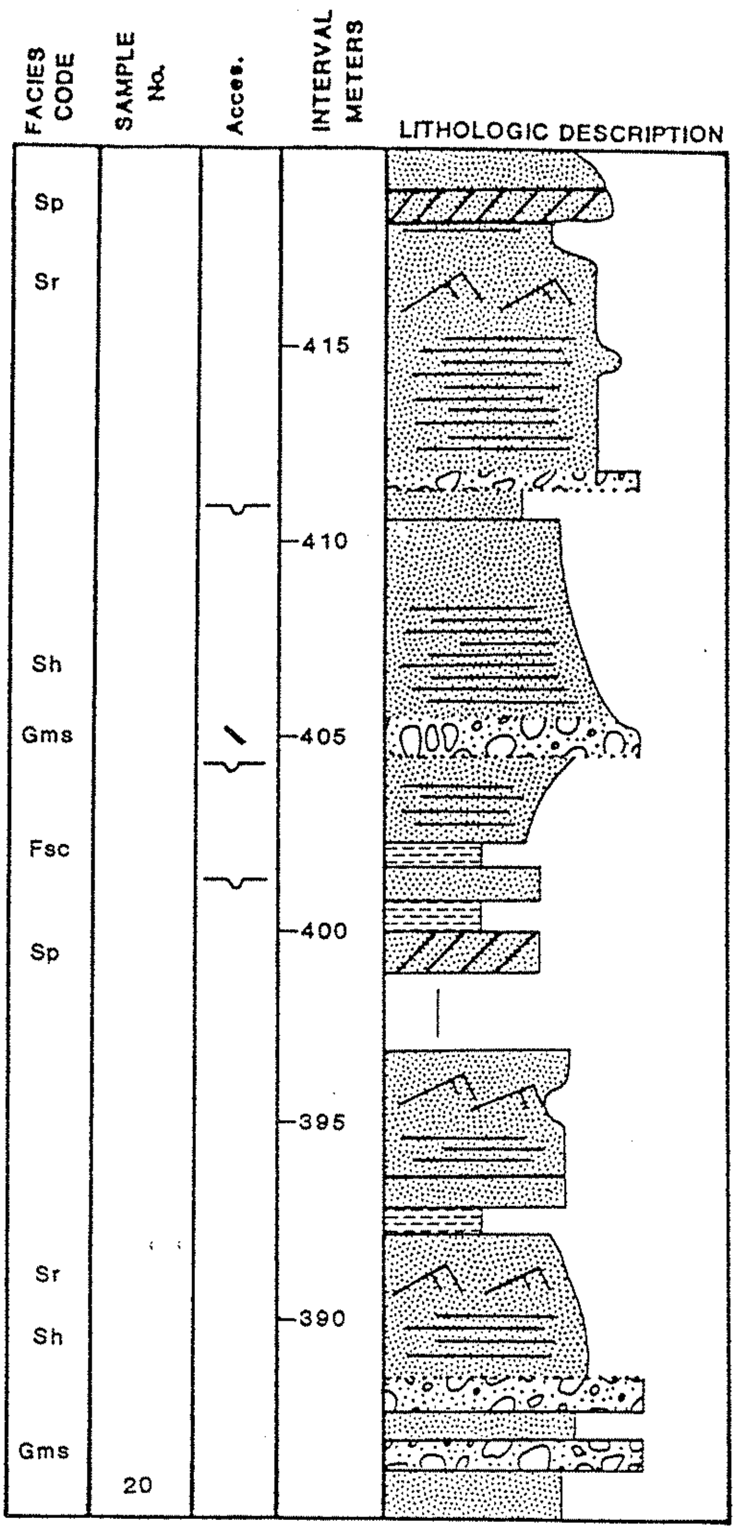
WHITEFACE CREEK STRATIGRAPHIC SECTION (CONTINUED)



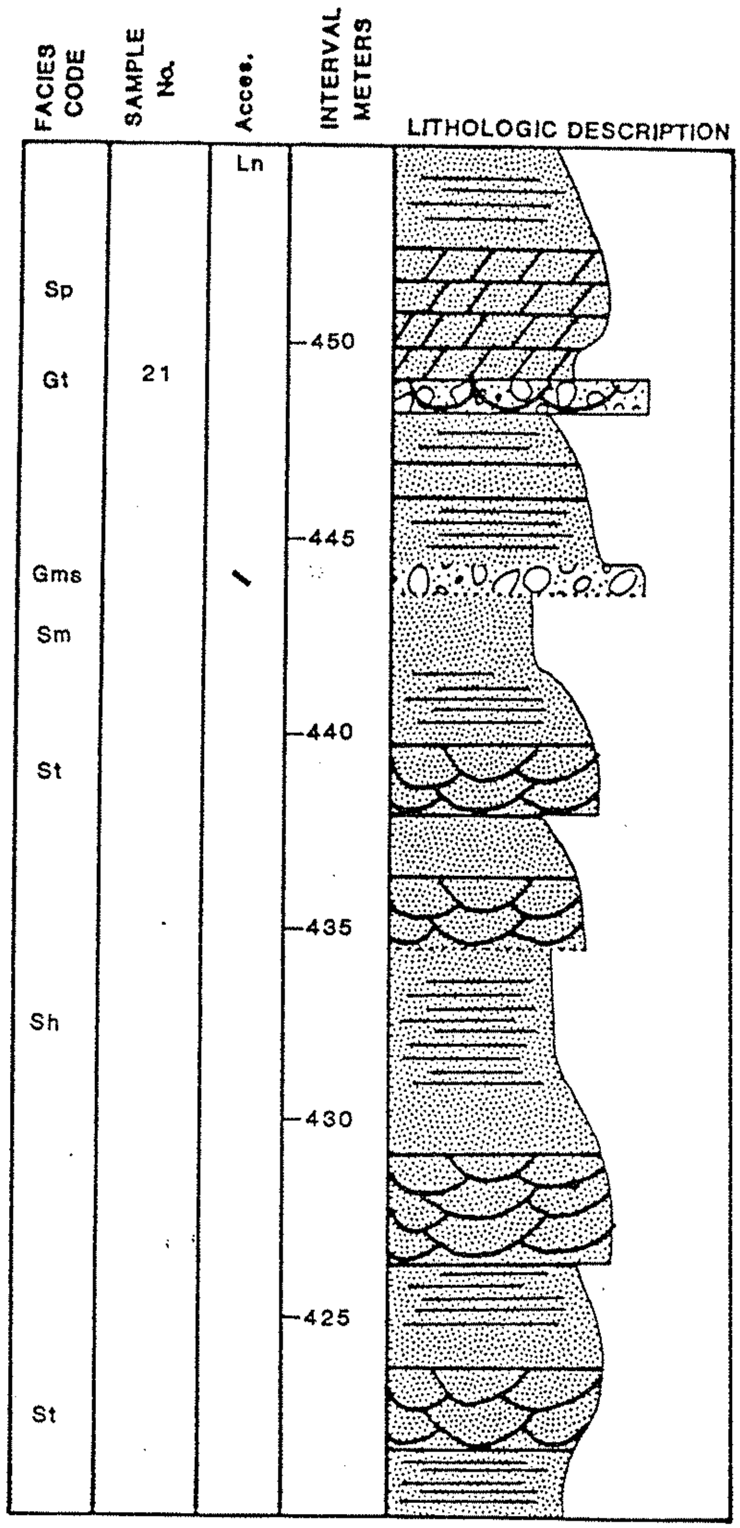
WHITEFACE CREEK STRATIGRAPHIC SECTION (CONTINUED)



WHITEFACE CREEK STRATIGRAPHIC SECTION (CONTINUED)



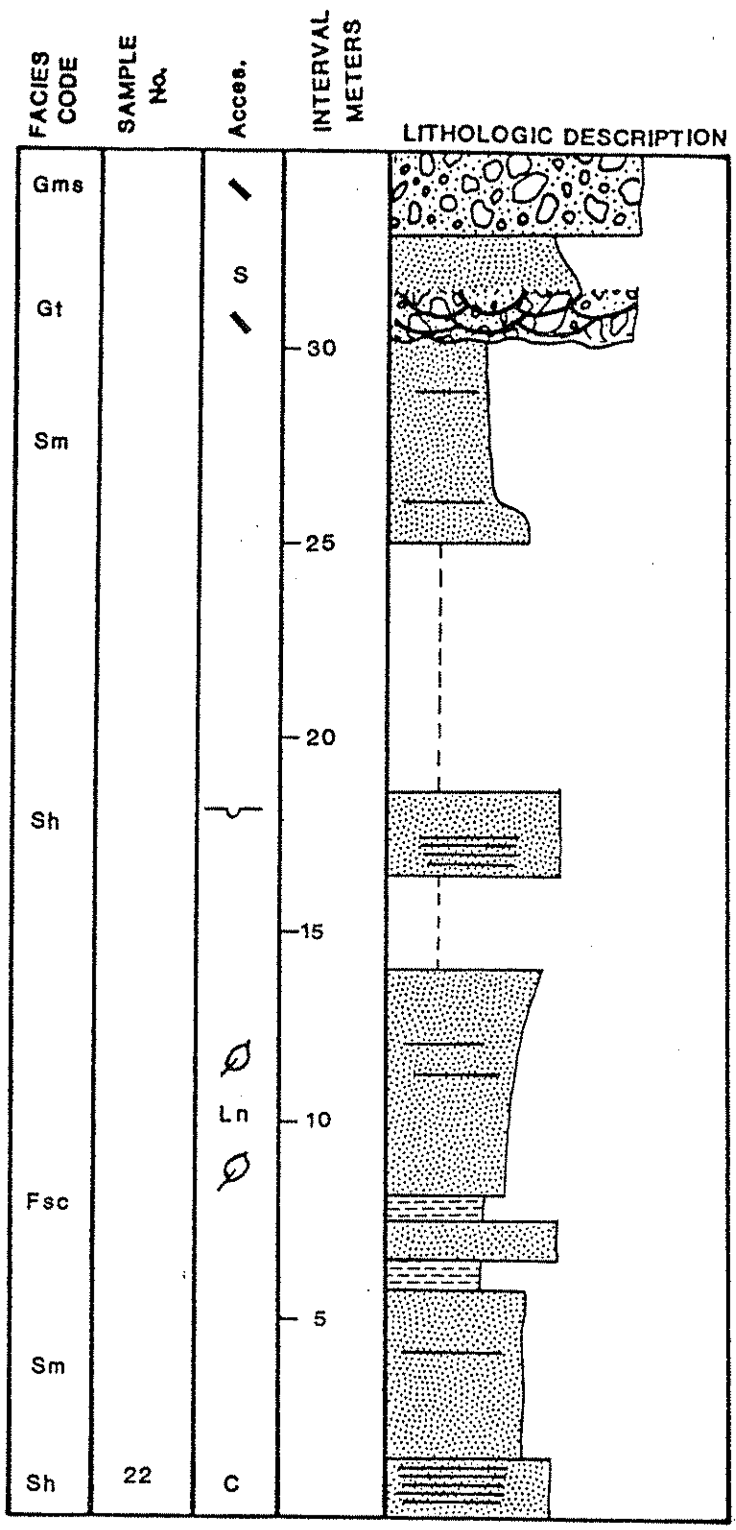
WHITEFACE CREEK STRATIGRAPHIC SECTION
(CONTINUED)



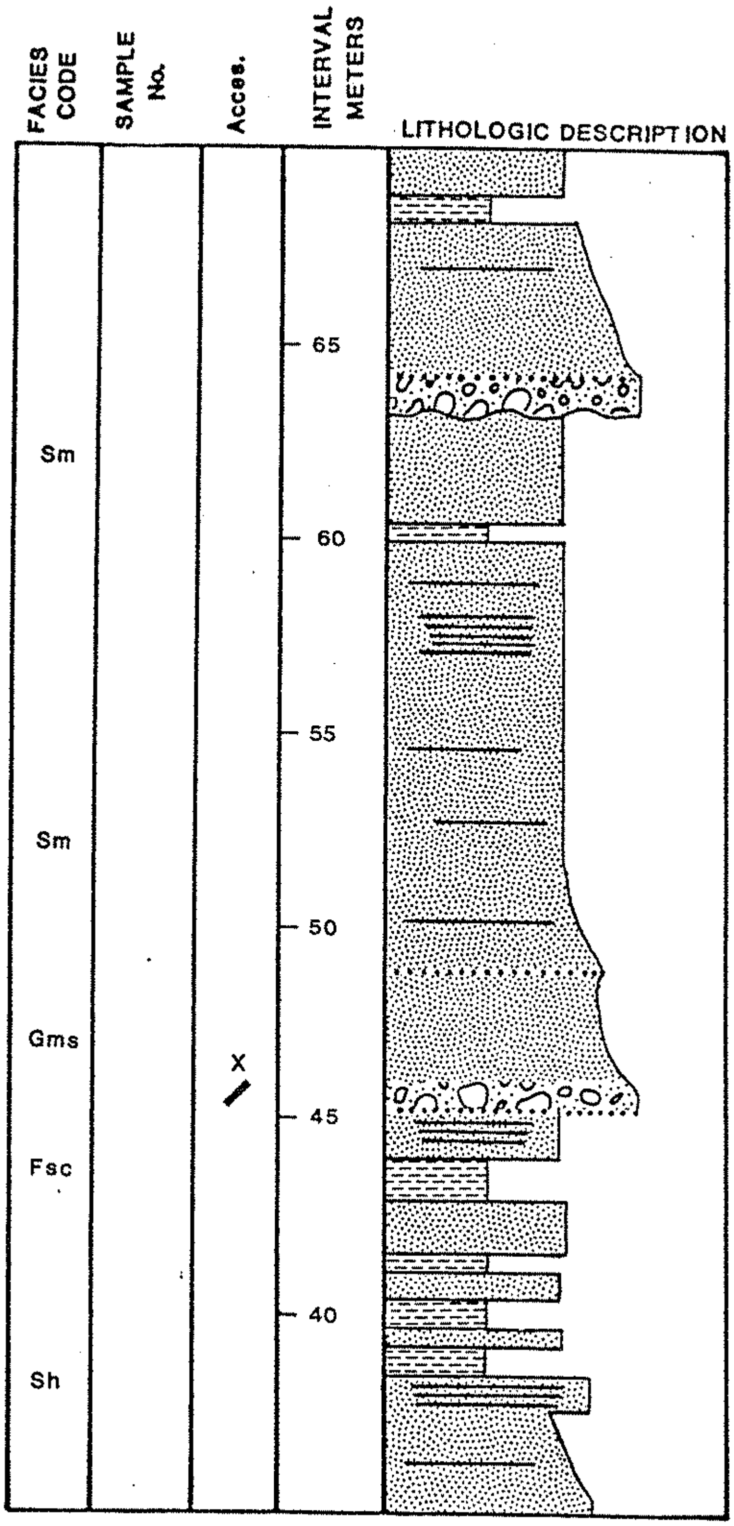
APPENDIX 5

EARLY WINTERS CREEK SECTION

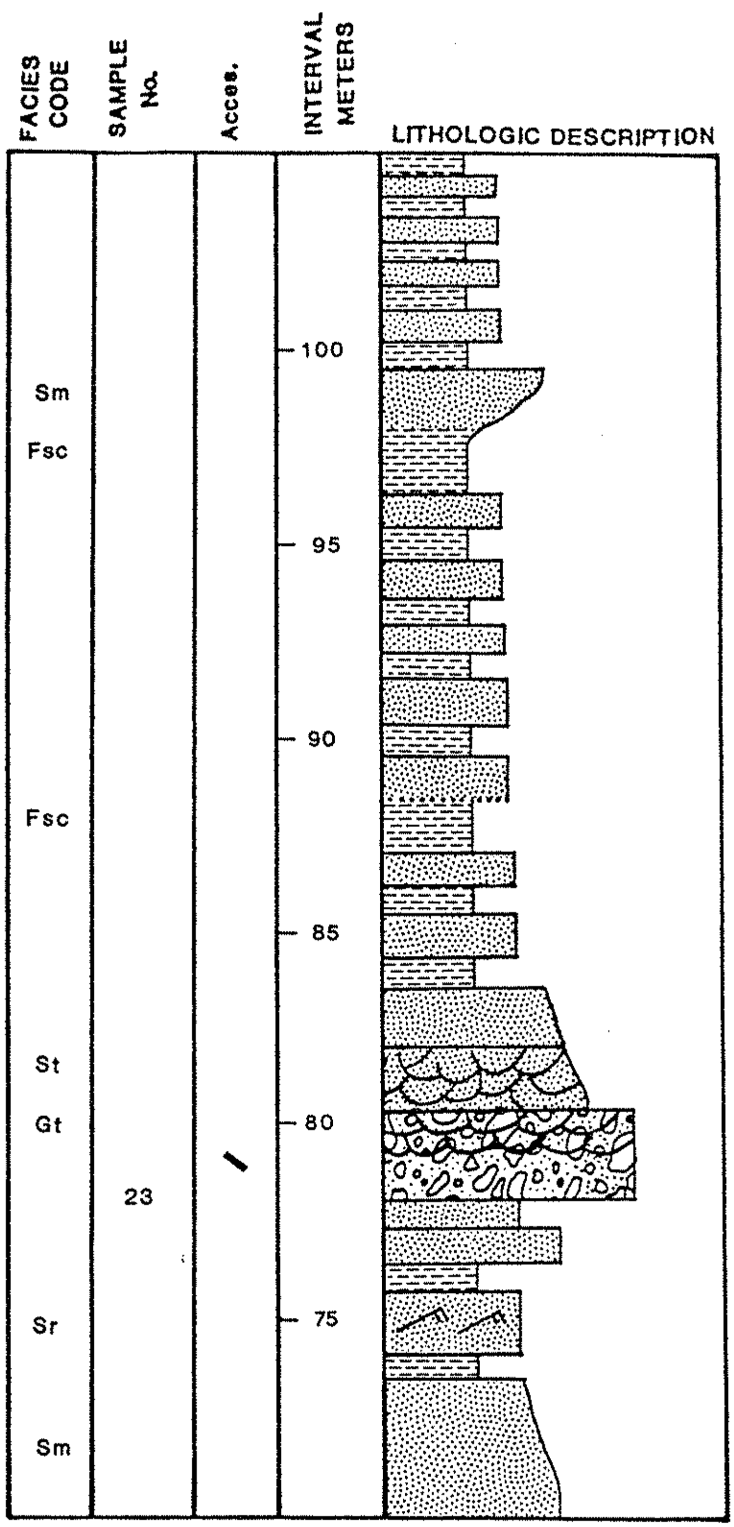
EARLY WINTERS CREEK STRATIGRAPHIC SECTION



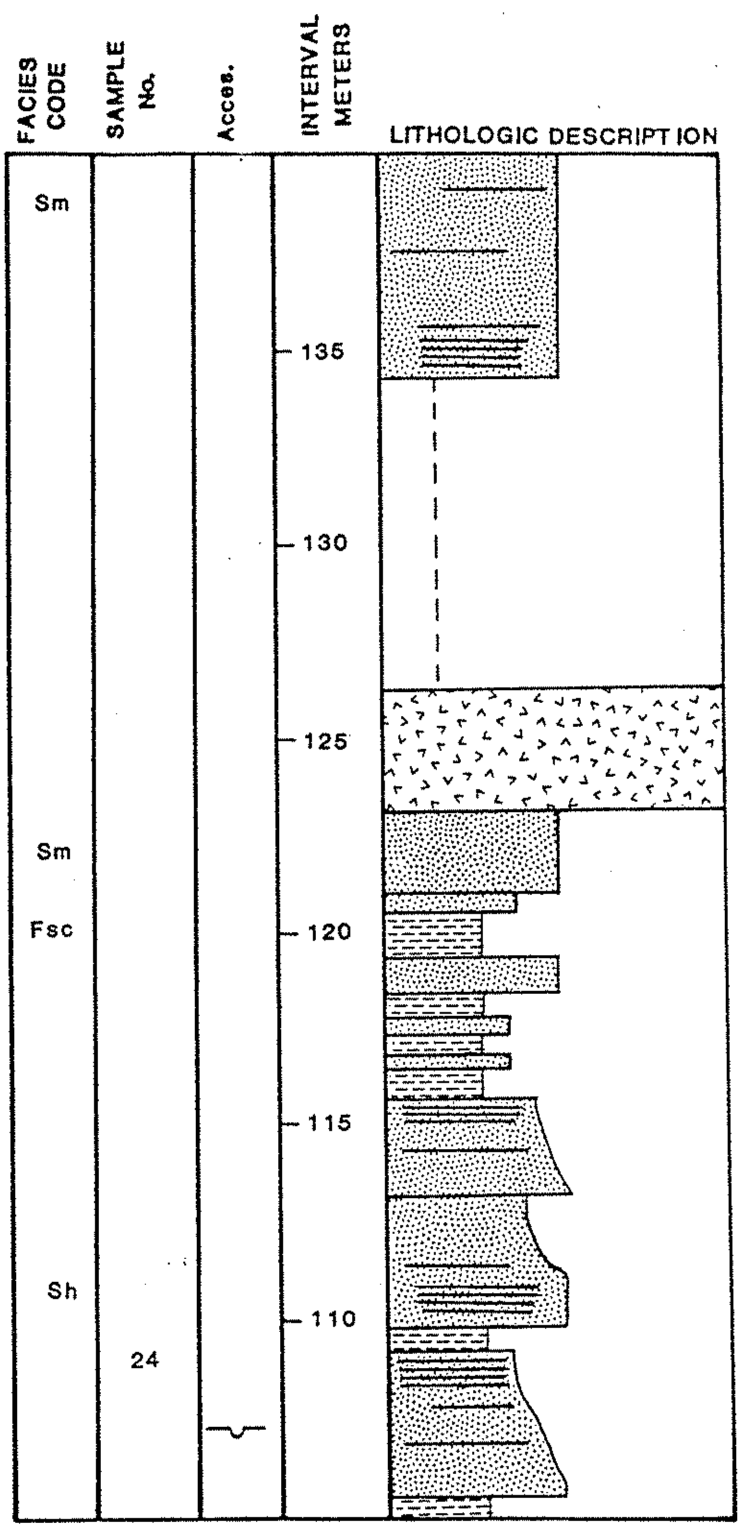
EARLY WINTERS CREEK STRATIGRAPHIC SECTION
(CONTINUED)



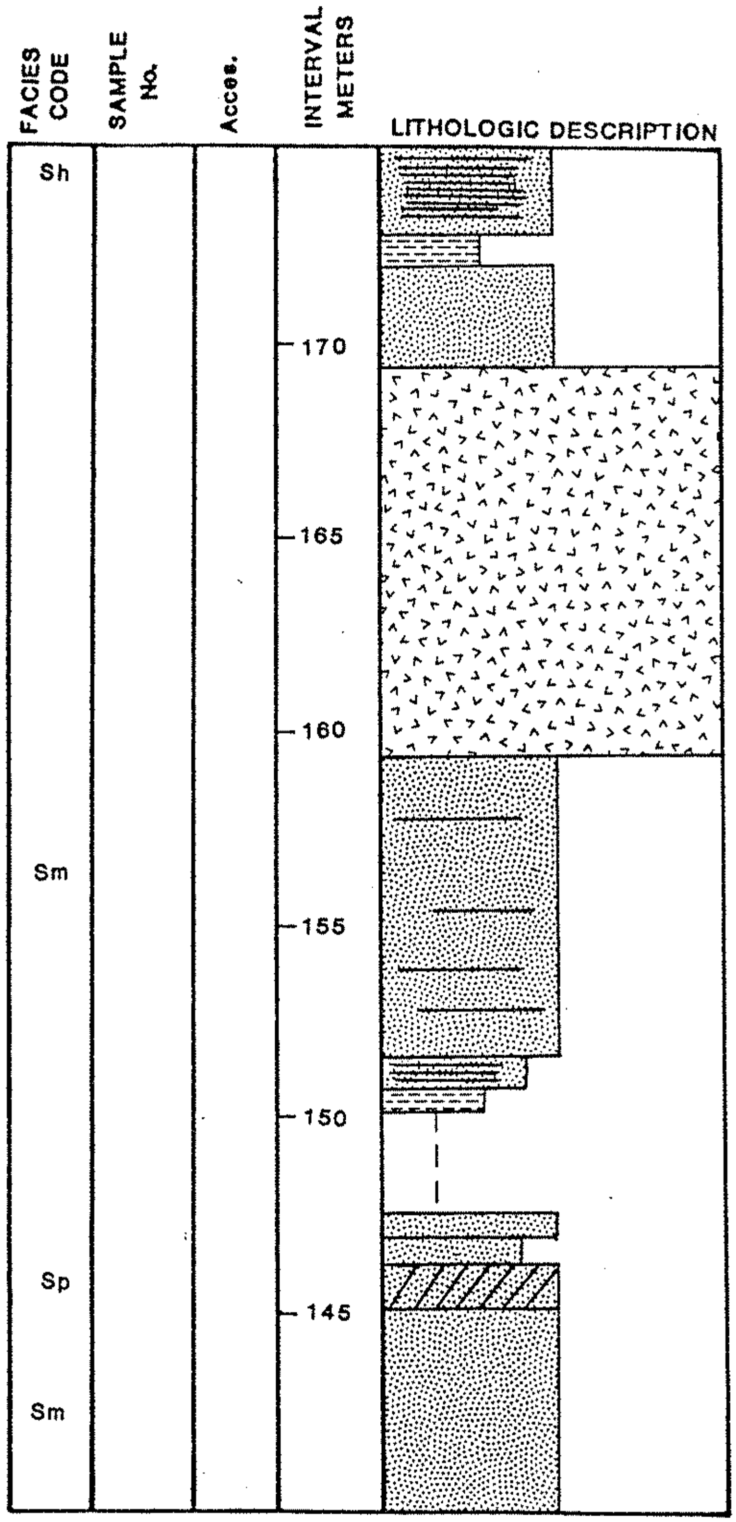
EARLY WINTERS CREEK STRATIGRAPHIC SECTION (CONTINUED)



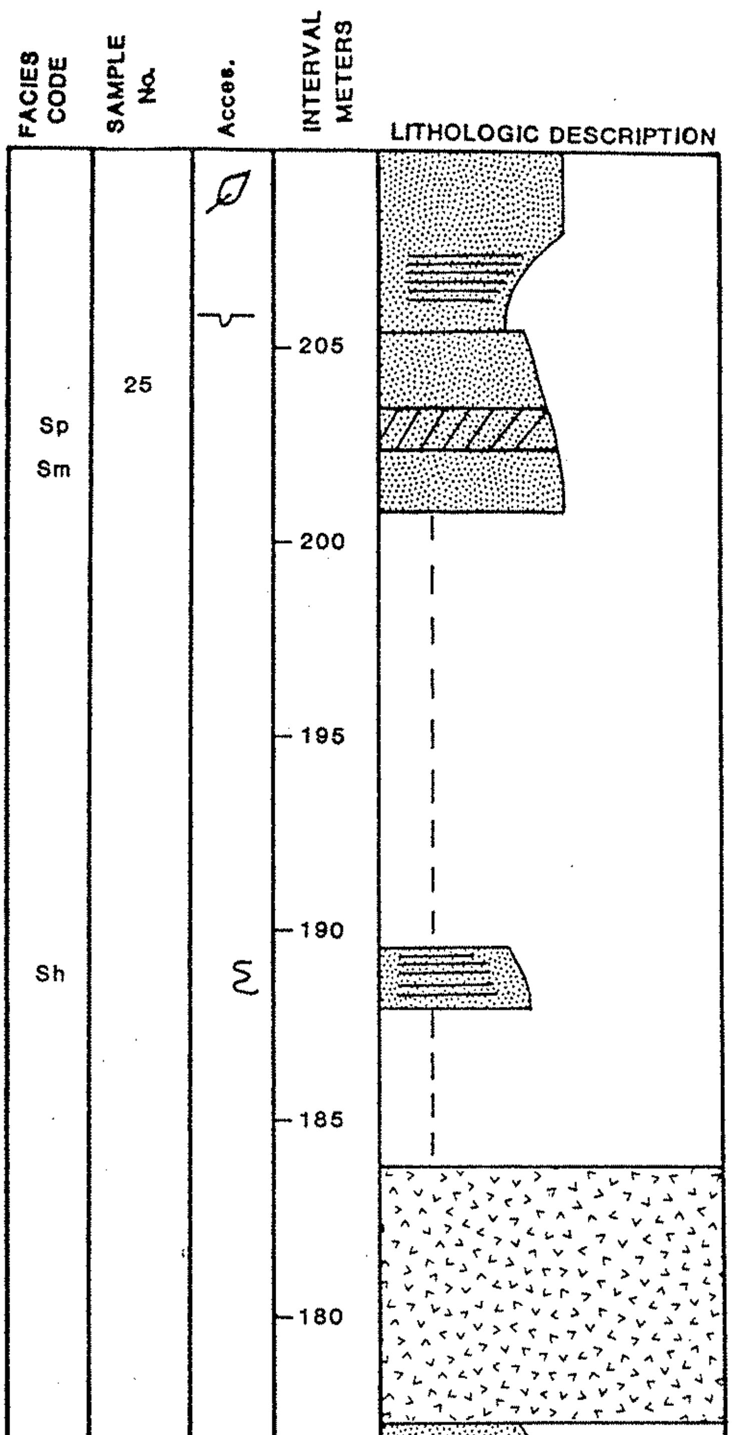
EARLY WINTERS CREEK STRATIGRAPHIC SECTION (CONTINUED)



EARLY WINTERS CREEK STRATIGRAPHIC SECTION (CONTINUED)

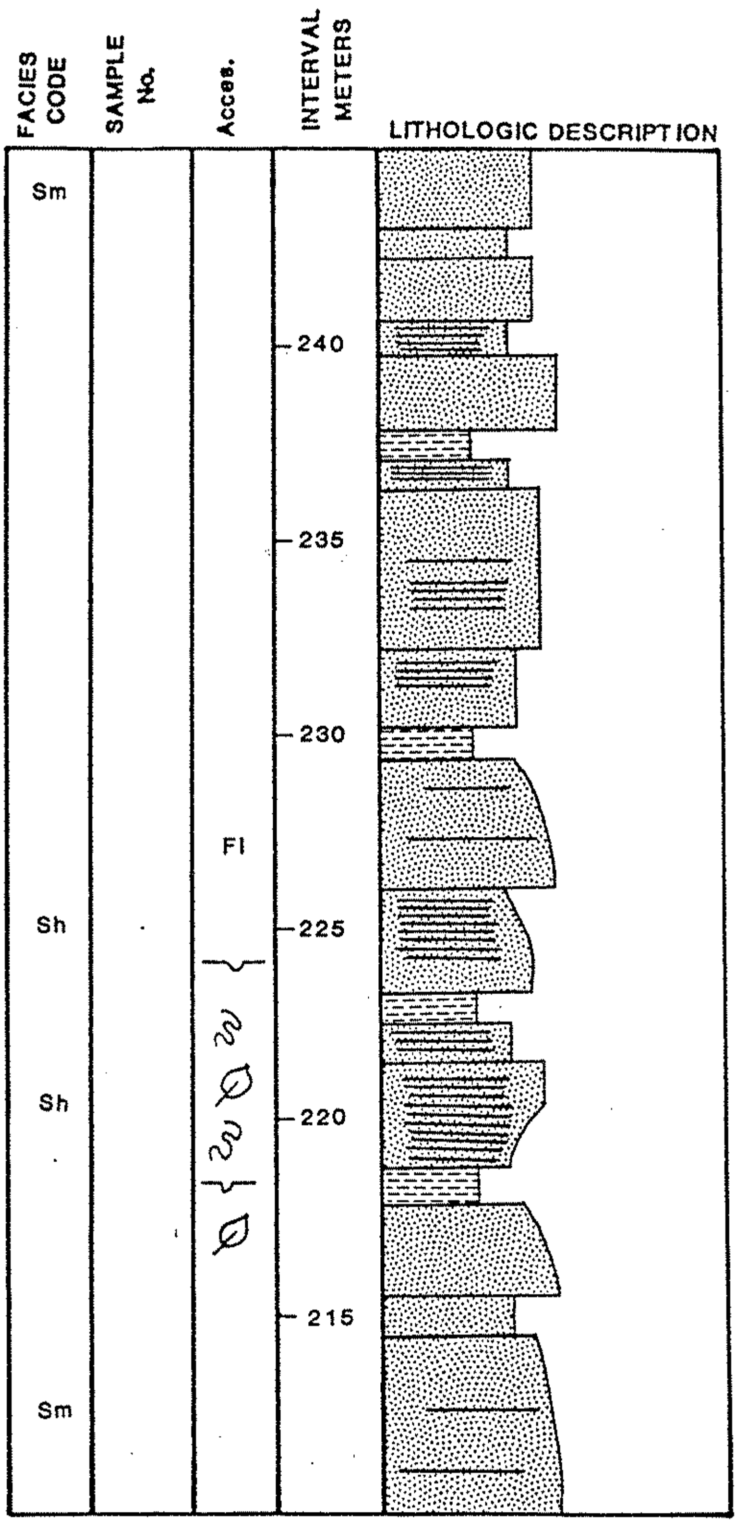


EARLY WINTERS CREEK STRATIGRAPHIC SECTION (CONTINUED)



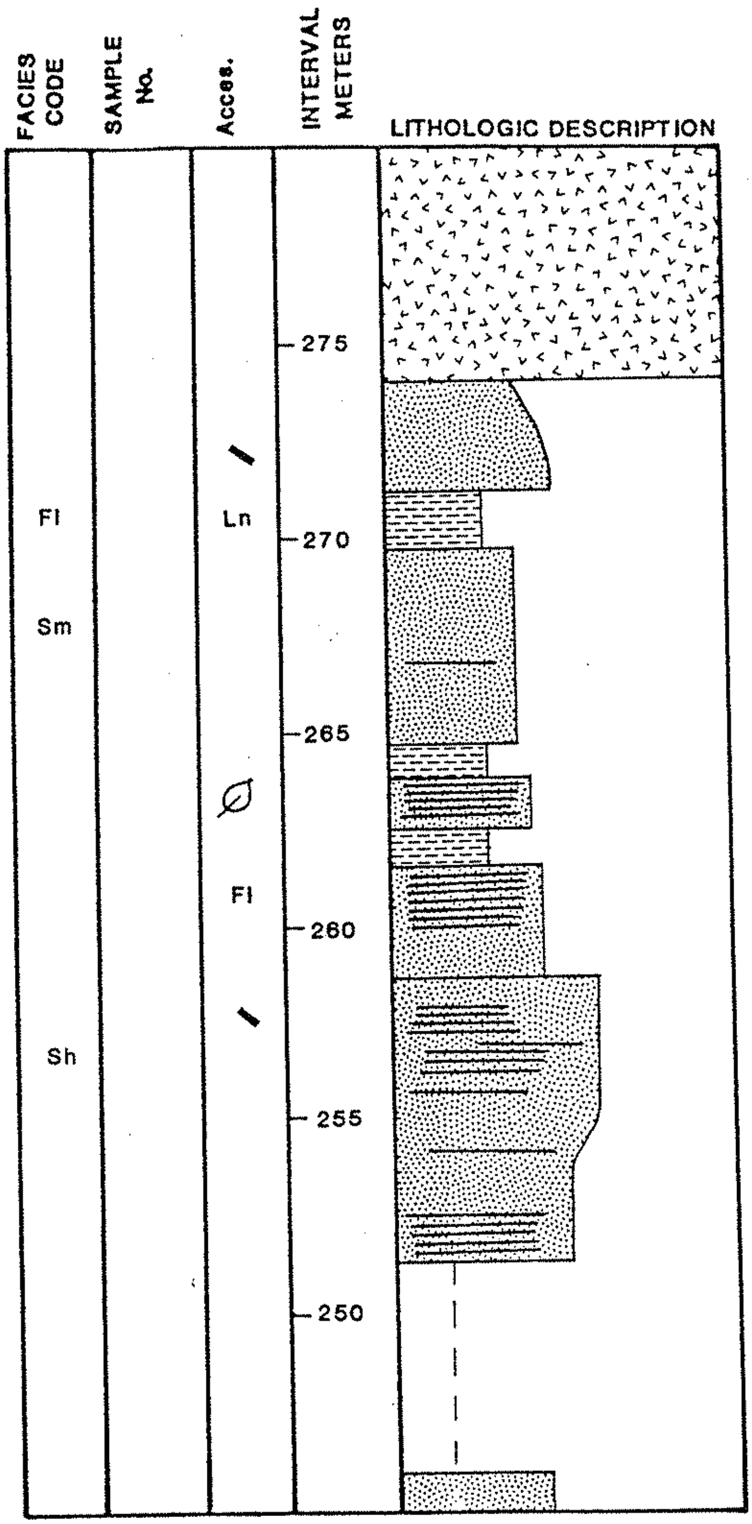
EARLY WINTERS CREEK STRATIGRAPHIC SECTION

(CONTINUED)

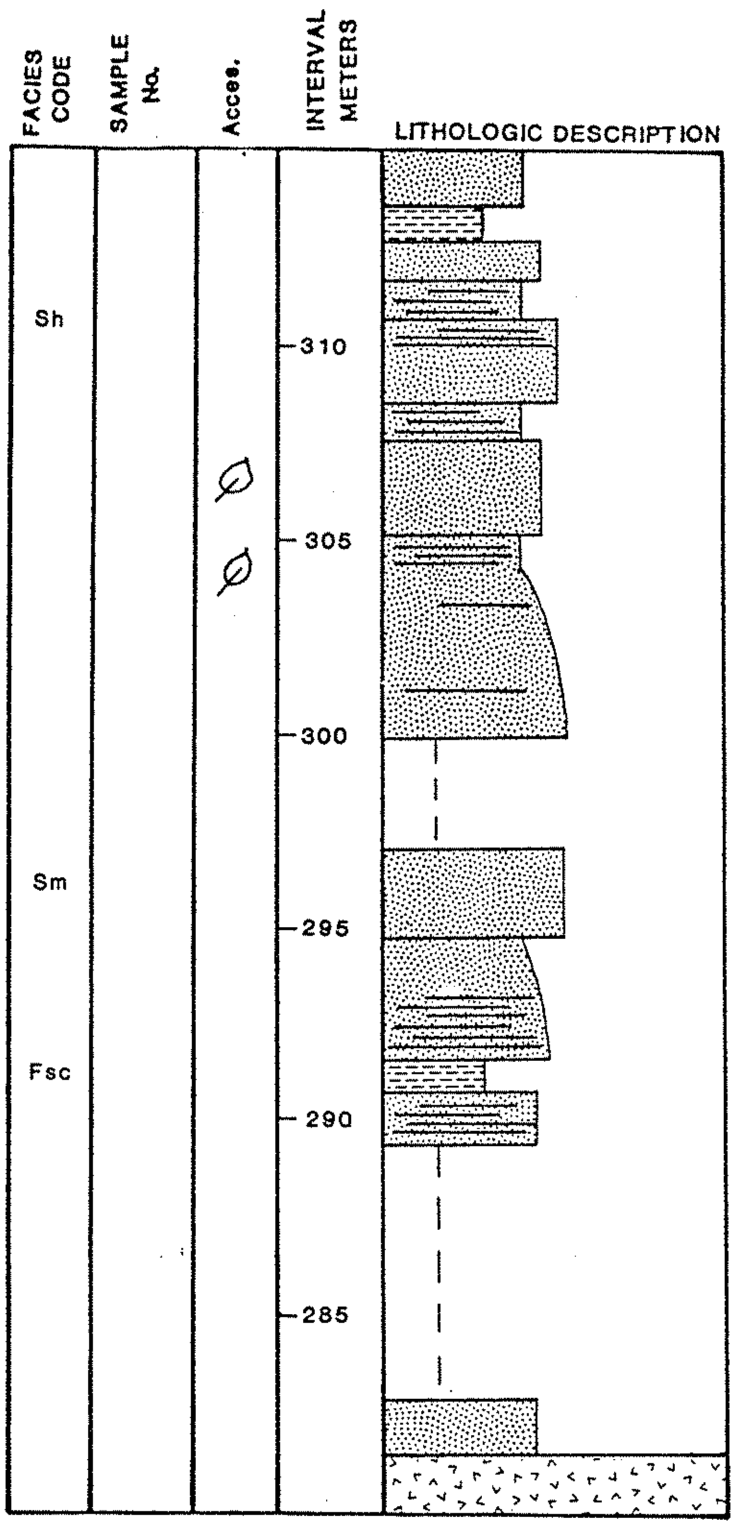


EARLY WINTERS CREEK STRATIGRAPHIC SECTION

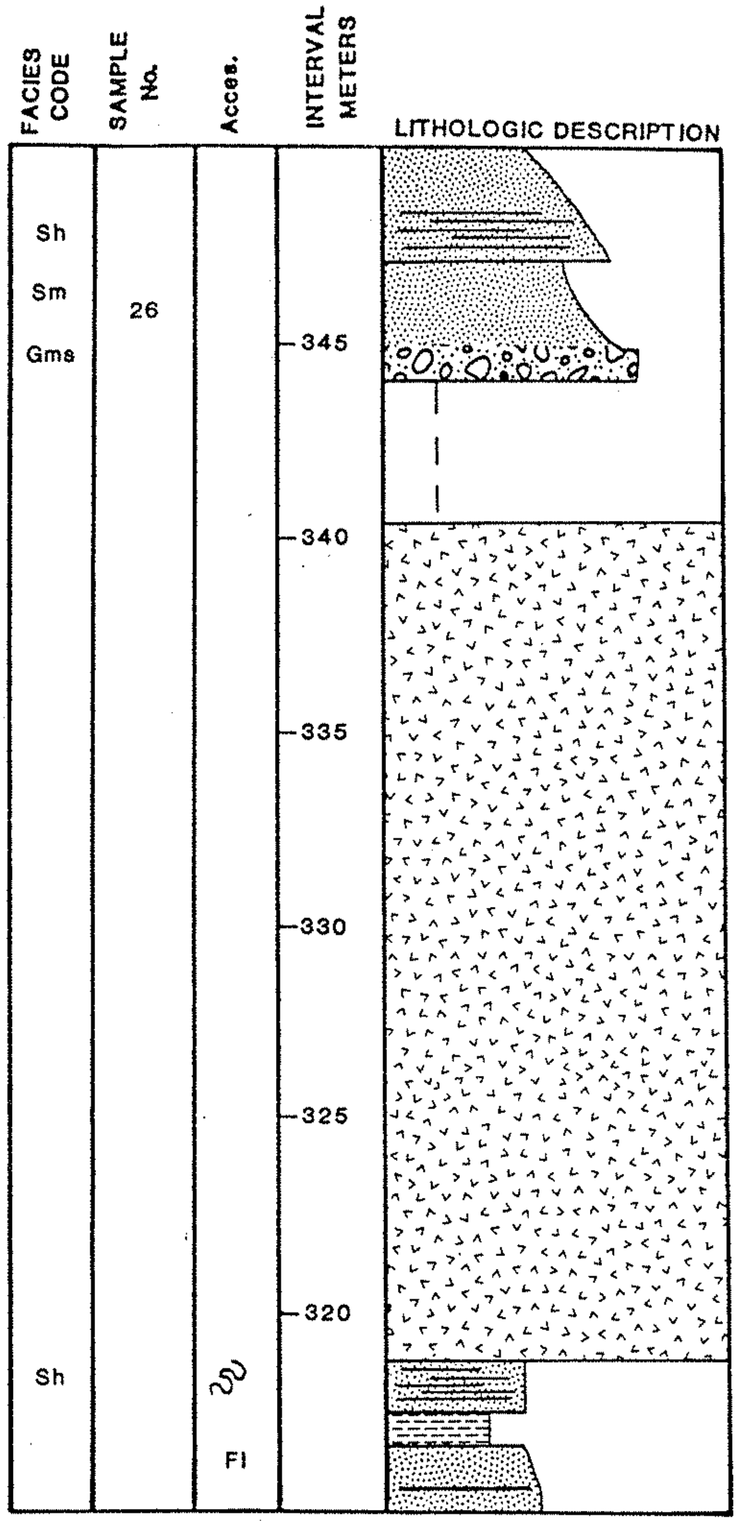
(CONTINUED)



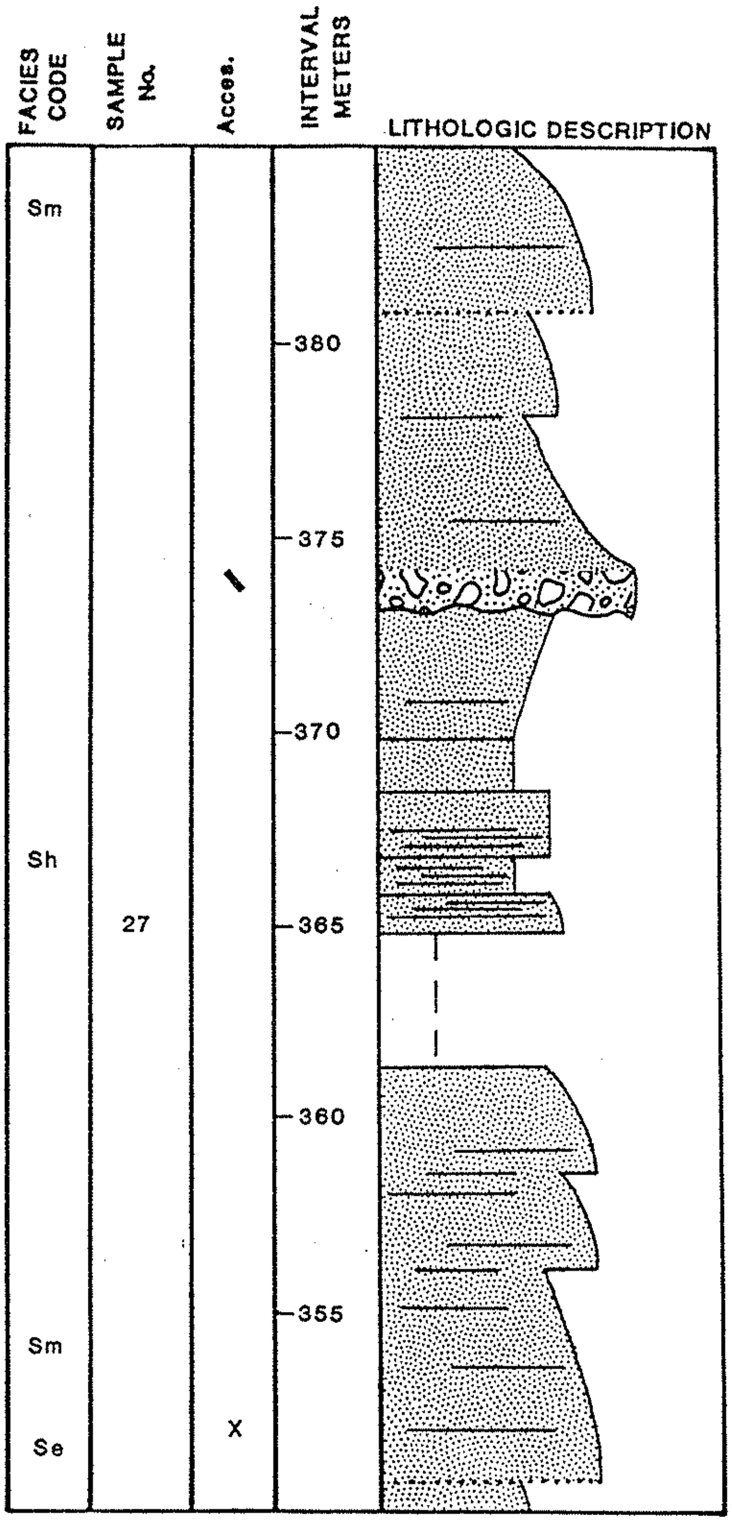
EARLY WINTERS CREEK STRATIGRAPHIC SECTION (CONTINUED)



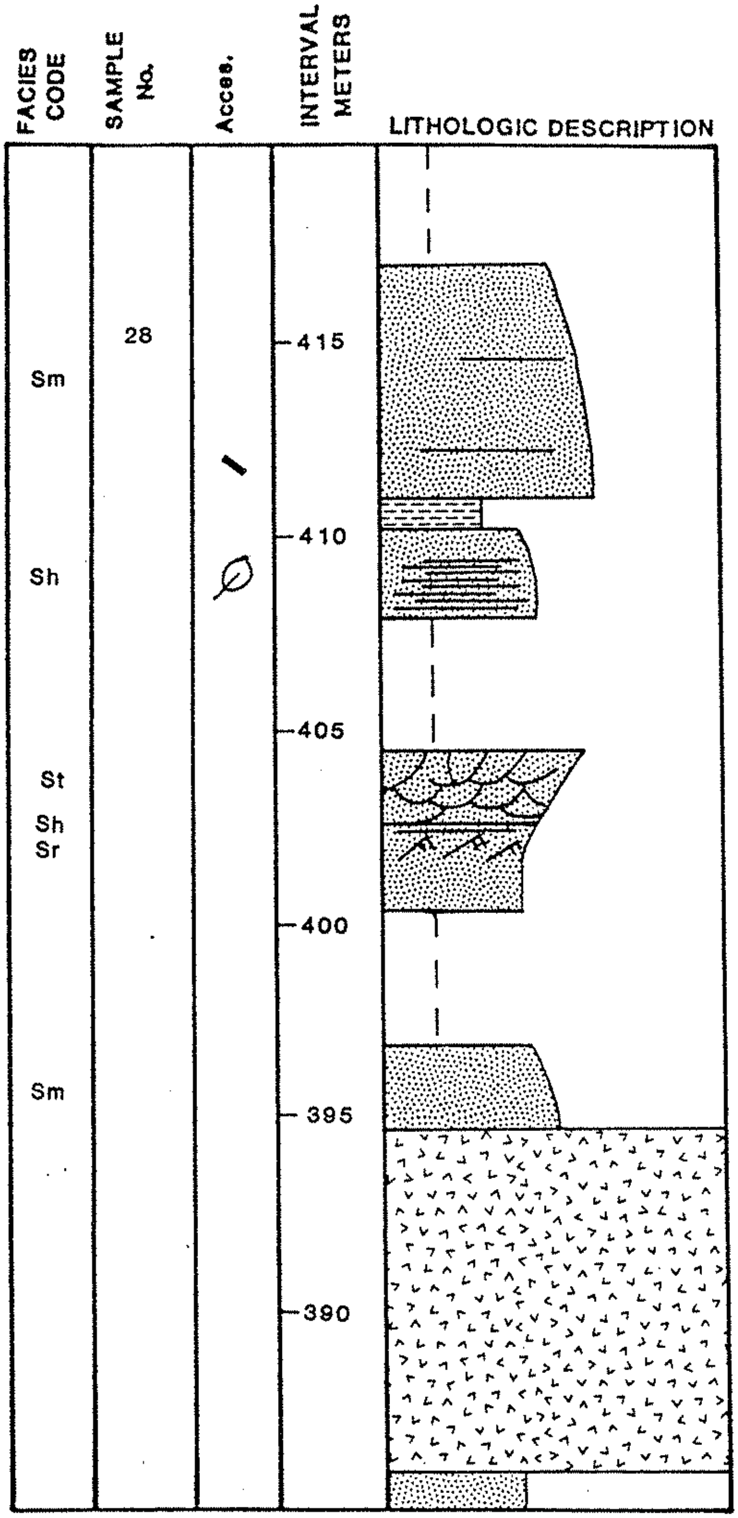
EARLY WINTERS CREEK STRATIGRAPHIC SECTION
(CONTINUED)



EARLY WINTERS CREEK STRATIGRAPHIC SECTION (CONTINUED)



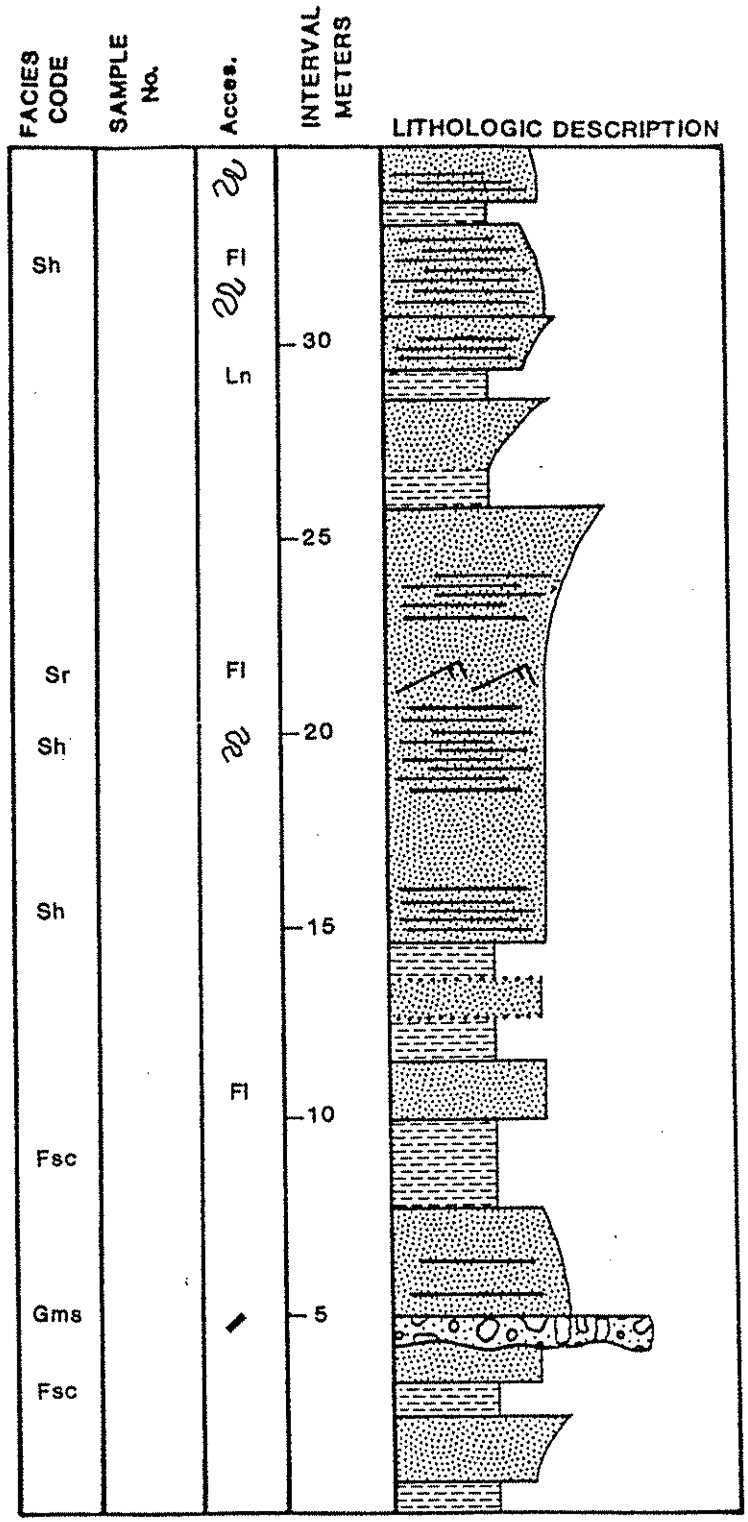
EARLY WINTERS CREEK STRATIGRAPHIC SECTION (CONTINUED)



APPENDIX 6

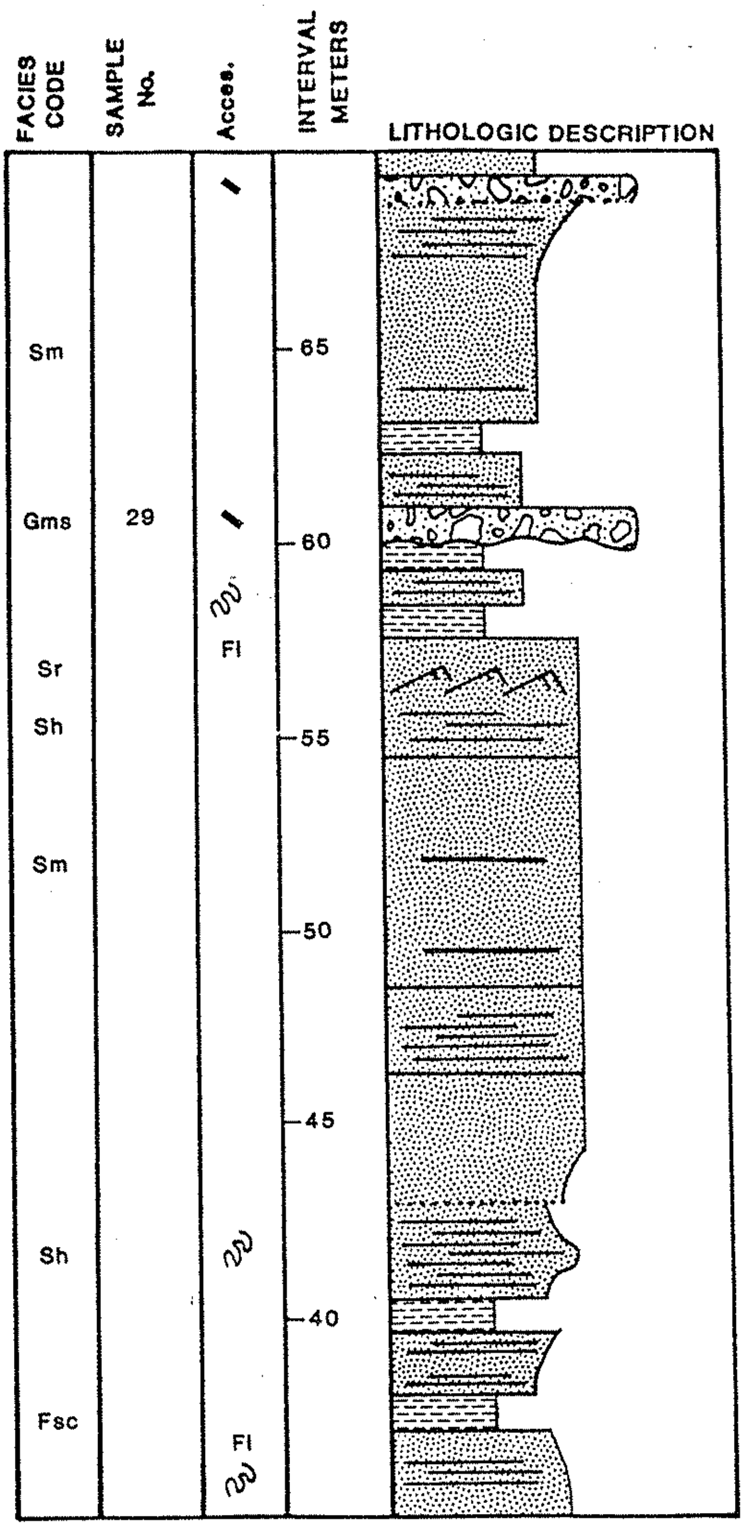
NORTH DEVILS PEAK SECTION

NORTH DEVILS PEAK STRATIGRAPHIC SECTION

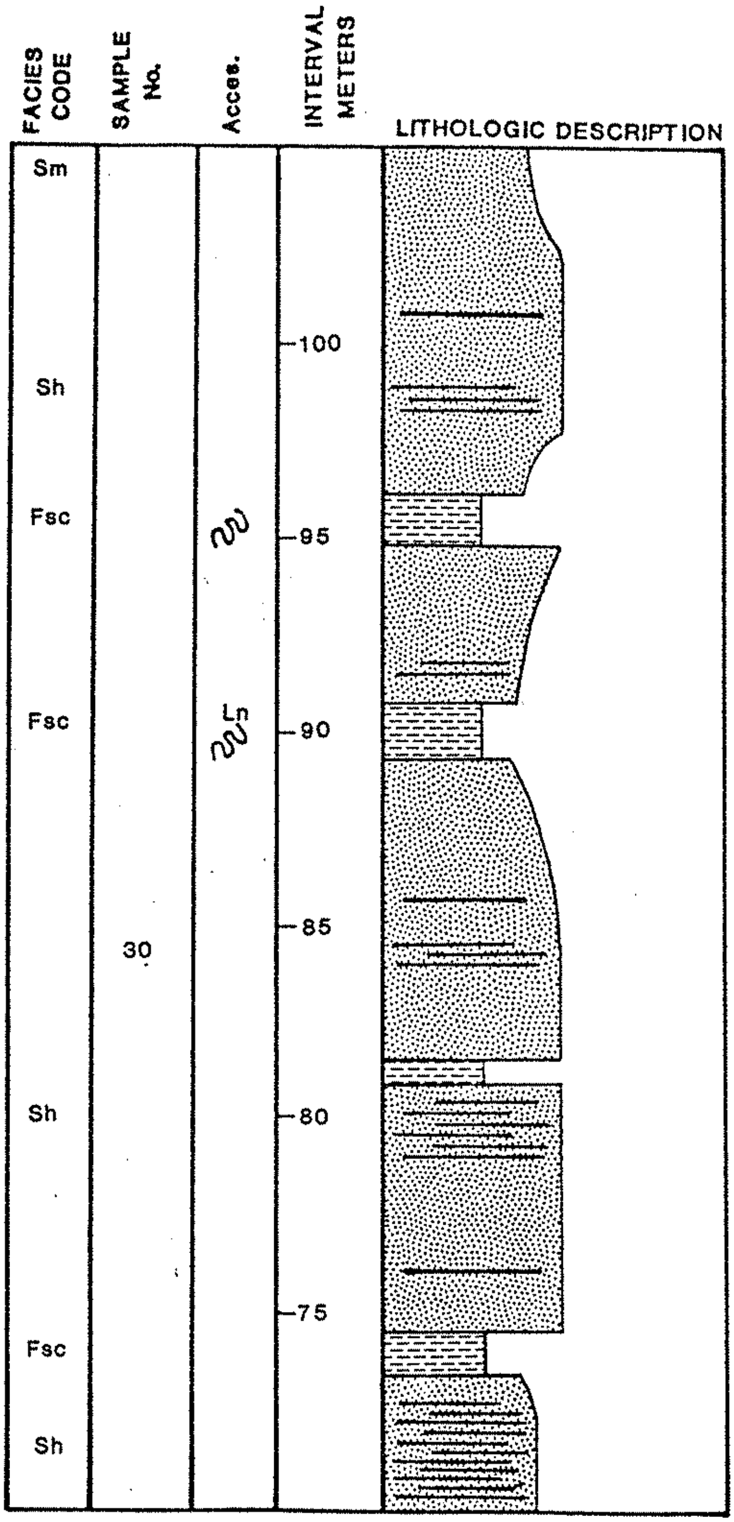


NORTH DEVILS PEAK STRATIGRAPHIC SECTION

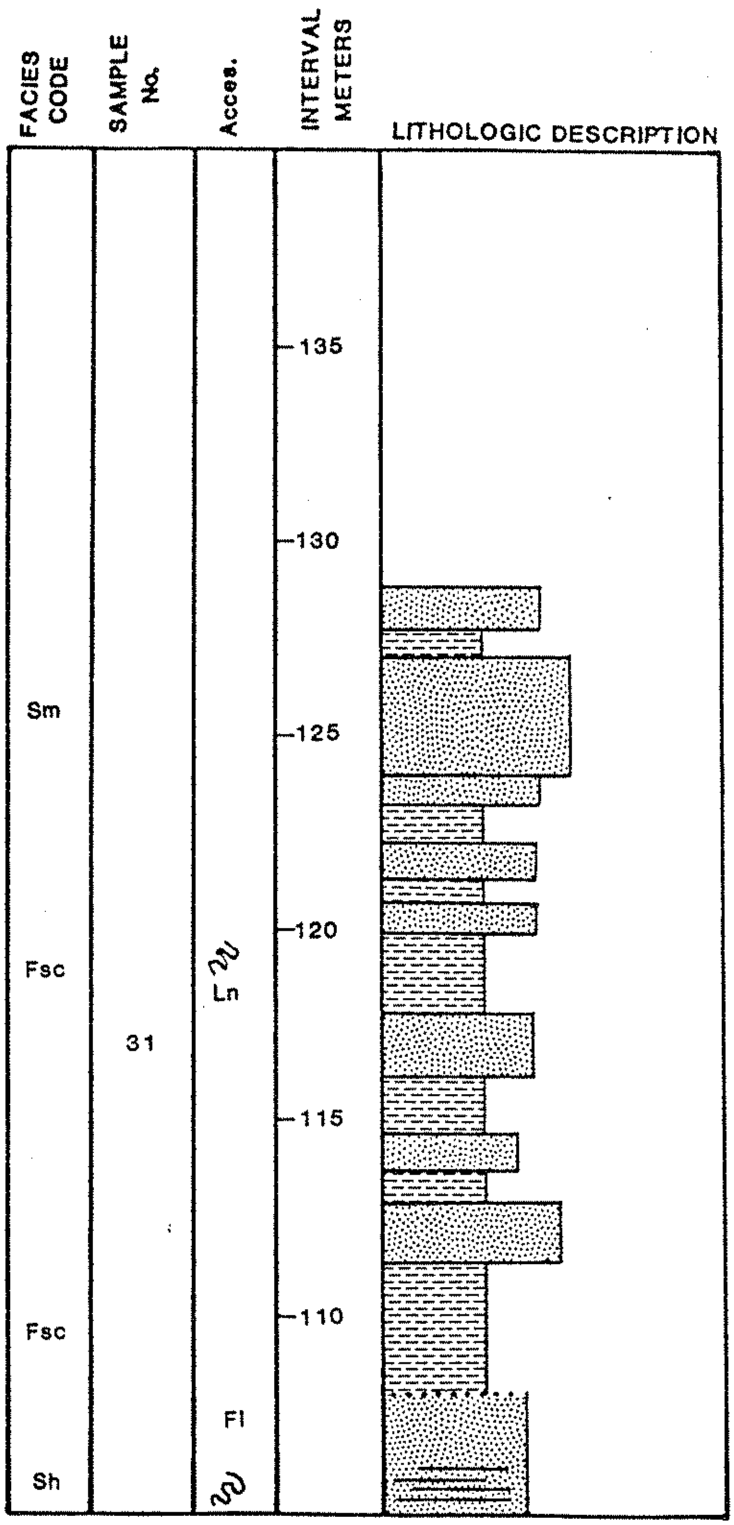
(CONTINUED)



NORTH DEVILS PEAK STRATIGRAPHIC SECTION
(CONTINUED)



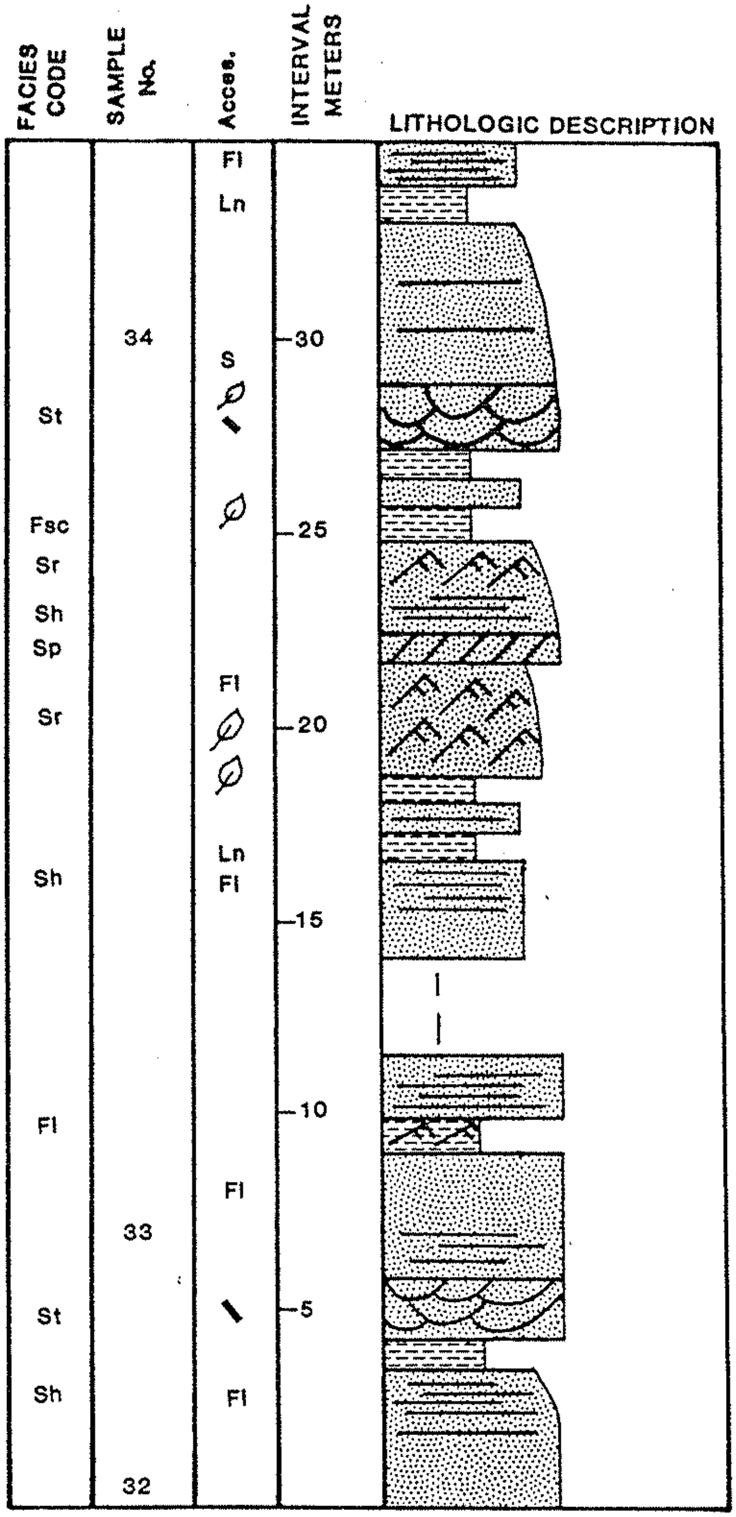
NORTH DEVILS PEAK STRATIGRAPHIC SECTION
(CONTINUED)



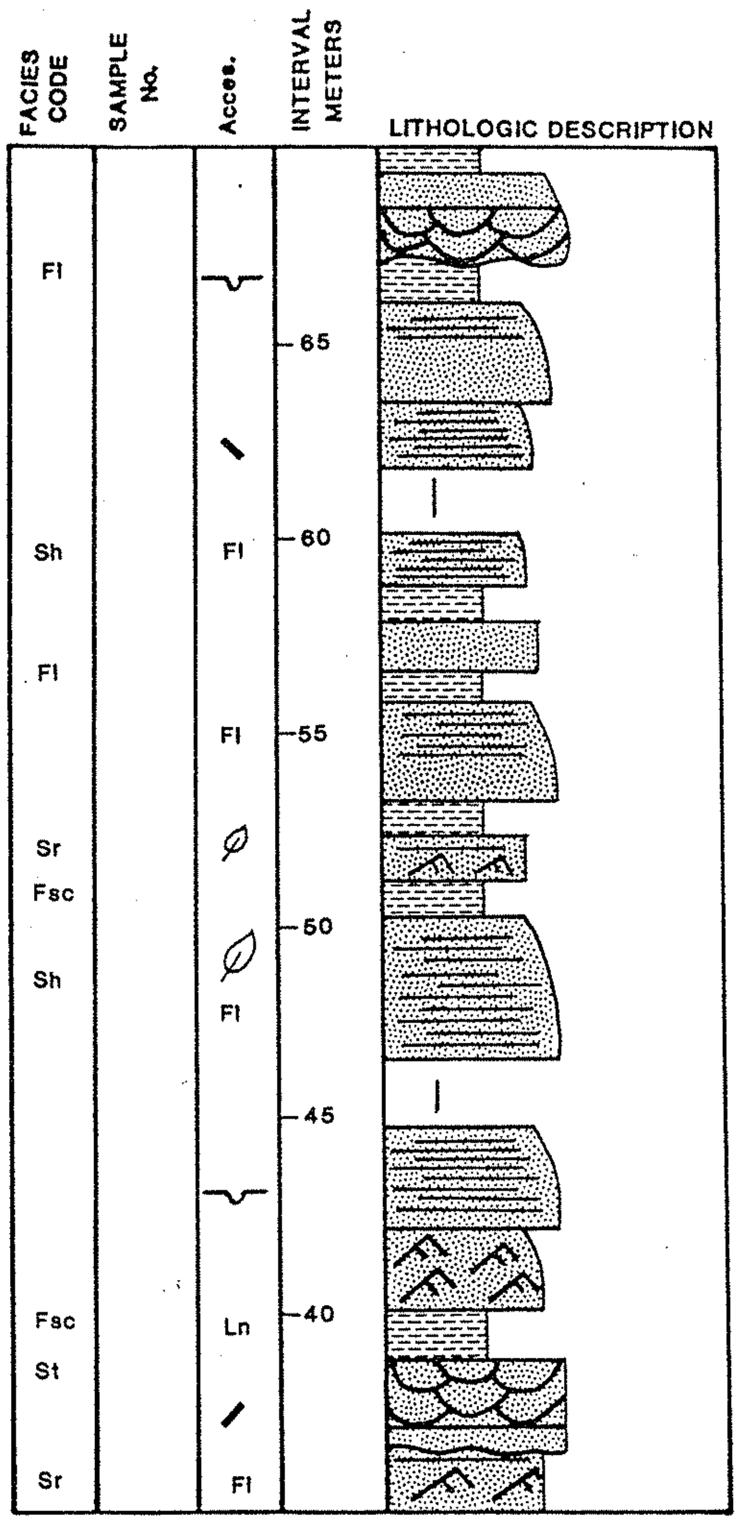
APPENDIX 7

SLATE PEAK SECTION

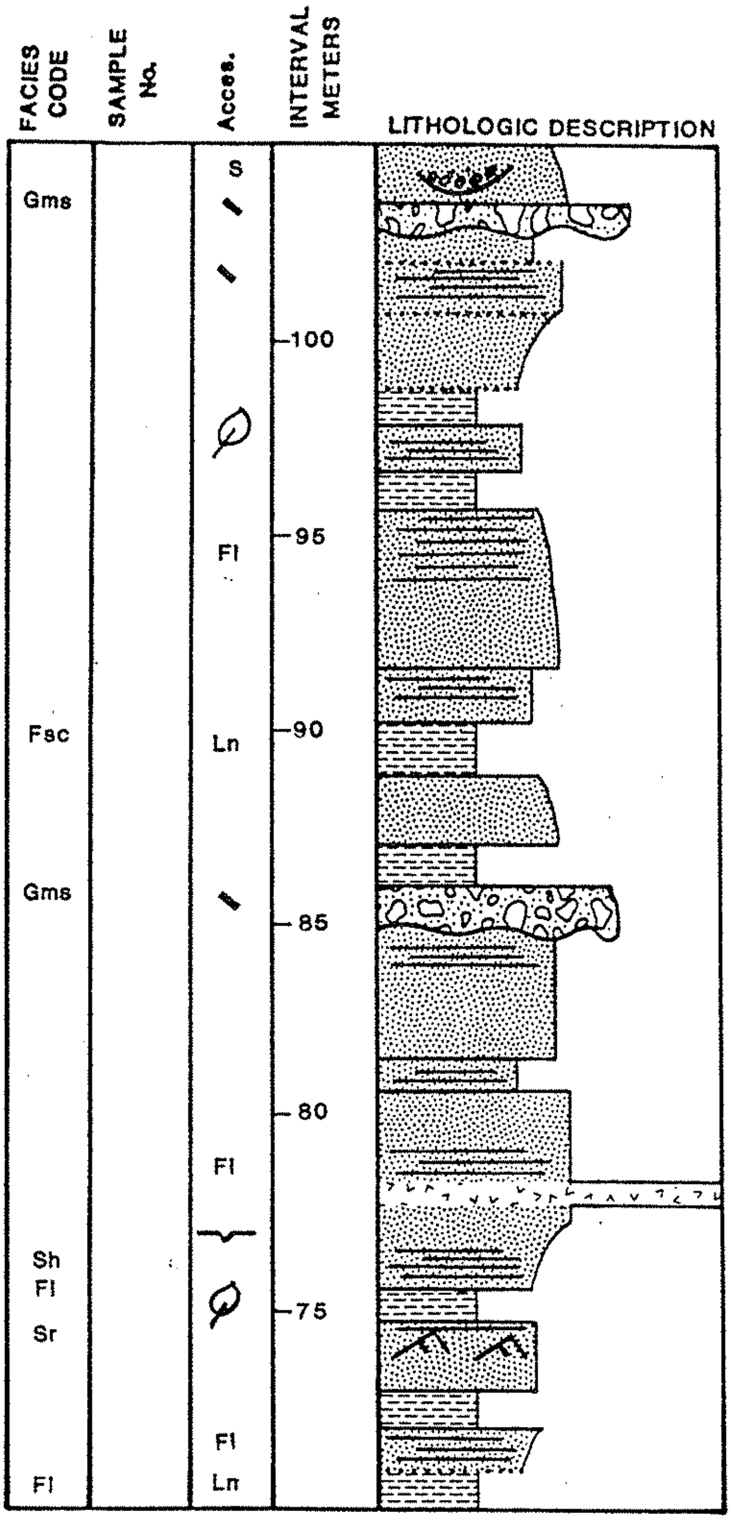
SLATE PEAK STRATIGRAPHIC SECTION



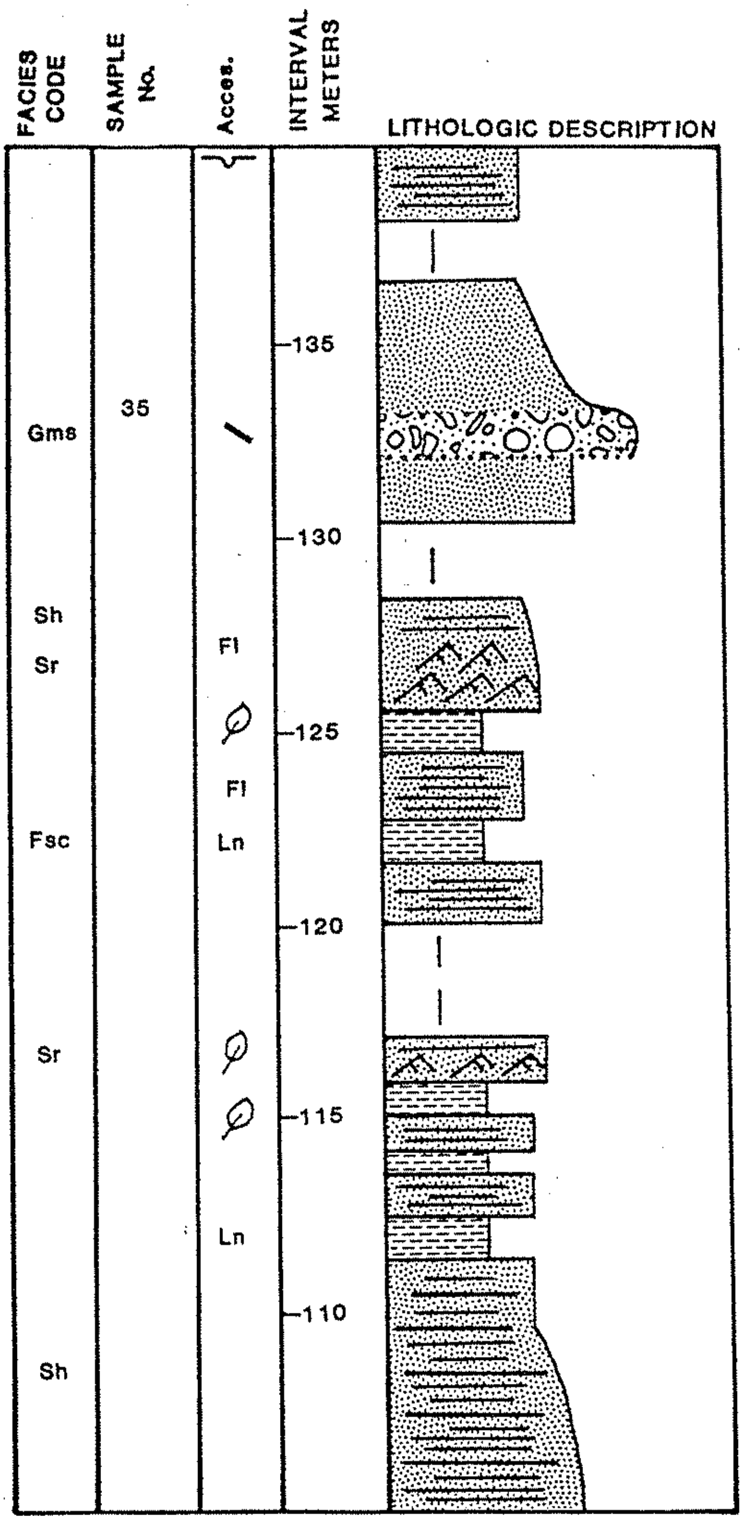
SLATE PEAK STRATIGRAPHIC SECTION
(CONTINUED)



SLATE PEAK STRATIGRAPHIC SECTION
(CONTINUED)



SLATE PEAK STRATIGRAPHIC SECTION
(CONTINUED)



APPENDIX 8

MODAL ANALYSES OF THE WINTHROP SANDSTONE
(200 COUNTS)

KEY:

Q = total quartz
F = total feldspar
L = total lithic fragments
A = accessory minerals
M = matrix
Mp= pseudomatrix
D = detrital fraction
C = cement
Qm= monocrystalline quartz
Qp= polycrystalline quartz
Lv= volcanic lithic fragments
Lm= metamorphic lithic fragments
Ls= sedimentary lithic fragments

MODAL ANALYSES OF THE WINTHROP SANDSTONE (TYPE SECTION)

Interval(m)	326	346	376	455	821	859	910
Q	11.5	34.8	50.5	54.7	20.6	17.3	17.0
F	0.6	20.5	46.8	44.7	47.0	35.1	50.0
L	82.5	44.7	2.7	0.6	32.4	47.6	33.0
Q	11.3	33.5	46.6	51.4	16.2	16.2	14.7
F	5.6	19.7	43.2	42.1	37.0	32.8	42.9
L	80.8	43.1	2.3	0.6	25.4	44.4	28.3
A	1.7	0.7	3.4	5.3	4.6	0.0	5.2
M	0.0	1.5	1.7	0.0	1.2	0.5	0.5
Mp	0.6	1.5	2.8	0.6	15.6	6.1	8.4
D	90.0	76.0	87.5	85.0	86.5	99.0	95.5
C	10.0	24.0	12.5	15.0	13.5	1.0	4.5
Qm	35.0	82.6	81.7	91.0	82.1	68.8	100
Qp	65.0	17.4	18.3	9.0	17.9	31.2	0.0
Lv	12.0	1.7	50.0	0.0	100	92.0	98.0
Lm	4.0	1.7	0.0	0.0	0.0	2.3	2.0
Ls	84.0	96.6	50.0	100	0.0	5.7	0.0

Interval(m)	927	942	1031	1124	1324
Q	13.0	11.9	23.4	38.8	43.5
F	41.8	31.4	54.5	39.6	47.7
L	45.2	56.7	22.1	21.6	8.8
Q	8.5	8.6	20.0	29.7	39.6
F	27.1	22.5	46.7	30.2	43.3
L	29.4	40.6	18.9	16.5	8.0
A	18.6	13.8	4.4	5.5	1.1
M	4.5	1.1	2.2	1.6	7.5
Mp	11.9	13.4	7.8	16.5	0.5
D	89.5	93.5	90.0	91.0	92.5
C	10.5	6.5	10.0	9.0	7.5
Qm	93.3	87.5	63.9	74.1	98.6
Qp	6.7	12.5	36.1	25.9	1.4
Lv	100	100	100	86.7	93.4
Lm	0.0	0.0	0.0	0.0	0.0
Ls	0.0	0.0	0.0	13.3	6.6

MODAL ANALYSES OF THE WINTHROP SANDSTONE (WHITEFACE CREEK SECTION)

Interval(m)	21	146	165	200	278
Q	31.6	44.2	39.6	23.4	27.9
F	68.4	52.9	58.0	76.7	60.4
L	0.0	2.9	2.4	0.0	11.7
Q	29.0	42.4	37.4	16.0	27.0
F	63.0	50.6	54.8	52.2	58.4
L	0.0	2.7	2.2	0.0	11.4
A	4.8	2.7	2.8	7.1	0.5
M	3.2	1.6	2.8	24.7	2.7
Mp	0.0	0.0	0.0	0.0	0.0
D	94.5	91.0	89.5	91.0	92.5
C	5.5	9.0	10.5	9.0	7.5
Qm	94.5	77.9	91.0	100	72.0
Qp	5.5	22.1	9.0	0.0	28.0
Lv	0.0	100	0.0	0.0	81.0
Lm	0.0	0.0	100	0.0	14.3
Ls	0.0	0.0	0.0	0.0	4.7

Interval(m)	307	317	386	449
Q	48.0	37.3	45.6	32.2
F	38.8	58.2	53.2	50.3
L	13.2	4.5	1.2	17.5
Q	40.3	35.9	41.9	26.6
F	32.7	54.9	49.0	41.0
L	11.0	4.3	1.1	14.5
A	3.9	2.7	7.5	2.3
M	5.5	2.2	0.5	3.5
Mp	6.6	0.0	0.0	12.1
D	90.5	93.0	92.0	90.0
C	9.5	7.0	8.0	10.0
Qm	79.5	83.3	82.1	63.0
Qp	20.5	16.7	17.9	37.0
Lv	65.0	62.5	0.0	72.0
Lm	0.0	0.0	0.0	0.0
Ls	35.0	37.5	100	28.0

MODAL ANALYSES OF THE WINTHROP SANDSTONE
(EARLY WINTERS CREEK SECTION)

Interval(m)	1	78	109	204	346	365	415
Q	27.2	9.4	36.4	18.6	43.3	46.7	32.4
F	36.4	18.1	54.6	43.0	42.3	51.7	54.1
L	36.4	72.5	9.0	38.4	14.4	1.6	13.5
Q	23.0	7.4	12.3	16.8	41.5	45.4	26.8
F	30.6	14.4	18.7	38.7	40.4	50.3	44.7
L	1.6	57.1	3.1	34.6	13.8	1.6	11.2
A	30.6	4.0	2.6	2.5	1.6	1.6	7.8
M	4.4	7.4	63.6	1.6	2.7	1.1	3.4
Mp	9.8	9.7	0.0	5.8	0.0	0.0	6.1
D	91.5	87.5	97.5	95.5	94.0	93.0	89.5
C	8.5	12.5	2.5	4.5	6.0	7.0	10.5
Qm	88.1	76.9	95.8	81.2	79.5	83.5	97.9
Qp	11.9	23.1	4.2	18.8	20.5	16.5	2.1
Lv	83.9	90.0	66.7	98.5	84.6	100	100
Lm	1.8	0.0	0.0	0.0	0.0	0.0	0.0
Ls	14.3	10.0	33.3	1.5	15.4	0.0	0.0

MODAL ANALYSES OF THE WINTHROP SANDSTONE
(NORTH DEVILS PEAK SECTION)

Interval(m)	61	84	117
Q	29.1	36.2	40.4
F	40.6	63.8	59.6
L	30.3	0.0	0.0
Q	25.3	35.0	40.2
F	35.3	62.5	59.3
L	26.3	0.0	0.0
A	1.6	0.0	0.0
M	2.1	2.5	0.5
Mp	9.4	0.0	0.0
D	95.0	98.5	97.0
C	5.0	1.5	3.0
Qm	83.3	73.9	85.9
Qp	16.7	26.1	14.1
Lv	0.0	0.0	0.0
Lm	0.0	0.0	0.0
Ls	100	0.0	0.0

MODAL ANALYSES OF THE WINTHROP SANDSTONE
(SLATE PEAK SECTION)

Interval(m)	0	7	30	133
Q	33.1	33.7	37.5	33.0
F	66.3	66.3	62.5	52.0
L	0.6	0.0	0.0	14.2
Q	31.0	32.0	33.5	31.0
F	62.0	62.8	55.9	49.7
L	0.6	0.0	0.0	13.4
A	2.9	1.7	2.4	3.2
M	3.5	3.5	8.2	2.7
Mp	0.0	0.0	0.0	0.0
D	85.5	89.0	85.0	93.5
C	14.5	11.0	15.0	6.5
Qm	100	91.2	79.0	81.0
Qp	0.0	8.8	21.0	19.0
Lv	100	0.0	0.0	68.0
Lm	0.0	0.0	0.0	0.0
Ls	0.0	0.0	0.0	32.0

APPENDIX 9

MEGAFOSSIL FLORAS OF THE WINTHROP SANDSTONE

ANGIOSPERMS:

Sapindopsis sp.
Menispermites sp. or Nelumbium sp.
*Araliaephyllum westoni (Dawson) Bell
*Araliaephyllum rotundiloba (Newberry) Fritel
*Ficus ovalifolia Berry
*Sapindopsis belviderensis Berry
*Nelumbites sp.
*Menispermites sp.
*Araliopsoides cretacea (Newberry) Berry
*Eucalyptophyllum sp.
palm fragment? and other dicotyledon fragments

FERNS:

Cladophlebis sp.
Cladophlebis cf. septentrionalis Hollick
*Cladophlebis virginiensis Fontaine
*Cladophlebis impressa Bell
Gleichenites cf. Gleichenites geiseckiana Heer
*Gleichenites giesekianus (Heer) Seward
*Sagenopteris williamsii Newberry
Anemia cf. A. supercretacea Hollick

CONIFERS:

Cyparissidium gracile Heer or Sequoia fastigiata Heer
*Widdringtonites reichii Heer
*Elatocladus sp. cf. Cephalotaxopsis heterophylla Hollick
Pseudocyas steenstrupi Heer

(*) - Indicates flora was first identified in this study by David Crabtree (written communication, 1986).

REFERENCES CITED

Allen, J.R.L., 1964, Studies in fluviatile sedimentation, six cyclothems from the Lower Old Red Sandstone, Anglo-Welsh Basin: Sedimentology, v. 3, pp. 163-198.

Arribas, J., Marfil, J., De La Pena, J.A., 1985, Provenance of Triassic feldspathic sandstones in the Iberian Range (Spain), significance of quartz types: Journal of Sedimentary Petrology, v. 55, no. 6, pp. 864-868.

Barksdale, J.D., 1975, Geology of the Methow Valley, Okanogan County, Washington: Washington Department of Natural Resources, Division of Geology and Earth Resources, Bulletin no. 68, 72 p.

Barron, E.J., Thompson, S.L., and Schneider, S.H., 1981, An ice-free Cretaceous? results from climate model simulations: Science, v. 212, no. 4494, pp. 501-508.

Basu, A., Young, S.W., Suttner, L.J., James, W.C., and Mack, G.H., 1975, Re-Evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation: Journal of Sedimentary Petrology, v. 45, no. 4, pp. 873-882.

Batten, D.J., 1984, Palynology, climate and the development of Late Cretaceous floral provinces in the northern hemisphere, a review: in, Brenchley, P.J., editor, Fossils and Climate, pp. 127-164.

Best, M.G., 1982, Igneous and metamorphic petrology: W. H. Freeman and Company, San Francisco. 630 p.

Biekman, H.M., 1980, Geologic map of Alaska: State of Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, Scale 1:2,500,000.

Blatt, H., and Christie, J.M., 1963, Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks: Journal of Sedimentary Petrology, v. 33, no. 3, pp. 559-579.

Blatt, H., Middleton, G., and Murray, R., 1980, Origin of sedimentary rocks: Prentice-Hall Inc., New Jersey, 782 p.

Boles, J.R., 1982, Active albitization of plagioclase, Gulf Coast Tertiary: American Journal of Science, v. 282, pp. 165-180.

Bridge, J.S., and Leeder, M.R., 1979, A simulation model of alluvial stratigraphy: Sedimentology, v. 26, pp. 617-644.

Burns, L.K., and Ethridge, F.G., 1979, Petrology and diagenetic effects of lithic sandstones, Paleocene and Eocene Umpqua Formation, southwest Oregon: in, Scholle, P.A., and Schluger, P.R., editors, Aspects of Diagenesis, Society of Economic Paleontologists and Mineralologists, Special Publication no. 26, pp. 307-317.

Cant, D.J., and Walker, R.G., 1978, Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology, v. 25, pp. 625-648.

Coates, J.A., 1974, Geology of the Manning Park area, British Columbia: Geological Survey of Canada, Bulletin no. 238, 177 p.

Cole, M.R., 1973, Petrology and dispersal patterns of Jurassic and Cretaceous sedimentary rocks in the Methow River area, North Cascades, Washington: Ph.D. thesis, University of Washington, 110 p.

Collinson, J.D., 1978, Vertical sequence and sand body shape in alluvial sequences: in, Miall, A.D., editor, Fluvial Sedimentology, Canadian Society of Petroleum Geologists, Memoir no. 5, Calgary, pp. 577-586.

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran "collage", central British Columbia to central California: in, Howell, D.G., and McDougall, K.A., editors, Mesozoic Paleogeography of the Western United States, Society of Economic Paleontologists and Mineralologists, Pacific Section, Pacific Coast Symposium no. 2, pp. 1-32.

Dickinson, W.R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, pp. 695-707.

Dickinson, W.R., and Suczek, C.A., 1979, Plate tectonics and sandstone composition: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, pp. 2164-2182.

Dickinson, W.R., et al., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, pp. 222-235.

Eisbacher, G.H., 1974, Evolution of successor basins in the Canadian Cordillera: in, Dott, R.H., and Shaver, R.H., editors, Modern and Ancient Geosynclinal sedimentation, Society of Economic Paleontologists and Mineralologists, Special Publication no. 19, pp. 274-291.

_____1981, Late Mesozoic-Paleogene Browser Basin molasse and Cordilleran tectonics, western Canada: in, Miall, A.D., editor, Sedimentation and Tectonics in Alluvial Basins, Geological Association of Canada Special Paper no. 23, pp. 125-151.

Engels, J.C., Tabor, R.W., Miller, F.K., and Obradovich, J.D., 1976, Summary of K-Ar, Rb-Sr, U-Pb, and Pb-alpha and fission-track ages of rocks from Washington State prior to 1975 (exclusive of the Columbia Plateau Basalts): United States Geological Survey Miscellaneous Field Studies Map MF-710, Scale 1:1,000,000.

Folk, R.L., 1974, Petrology of sedimentary rocks: Hempill Publishing Company, Austin, Texas, 185 p.

Fox, K.F., Rinehart, C.D., and Engels, J.C., 1977, Plutonism and orogeny in North-Central Washington, timing and regional context: United States Geological Survey Professional Paper no. 989, 27 p.

Friend, P.F., 1978, Distinctive features of some ancient river systems: in, Miall, A.D., editor, Fluvial Sedimentology, Canadian Society of Petroleum Geologists, Memoir no. 5, Calgary, pp. 531-542.

_____1983, Towards the field classification of alluvial architecture or sequence: in, Collinson, J.D., and Lewin, J., Modern and Ancient Fluvial Systems, Blackwell Scientific Publications, Oxford, pp. 345-354.

Galloway, W.E., 1974, Deposition and diagenetic alteration of sandstone in Northwest Pacific arc-related basins, implications for graywacke genesis: Geological Society of America Bulletin, v. 85, pp. 379-390.

Goddard, E.N., (Chairman), 1963, Rock-color chart: Geological Society of America, Boulder, Colorado.

Hawkins, J.W., 1968, Regional metamorphism, metasomatism, and partial fusion in the Northwestern part of the Okanogan Range, Washington: Geological Society of American Bulletin, v. 79, pp. 1785-1820.

Helmold, K.P., and van de Kamp, P.C., 1984, Diagenetic mineralogy and controls on albitization and laumontite formation in Paleogene arkoses, Santa Ynez Mountains, California: in, McDonald, D.A., and Surdam, R.C., editors, Clastic Diagenesis, American Association of Petroleum Geologists, Memoir no. 37, pp. 239-276.

Hibbard, M.J., 1971, Evolution of a plutonic complex, Okanogan Range, Washington: Geological Society of America Bulletin, v. 82, pp. 3013-3048.

Hyndman, D.W., 1972, Petrology of igneous and metamorphic rocks: McGraw-Hill Book Company, New York, 533 p.

Jackson, R.G., 1978, Preliminary evaluation of lithofacies models for meandering alluvial streams: in, Miall, A.D., editor, Fluvial Sedimentology, Canadian Society of Petroleum Geologists, Memoir no. 5, Calgary, pp. 543-576.

Kleinspehn, K.L., 1984, Cretaceous sedimentation and tectonics, Tyaughton-Methow Basin, Southwestern British Columbia: Canadian Journal of Earth Science, v. 22, pp. 154-174.

McGowen, J.H., and Garner, L.E., 1970, Physiographic features and stratification types of coarse-grained point bars, modern and ancient examples: Sedimentology, V. 14, pp. 77-111.

McKerrow, W.S., 1981, The ecology of fossils: 2nd Edition, The MIT Press, Cambridge, Massachusetts, 283 p.

Menzer, F.J., 1983, Metamorphism and plutonism in the central part of the Okanogan Range, Washington: Geological Society of America Bulletin, v. 94, pp. 471-498.

Miall, A.D., 1974, Paleocurrent analysis of alluvial sediments, a discussion of directional variance and vector magnitude: Journal of Sedimentary Petrology, v. 44, no. 4, pp. 1174-1185.

____1978, Lithofacies types and vertical profile models in braided River deposits, a Summary: in, Miall, A.D., editor, Fluvial Sedimentology, Canadian Society of Petroleum Geologists, Memoir no. 5, Calgary, pp. 597-605.

____1978b, Tectonic setting and syndepositional setting of molasse and other nonmarine-paralic sedimentary basins: Canadian Journal of Earth Science, v. 15, pp. 1613-1632.

____1980, Cyclicity and the facies model concept in fluvial deposits: Bulletin of Canadian Petroleum Geologists, v. 28, pp. 59-80.

____1981, Alluvial sedimentary basins, tectonic setting and basin architecture: in, Miall, A.D., editor, Sedimentation and Tectonics in Alluvial Basins, Geological Association of Canada Special Paper no. 23, pp. 1-33.

____1985, Architectural-element analysis, a new method of facies analysis applied to fluvial deposits: Earth Science Reviews, v. 20, pp. 261-308.

Nijman, W., and Puigdefabregas, C., 1978, Coarse-grained point bar structure in a molasse-type fluvial system, Eocene Castisent Sandstone Formation, South Pyrenean Basin: in, Miall, A.D., editor, Fluvial Sedimentology, Canadian Society of Petroleum Geologists, Memoir no. 5, Calgary, pp. 487-510.

Odom, E., 1975, Feldspar-grain size relationships in cambrian arenites, Upper Mississippi Valley: Journal of Sedimentary Petrology, v. 45, no. 3, pp. 636-650.

Parrish, J.T., Ziegler, A.M., Scotese, C.R., 1982, Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic: Paleogeography, Paleoclimatology, Paleoecology, v. 40, pp. 67-101.

Pierson, T.C., 1972, Petrologic and tectonic relationships of the Cretaceous sandstones in the Harts Pass area, North Cascade Mountains, Washington: M.S. thesis, University of Washington, 37 p.

Pittman, E.D., 1970, Plagioclase feldspar as an indicator of provenance in sedimentary rocks: Journal of Sedimentary Petrology, v. 40, no. 2, pp. 591-598.

Reineck, H.E., and Singh, I.B., 1980, Depositional sedimentary environments: Springer-Verlag, New York, 549 p.

Rinehart, C.D., 1981, Reconnaissance geochemical survey of gully and stream sediments, and geologic summary in part of the Okanogan Range, Okanogan County, Washington: State of Washington, Department of Natural Resources, Division of Geology and Earth Resources, Bulletin no. 74, 24 p.

Rinehart, C.D., and Fox, K.F., 1972, Geology of the Loomis Quadrangle, Okanogan County, Washington: Washington Division of Mines and Geology Bulletin, no. 64, 124 p.

____1976, Bedrock geology of the Conconully Quadrangle, Washington: United States Geological Survey Bulletin, no. 1402, 58 p.

Russell, I.C., 1900, A preliminary paper on the geology of the Cascade Mountains in northern Washington: United States Geological Survey 20th Annual Report, part 2, pp. 83-210.

Scholle, P.A., 1979, A color illustrated guide to constituents, textures, cements, and porosities of sandstones and associated rocks: American Association of Petroleum Geologists Memoir no. 28. Tulsa, Oklahoma.

Schumm, S.A., 1981, Evolution and response of the fluvial system, sedimentologic implications: in, Ethridge, F.G., and Flores, R.M., editors, Recent and Ancient Nonmarine Depositional Environments, Models for Exploration, Society of Economic Paleontologists and Mineralogists, Special Publication no. 31, pp. 19-29.

Scott, D.F., 1973, Lower Cretaceous Bullhead Group between Bullmoose Mountain and Tetsa River, Rocky Mountain foothills, Northeastern British Columbia: Geological Survey of Canada, Bulletin no. 219, 228 p.

Suttner, L.J., and Dutta, P.K., 1986, Alluvial sandstone composition and paleoclimate, framework mineralogy: Journal of Sedimentary Petrology, v. 56, no. 3, pp. 329-345.

Tennyson, M.E., 1974, Stratigraphy, structure, and tectonic setting of Jurassic and Cretaceous sedimentary rocks in the west-central Methow-Pasayten area, northeast Cascade Range, Washington and British Columbia: Ph.D. thesis, University of Washington, 112 p.

Tennyson, M.E., and Cole, M.R., 1978, Tectonic significance of upper Mesozoic Methow-Pasayten sequence, northeastern Cascade Range, Washington and British Columbia: in, Howell, D.G., and McDougall, K.A., Mesozoic Paleogeography of the Western United States, Society of Economic paleontologists and Mineralologists, Pacific Coast Symposium no. 2, pp. 499-508.

Trexler, J.H., 1984, Stratigraphy, sedimentology and tectonic significance of the Upper Cretaceous Virginian Ridge Formation, Methow Basin, Washington, implications for tectonic history of the North Cascades: Ph.D. thesis, University of Washington, 172 p.

_____1985, Sedimentology and stratigraphy of the Cretaceous Virginian Ridge Formation, Methow Basin, Washington: Canadian Journal of Earth Science, v. 22, pp. 1274-1285.

Tucker, M.E., 1982, The field description of sedimentary rocks: The Geological Society of London Handbook Series, The Open University Press, New York, 111 p.

Walker, R.G., editor, 1984, Facies models: Geoscience Canada Reprint Series 1, Ainsworth Press Limited, Kitchener, Ontario. pp. 71-89.

VITA

Robert Louis Rau was born in St. Paul, Minnesota and reared in Scarsdale, New York. He graduated from the University of Vermont in the Spring of 1983 (BA Geology) and terminated his Eastern experience in Summer, 1987 (MS Geology).