# PHYSICAL VOLCANOLOGY OF THE EARLY PROTEROZOIC BEAR LAKE MAFIC METAVOLCANIC SUCCESSION, FLIN FLON, MANITOBA

by

© Michael B. Dolozi

A Thesis submitted to the Faculty of Graduate Studies
of the University of Manitoba
in partial fulfillment of the requirements for the degree
of
Doctor of Philosophy
Department of Geological Sciences

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## ABSTRACT

The 3.3-km thick, Early Proterozoic, Bear Lake mafic metavolcanic succession near Flin Flon, Manitoba, is a vertically dipping, homoclinal sequence within a fault block. The base of the mafic succession is a fault, and the mafic units are overlain by 1.8 km of felsic to intermediate metavolcanic rocks. Six formations have been defined within the mafic sequence: formation 1, 3 and 5 are dominantly pillowed flows, formation 2 comprise equal abundances of pillowed and massive flows, and formations 4 and 6 are dominantly bedded breccias and tuff-breccias with intercalated pillowed flows. These formations show an increase in amygdule abundances with stratigraphic height; amygdule abundance increases from 0 to 25% in the lower part to 10 to 75% in the upper part, the formations thus record the evolution of an upward shoaling, flank section through a mafic sheild volcano. High amygdule abundances and the possible presence of a flow-foot breccias in formation 5 indicate that the volcano may have become locally emergent.

The main focus of this study was the bedded fragmental units of formation 4. This 416-m thick formation is lens-shaped, and has been traced laterally for 11.2 km. The dominant lithology is breccias and tuff-breccias that are commonly matrix-supported but are occasionally clast-supported. Bed thicknesses are 0.5 to 15 m, and beds are

ungraded, normally graded or reversely graded with non-erosive bed contacts. Fragments are commonly amygdaloidal (range 5-55%; mean 31%), angular to subangular, and 0.5 to 100 cm in size with partial or complete chilled rims; the matrix is microlitic and weakly microlitic, blocky, vesicular and non-vesicular lapilli and ash. A few tuff-breccia beds contain irregular, plastically deformed particles and an unusually high proportion of vesicular matrix particles. Medium- to thinly-bedded lapilli-tuffs and tuffs that are dominantly normally graded with sharp bed contacts and occasional scour-and-fill and flame structures form a small proportion of the formation. The enclosing and intercalated pillowed flows have a lower amygdule content (range 5 to 35%, mean 21%) with amygdules concentrated near pillow margins.

Breccias and tuff-breccias were apparently deposited by a series of debris flows generated by slumping of preexisting fragmental material that was explosively erupted in shallow water by a combination of magmatic and contact steam explosions. During the eruptions, the fragmental material was periodically transported to deeper water depositional environments and locally incorporated some fragments derived from pillowed flows. Tuff-breccias with plastically deformed particles and more vesicular matrix probably indicate hot emplacement, possibly by block-and-ash flows. These hot units are stratigraphically restricted and thus indicate temporal variations in the types of explosive activity. The medium- to thinly-bedded tuffs at the top of the formation were probably deposited by turbidity currents during the wanig stages of explosive activity.

# ACKNOWLEDGEMENTS

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This project resulted from a suggestion from A.H. Bailes and E.C. Syme of the Manitoba Department of Energy and Mines. I would like to thank them for letting me use some of their geochemical data from the study area and for friendly and stimulating discussions.

In the field, I was assisted in the enormous task of mapping, measurement of stratigraphic sections and sample collection by several people to whom I am indebted for their hard work and friendliness. For this I thank Dave Bruneau, Dave Owens, Jan Fingler, Greg Partyka, Brian Langlois, and Stan Beaubien.

I am grateful to Dr. Lorne Ayres, who supervised this project and introduced me to volcanological problems in Precambrian greenstone belts particularly in the study area near Flin Flon, Manitoba. His willingness to share his experience and knowledge both in the field and during the preparation of this thesis was very valuable to me. I would also like to thank Dr. Bob Elias for letting me use his photomicrograph camera equipment, Ron Pryhitko for assisting me with the drafting, and Irene Berta for the preparation of thin-sections.

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# Chapter 1

# INTRODUCTION

**Statement of the Problem.**

In Precambrian greenstone belts the predominant mafic metavolcanic successions are composed of lava flows and various types of fragmental deposits (Henderson, 1953; Dimroth et al., 1978; Bailes and Syme, 1979, 1980; Ayres, 1981; Ferreira, 1984). Of these fragmental rocks, subaqueous deposits are the most difficult to recognize and interpret because of the varied processes which lead to their formation (Fisher, 1984; Kokelaar, 1986). However, this is an important group of rocks to study because it is fairly common and contains measurable parameters which are useful in interpreting volcanic processes (Ayres, 1977a).

The Bear Lake mafic metavolcanic succession near Flin Flon, Manitoba, consists of lava flows as well as abundant, bedded fragmental deposits (Bailes and Syme, 1979, 1980). The mechanisms of formation of some of the bedded fragmental rocks in this area, and hence the evolution of the volcano represented by this succession are poorly understood. This study uses primary structures and textures of these rocks in order to decipher their mode of formation.

Understanding Precambrian volcanic processes from physical volcanology requires comparisons with younger volcanoes where primary structures and volcanic environments are relatively well understood. The problems of reconstructing ancient Precambrian paleovolcanic environments and recognition of volcanic lithologies arise mainly because of deformation, metamorphism and alteration which obscured primary structures, as well as disruption of the stratigraphy by faulting and intrusions (Ayres, 1977a). In this study area, the volcanic stratigraphy is represented by a cross-section confined to a single, largely homoclinal, fault block (Bailes and Syme, 1979, 1980). Although faulting has removed the lowermost part of the sequence, and there are a number of diorite and gabbro intrusions, the volcanic succession has not been greatly disrupted. Furthermore, because internal deformation of rock units is weakly developed and metamorphic grade is low greenschist facies, primary structures, textures, and, in many places, mineralogy, are well preserved.

**Location and Access.**

The study area, which is about 40 $km^2$ in size, is centered on Bear Lake about 12 km southwest of Flin Flon near the Manitoba-Saskatchewan border (Fig. 1). Access to the area is via highway 10 between Cranberry Portage and Flin Flon. Traversing in the area was facilitated by access through Lake Manistikwan and Bear Lake (Fig. 2). These north-south routes made convenient starting points for east-west traverse lines across the north-striking sequence. Outcrop density is variable, but many outcrops are large, and, because of the smelter at Flin Flon, the available outcrops are exceptionally well exposed.

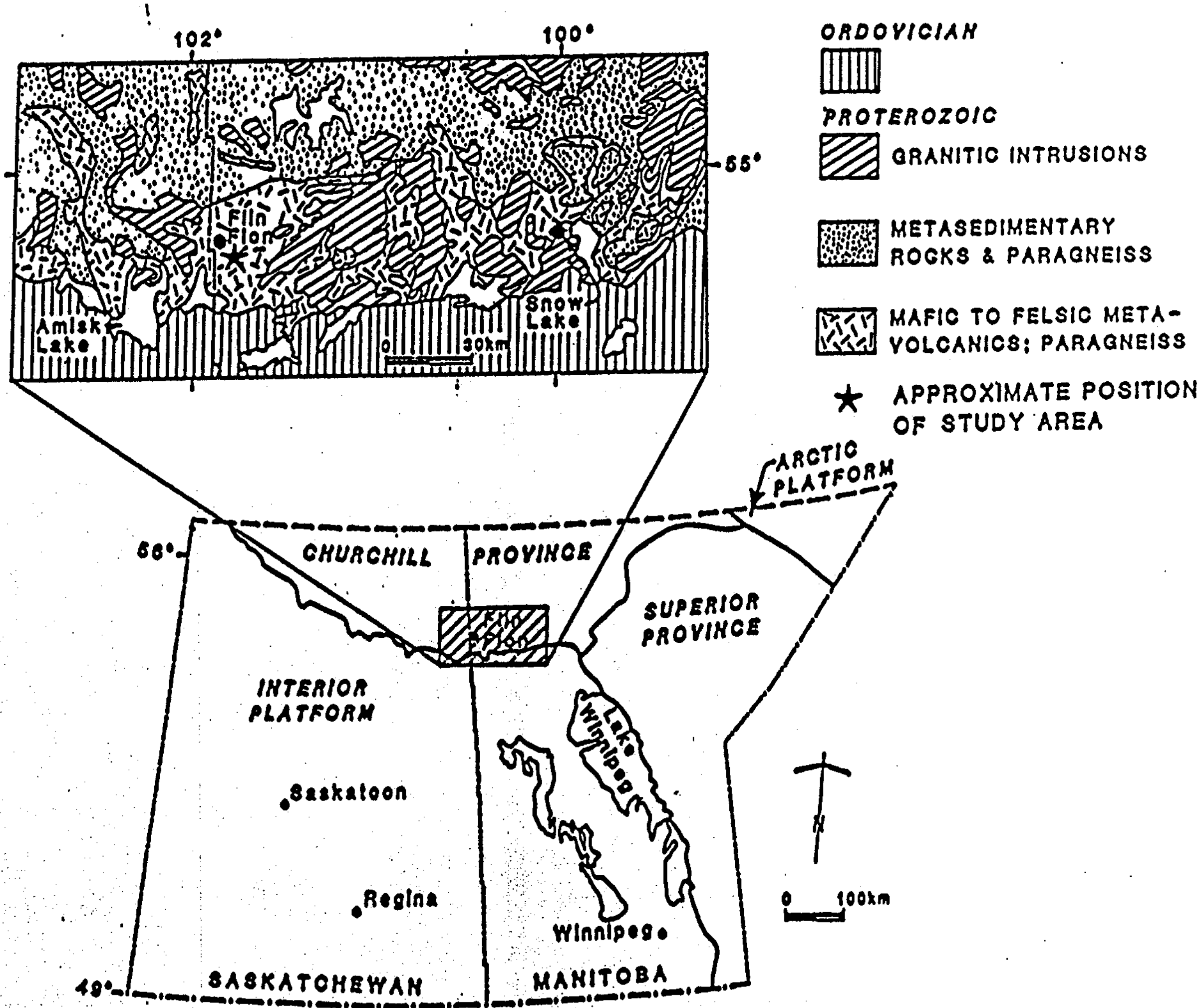



Figure 1. Location map showing the study area in relation to the Flin Flon-Snow Lake greenstone belt of northern Manitoba (modified from Van Wagoner and Van Wagoner, 1981).

**Previous Work in the Study Area.**

Most of the work previously done in the study area was part of the general mapping of the Flin Flon area by government geologists. This includes maps by Tanton (1941a, b); Stockwell (1960); and Bailes and Syme (1980, 1987, in press). Other studies in the Flin Flon area dealing with special geologic problems such as geochronology (Bell et al., 1975; Syme et al., 1987), structure (Stauffer, 1974), and geochemistry (Stauffer et al., 1975) are peripheral to the study area. Previous volcanologic studies in the Flin Flon area are even farther away and were mainly centered around Amisk Lake in Saskatchewan (Ayres, 1977b; 1981; Ferreira, 1984; Van Wagoner and Van Wagoner, 1981). Bailes and Syme (1979, 1980, Syme et al., 1982) were the first workers to address the volcanological problems in the study area. They established the general stratigraphy and structural setting and addressed the problem of the genesis of the bedded fragmental rocks. Langlois (1987) studied felsic units which occur in the study area and assessed the relationship of one of these units to adjacent volcanic rocks.

**Aims and Objectives of this Study.**

The aims and objectives of this study are:

1) detailed examination of the bedded, mafic fragmental rocks in the Bear Lake fault block near Flin Flon and their bearing on the evolution of the

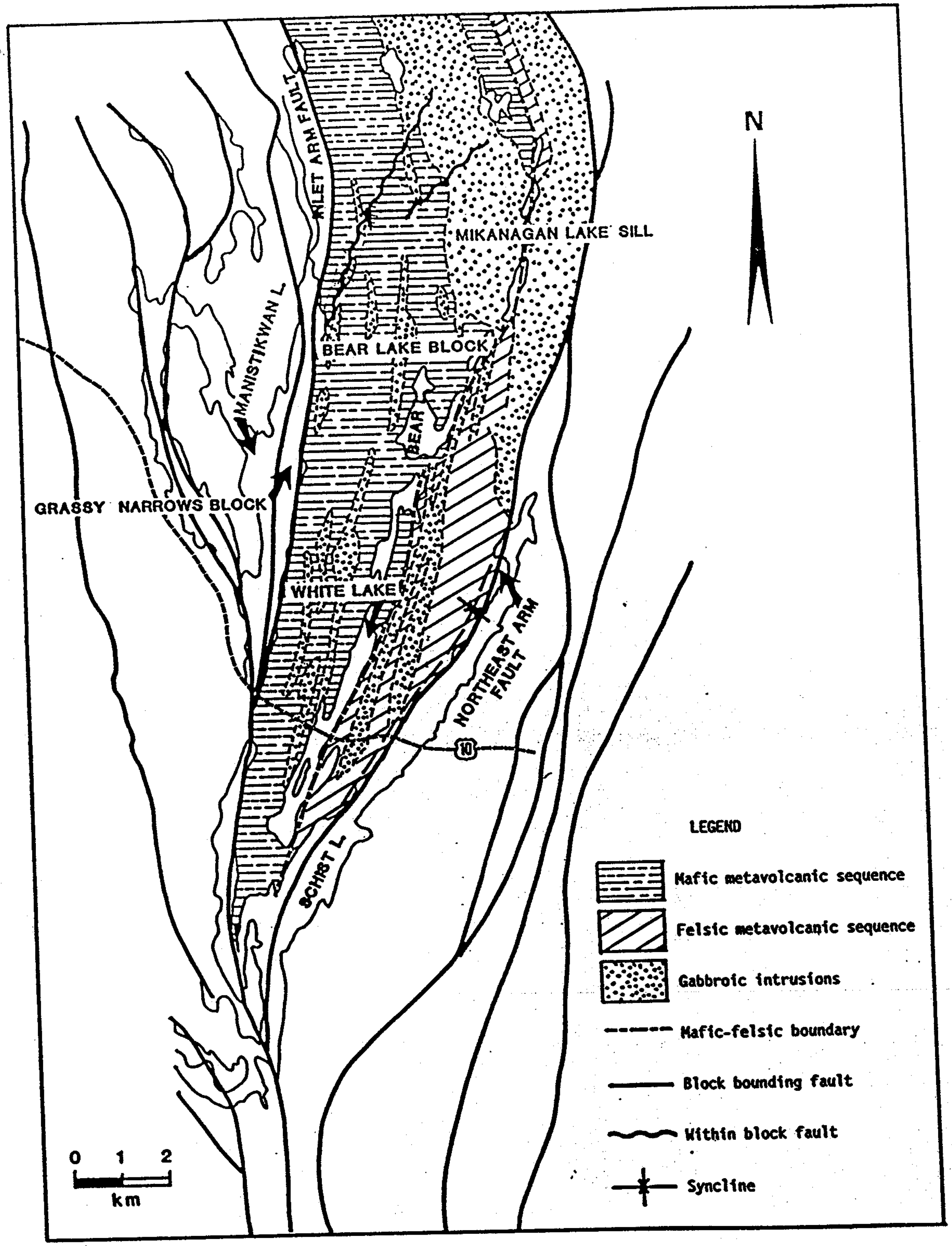



**Figure 2.** General geology of the Bear Lake fault block and relationship to adjacent fault blocks. Sources of data: Bailes and Syme, 1982, 1987; Syme, 1986.

volcano,

2) documentation of the morphology of mafic lava flows,

3) documentation and analysis of lateral and vertical volcanic facies changes in the 3.3-km thick mafic sequence of the Bear Lake fault block,

4) description and evaluation of the nature of epidote alteration in mafic pillowed and massive lava flows in the southern part of the succession, and

5) interpretation of the morphology and evolution of the mafic volcano in the Bear Lake block.

**Field and Laboratory Investigations.**

Reconnaissance field work started in the summer of 1983 and the collection of detailed field data was done mainly in the summers of 1984, 1985, and 1986. The methods of field data collection included: 1) general geological mapping at a scale of 1:15,840, 2) measurement of stratigraphic sections across the bedded fragmental rocks, 3) description and detailed mapping of lava flow morphologies, and 4) collection of rock samples for petrologic studies.

Field data collected from the bedded fragmental rocks included: bed thicknesses; maximum clast sizes; depositional structures; matrix abundances; and fragment type descriptions. In the field, matrix abundances were determined by point counting on rock outcrop surfaces using a fish net for control.

Laboratory investigations involved mainly petrographic studies. These included point counting of amygdules on etched slabs; phenocryst point counting on thin-sections; and general petrographic descriptions.

# Chapter 2

# GEOLOGICAL SETTING OF THE STUDY AREA

## Regional Setting.

The study area is part of the east-trending, early Proterozoic, Flin Flon-Snow Lake greenstone belt in the Churchill Province. The belt is approximately 230 km long and 50 km wide. In the north, it is bounded by the Kisseynew metasedimentary gneiss belt which separates the Flin Flon-Snow Lake greenstone belt from the Lynn Lake greenstone belt farther north. In the south, Precambrian rocks are covered under younger Paleozoic strata (Fig. 1).

The volcanic rocks in the Flin Flon area are assigned to the Amisk Group. In the type area north of Amisk Lake, this comprises 1) a lower mafic to intermediate lava flow and fragmental rock sequence and 2) an upper felsic to intermediate lava flow and fragmental rock sequence (Byers and Dahlstrom, 1954; Fox, 1976; Staufer et al., 1975; Ayres, 1977b). The estimated minimum thickness of the Amisk Group is 9 km (Ayres et al., 1981). The Amisk Group is unconformably overlain by sandstone and conglomerate of the Missi Group (Bruce, 1918; Syme et al., 1982). In the Flin Flon area the Amisk Group was tightly folded and deeply eroded before the Missi Group was deposited (Stockwell, 1960). Subsequent to this the Amisk Group underwent four phases of deformation which included: 1) early, tight, east-trending folds, 2) north-trending folds, 3) a large northeast-trending antiform, and 4) north to northwest-trending oblique-slip faults (Stauffer and Mukherjee, 1971; Bailes and Syme, 1987). Both groups have been metamorphosed to low to medium grades with metamorphic grade increasing northward (Syme et al., 1982). Metavolcanic rocks in the study area near Flin Flon, are assigned to the lower mafic to intermediate volcanic unit of the Amisk Group and have been metamophosed to lower to upper greenschist facies.

The Flin Flon area contains a variety of intrusive rocks which includes: 1) small, synvolcanic mafic sills and dykes; 2) large, pre-and post-Missi Group, felsic plutons; 3) major differentiated mafic sills; and 4) heterogeneous late tectonic ultramafic to felsic dykes (Syme et al., 1982). The largest gabbroic intrusion in the study area is the Mikanagan Lake sill which is 1.2 km thick and more than 15 km long (Bailes et al., 1987).

There is general agreement that the Amisk Group is Aphebian in age (Park, 1975; Bell et al., 1975; MacQuarrie, 1980). Zircons separated from a rhyolite crystal tuff, which overlies the mafic volcanic unit of the study area, yielded a U-Pb age of 1886 +/- 1.3 Ma (Syme et al., 1987).

In the Flin Flon area, there are a number of generally north-trending faults that define a series of fault blocks that generally range in width from 1 to 5km (Fig. 2). Although faults with smaller displacements occur within the fault blocks, an internally coherent stratigraphy can be deciphered within each block. Stratigraphic correlation between blocks, however, is uncertain because of the general lack of marker units (Syme et al., 1982). The present study is confined to the Bear Lake fault block which is bounded on the west by the north-trending Inlet Arm fault, and on the east by the Northeast Arm fault (Fig. 2). The sequence in the fault block is dominantly east-facing with an isoclinal syncline near the east edge. The lower part of this succession is 3.3 km of massive and pillowed mafic lava flows and fragmental rocks. This is overlain by up to 1.8 km of felsic and intermediate flows and fragmental rocks (Syme et al., 1982). This study deals only with the lower mafic volcanic succession.

When the present study was initiated, the northwest boundary of the Bear Lake block was thought to be a fault along the axis of the northeast arm of Manistikwan Lake (Syme et al., 1982). Mapping in 1984 revealed that the volcanic units near the perceived northwest boundary were lithologically different, and faced in the opposite direction relative to the main east-facing Bear Lake sequence. This west-facing sequence has subsequently been assigned to the Grassy Narrows block (Bailes and Syme, 1987) and the northwest boundary of the Bear Lake block has been shifted eastwards. The mapped part of the Grassy Narrows block is incorporated in Figure 3, but is not included in the following description and discussion.

**Economic Deposits in the Flin Flon Area.**

A number of economic mineral deposits occur in the Flin

Flon area. The most important of these are: 1) volcanogenic massive Cu-Zn sulphide deposits (Syme et al., 1982), and 2) gold deposits. To date, the largest of these is the Flin Flon deposit which contained 62 million tonnes of Cu-Zn sulphide ore (Price, 1977; Koo and Mossman, 1975; Bristol, 1974; Hawkins and Martin, 1970; Byers et al., 1965).

# Chapter 3

# VOLCANIC STRATIGRAPHY OF THE MAFIC SUCCESSION IN THE BEAR LAKE BLOCK

## Introduction.

The mafic metavolcanic succession in the Bear Lake fault block is tentatively divided into six formations which, from base to top, have been designated as Formation 1 to Formation 6 (Figs. 3, 4). In ascending order, the formations comprise: 1) 300 to 900 m of pillowed and massive flows, 2) 220 to 300 m of massive lava flows and minor pillowed lava flows, 3) 200 to 1120 m of pillowed lava flows, 4) 140 to 416 m of bedded fragmental rocks intercalated with pillowed lava flows, 5) 230 to 600 m of intercalated pillowed and massive flows, and minor bedded fragmental rocks, and 6) 300 to 400 m of bedded fragmental rocks intercalated with pillowed flows (Table 1). In spite of numerous faults, and diorite and gabbro intrusions which appear to have both expanded and removed parts of the stratigraphy, the volcanic stratigraphy is generally well preserved (Fig. 3). The exception is the Mikanagan Lake intrusion in the northeast part of the area; this intrusion has removed parts of formations 5 and 6. The stratigraphy is generally similar to that presented by Bailes and Syme (1979, 1980).

Because many of the formations contain similar morphologic units (Table 1), the author will not describe each formation in detail. Instead, the emphasis in subsequent

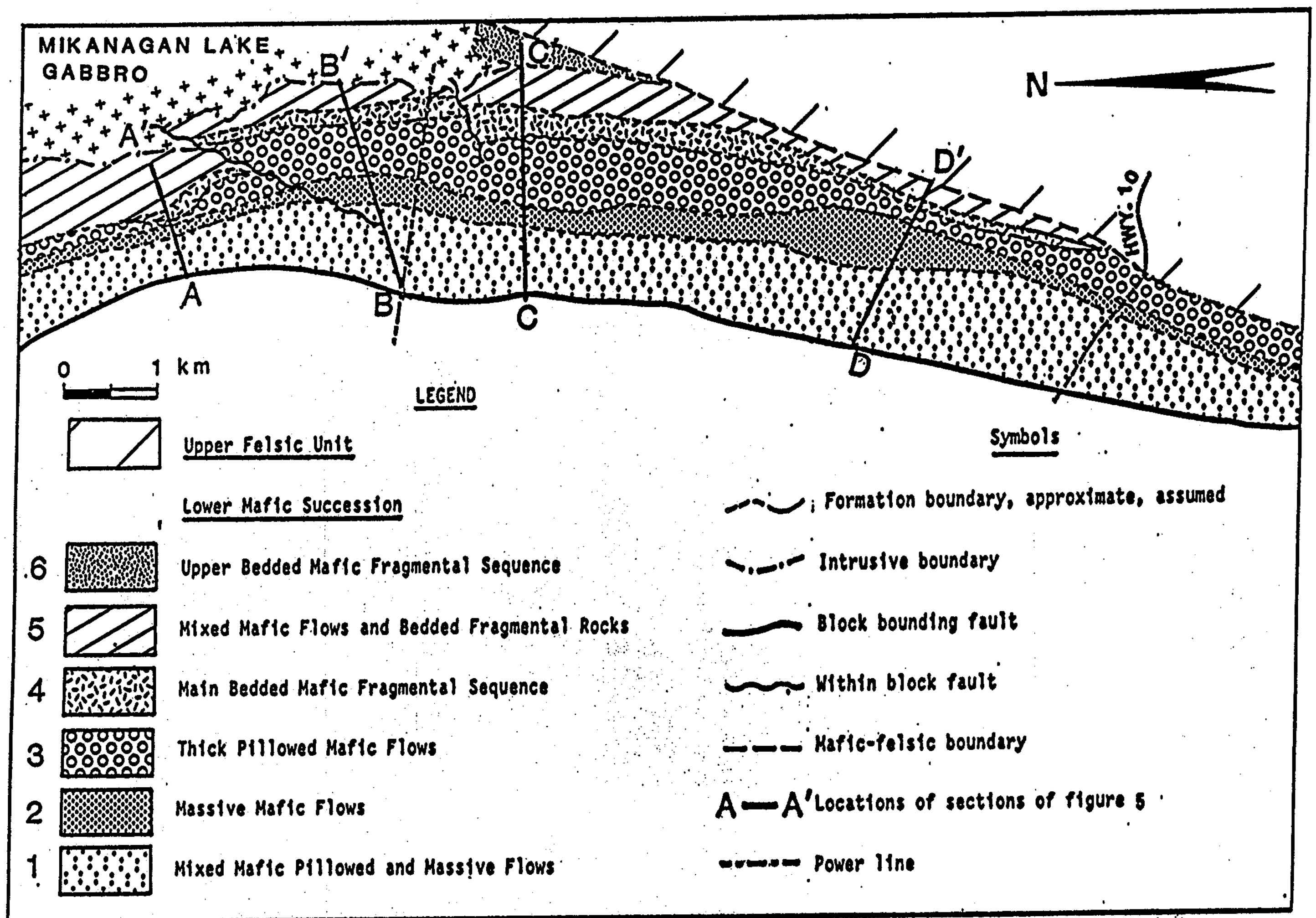



Figure 4. Generalized geologic map of the mafic succession in the Bear Lake block showing volcanic formations (1 to 6) and location of Figure 5.

Table 1 Table of Formations of the Bear Lake Mafic Metavolcanic Succession.

| FORMATIONS | THICKNESS (meters) | LITHOLOGIC UNITS* | COMMENTS |
|---|---|---|---|
| 6. Upper bedded mafic fragmental sequence. | 300-400 | Bedded breccias and tuff-breccias<br>Bedded lapilli-tuffs | Limited exposure. |
| 5. Mixed mafic flows and bedded fragmental rocks | 230-600 | Pillowed flows.<br>Massive flows.<br>Pillowed flows with large pillows and thermal fractures.<br>Bedded breccias and tuff-breccias.<br>Bedded lapilli-tuffs.<br>Bedded tuffs.<br>Pillowed flows with $>25\%$ phenocrysts.<br>Pillowed flows with megapillows.<br>Concordant, quartz-phyric felsic units. | Most diverse of the formations in terms of volcanic morphologic types. |
| 4. Main bedded mafic fragmental sequence | 140-380 | Bedded breccias and tuff-breccias.<br>Pillowed flows.<br>Bedded lapilli-tuffs.<br>Bedded tuffs.<br>Lava lobe units.<br>Breccias and tuff-breccias with plastically deformed particles. | The ratio between bedded fragmental rocks and intercalated pillowed flows changes laterally and is highest in the center of the formation. |
| 3. Thick pillowed mafic flows | 200-1120 | Pillowed flows.<br>Pillowed flows with variolites .<br>Pillowed flows with$>25\%$ phenocrysts .<br>Pillowed flows with megapillows. | Least diverse of the formations in terms of volcanic morphologic types. |
| 2. Massive mafic flows | 220-300 | Massive flows.<br>Pillowed flows.<br>Concordant quartz-phyric felsic units | The ratio between massive and pillowed flows changes laterally and is highest in the center of the formation. |
| 1. Mixed mafic pillowed and massive flows | 300-900 | Pillowed flows.<br>Pillowed flows with variolites.<br>Massive flows.<br>Concordant and discordant quartz-phyric felsic units. | Massive flows common in the north, pillowed flows in the center and south. |

**Explanations:**

**In pillowed flows, pillows are normal size, about $\leq 1.5$m**
**In pillowed flows with large pillows, pillows are 1.6-2.5m**
**In pillowed flows with megapillows, pillows are $>2.5$m**
*** Lithologies are listed in order of decreasing abundance**

chapters will be on morphologic units. The exception is formation 4 which contains a number of distinctive and genetically important units, and was the focus of much of the field and laboratory work. Because of its importance, formation 4 will be described first, although stratigraphically, it is in the middle part of the Bear Lake mafic succession.

Five main volcanic morphologic types have been recognized. In order of decreasing abundance, these are: 1) pillowed lava flows, 2) massive lava flows, 3) bedded fragmental rocks, 4) partly brecciated pillowed and massive lava flows, and 5) genetically diverse lava lobe units (Figs. 3, 5, 6). Other, locally developed morphologic types include 1) about 10m of pillowed lava flows composed of extremely large pillows or megapillows (Table 1) within abundant interpillow fragmental material in the upper-middle part of formation 3, and 2) pillowed flows composed of large pillows with well developed thermal contraction fractures in the northern part of formation 5. Minor felsic units occur in the mafic succession: some of these appear to be concordant with the mafic rock units and may be flows or sills; others are discordant and appear to be dykes. One of the concordant units in formation 2 was examined by Langlois (1987) who concluded that it was a rhyolitic intrusion although localized felsic pyroclastic rocks are spatially associated with the intrusion.

Vertical and lateral changes in volcanic morphologies were observed in the mafic sequence. Vertical changes include:

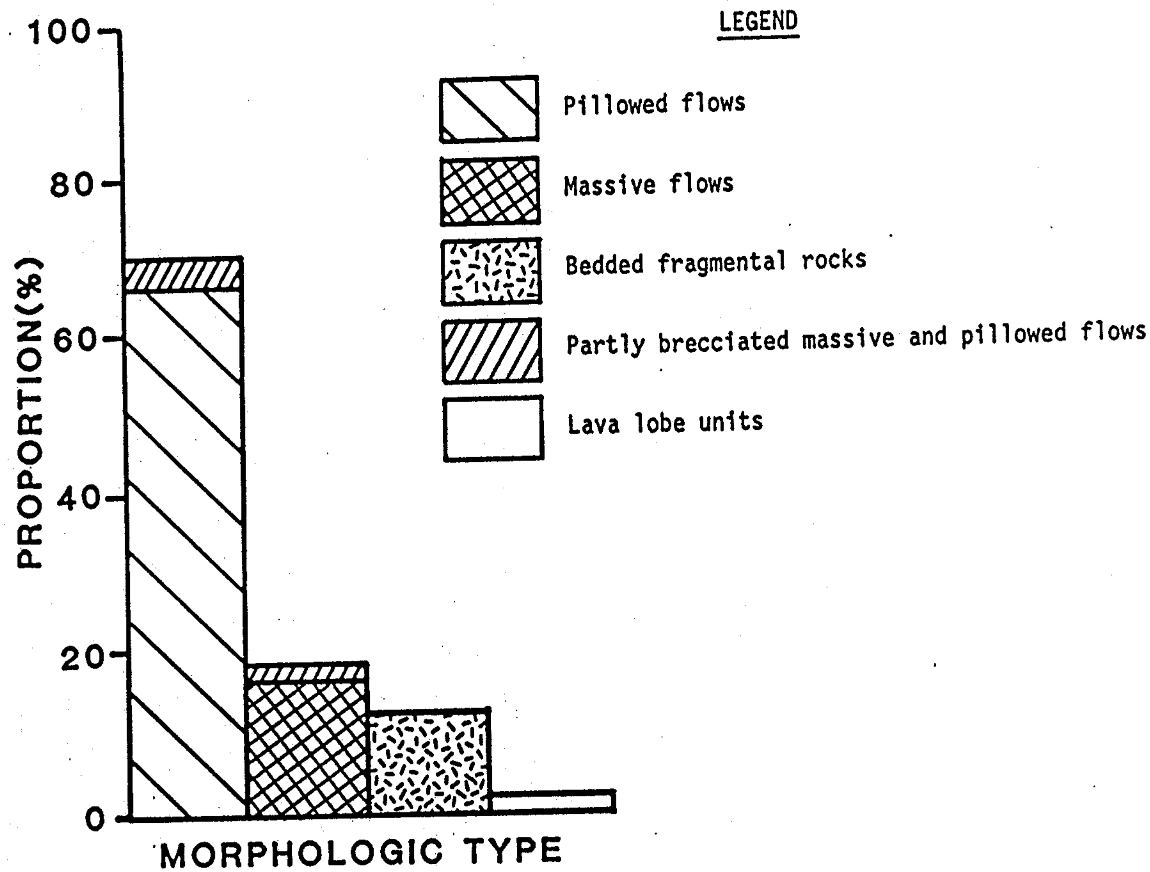



**Figure 6.** Summary of volcanic morphologic types of the mafic sequence in the Bear Lake fault block. Proportions are based on planimetry of map (Fig. 3) except for minor rock units which are based on measured sections within formations.

1) a general increase in vesicularity of lava flows with stratigraphic height, 2) restriction of massive flows mainly to the lower-middle part which constitutes formation 2, 3) occurrence of variolitic pillows dominantly in formations 1 and 3, 4) occurrence of pillowed flows with greater than 25% clinopyroxene phenocrysts in the upper part of formation 3, and 5) the occurrence of bedded lapilli-tuff, tuff-breccia and breccia at three stratigraphic levels in the upper half of the sequence. Lateral changes observed in the mafic sequence include 1) occurrence of dominantly massive flows in the north part of formation 1 and pillowed flows in the center and south, 2) lateral thickening and thinning of formations; this is best developed in formation 4, the main fragmental unit, which thins to both north and south, 3) restriction of pillowed flows with well developed thermal contraction fractures to the north part of formation 5, and 4) in formation 5, the restriction of pillowed flows with more than 25% clinopyroxene phenocrysts to the south part of the formation.

Chemical data provided by A.H. Bailes and E.C. Syme (pers. comm., 1988) indicate that the mafic flows of the Bear Lake block are tholeiitic basalts. Mineralogically, the flows are generally porphyritic with variable abundances of both plagioclase and clinopyroxene phenocrysts. Locally, flows containing greater than 25% clinopyroxene phenocrysts form distinctive map units (Fig. 3). The groundmass was composed originally of plagioclase and clinopyroxene microlites with variable amounts of glass; any original oxide phases are only locally recognized, and no apatite was observed.

The original components have now been replaced by greenschist-facies metamorphic assemblages. The plagioclase has been replaced by albite plus epidote and quartz and the clinopyroxene by actinolite, chlorite and epidote; however, in many samples, the original textures are still preserved by pseudomorphs. The original glass component is more difficult to identify; it now comprises interstitial aggregates of chlorite and epidote.

Superimposed on the normal metamorphic mineral assemblages, there are abnormal concentrations of epidote and chlorite in flows, particularly in the southern and lower parts of the sequence. The epidote and chlorite concentrations occur in pillow rims, and as ovoid to irregular aggregates in flows. These concentrations mask primary textures and structures and are probably the result of pre-metamorphic alteration of the mafic sequence.

**Formation Description.**

Formation 1.

The lowermost contact of the formation is the major fault forming the western boundary of the fault block (Fig. 3) and thus lateral changes in thickness of the formation are probably not meaningful. There is a general increase in the intensity of deformation and alteration as the lower fault boundary is approached, and it becomes increasingly difficult to recognize primary volcanic morphologic types. However, an overall assessment of this formation shows that pillowed lava flows predominate with about 10% massive sheet flows which are mainly in the north part of the formation (Figs. 3, 5, 7). Both pillowed and massive sheet flows are generally sparsely porphyritic with 1 to 5% clinopyroxene and/or plagioclase phenocrysts.

Formation 2.

Where massive lava flows of formation 2 overlie the pillowed and/or massive flows of formation 1, the contact between the two formations is a transitional zone, about 50 m thick, in which pillowed and massive flows are intercalated. Pillowed flows form only a small proportion of the formation in the central part of the area (Figs. 3, 5, 7) but increase in abundance to both north and south; they are the dominant lithology in the north (Fig. 3). The massive flows are sparsely porphyritic to aphyric whereas the pillowed flows are sparsely porphyritic.

Formation 3.

This formation is composed largely of pillowed flows (Figs. 3, 5, 7). The contact between the two formations is a transitional zone, about 50 m thick, in which pillowed and massive flows are intercalated. Four types of pillowed flows were identified in this formation based on size of pillows, phenocryst content, and textures. The most common type of

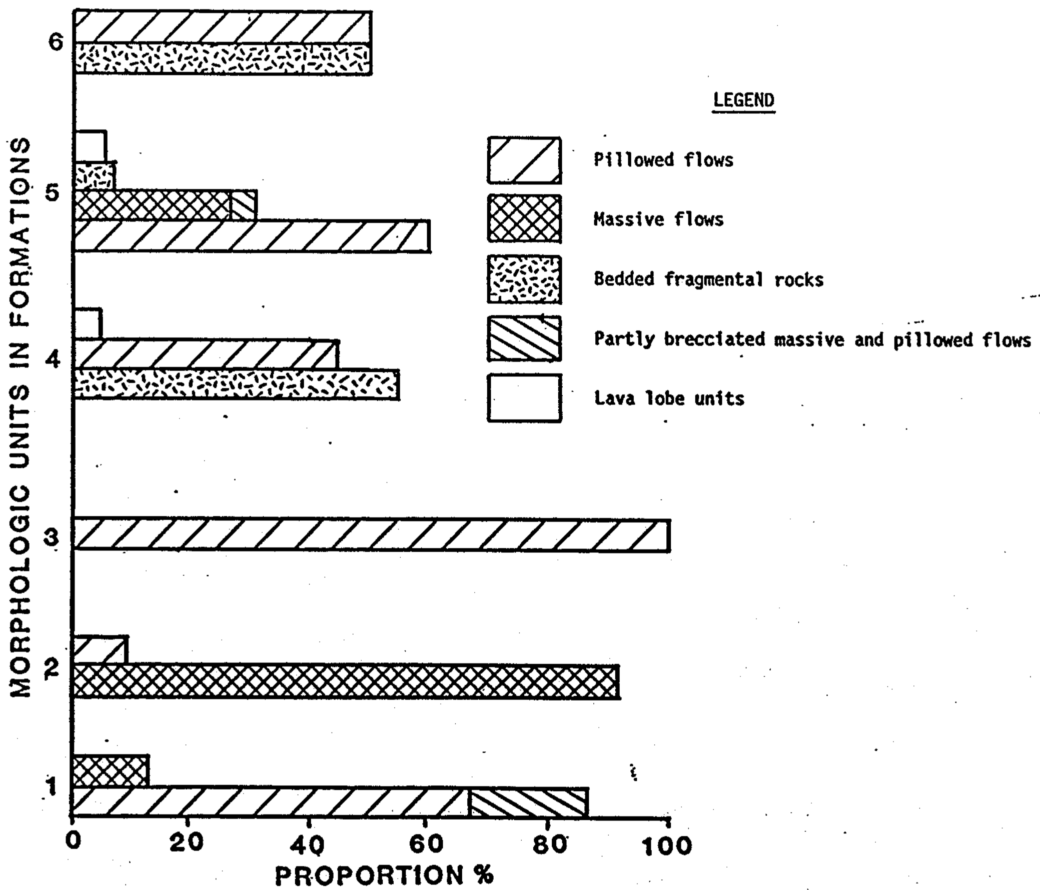



**Figure 7.** Proportion of major morphologic types in the six formations of the mafic sequence in the Bear Lake fault block. Proportions are based mainly on planimetry of map (Fig. 3) except for minor rock units which are based on measured sections within the formations.

pillowed flow is composed of normal-sized (as defined in Table 1), non-variolitic pillows that contain 5 to 10% pyroxene and/or plagioclase phenocrysts; they constitute the lower 80% of the formation in the northern and central part of the area. These are overlain by flows composed of sparsely to moderately porphyritic variolitic megapillows and about 5% interpillow fragmental material. Contacts of this rock unit with underlying and overlying units are not exposed. The minimum thickness is 10 m, the thickness of the exposure; the maximum thickness is 20 m, the distance between overlying and underlying units. The flows with megapillows are overlain in turn by flows with normal-sized, variolitic, sparsely porphyritic pillows. This unit constitutes about 15% of the formation and extends laterally across most of the central and southern part of this formation. Locally the uppermost part of this formation comprises flows composed of normal-sized, non-variolitic, highly porphyritic pillows that contain 20 to 40% pyroxene phenocrysts. These constitute about 3% of the formation and have a limited lateral extent.

Formation 4.

The Main Bedded Fragmental formation has a sharp contact with underlying pillowed flows of formation 3. This formation is heterogeneous and is composed of about 55% bedded fragmental rocks in which fragments are generally highly amygdaloidal, and 45% intercalated, moderately amygdaloidal, pillowed flows (Figs. 3, 5, 7). Both the fragmental rocks and pillowed flows contain 5 to 15% pyroxene and/or plagioclase phenocrysts. The bedded fragmental rocks comprise several lithologies defined on the bases of bed thickness, clast abundance, and clast types (Table 1). This formation is lens-shaped, being thickest in the center and thinning both to the north and south (Figs. 3, 4); the proportion of fragmental rocks relative to pillowed flows also decreases from the center to the north and south.

Formation 5.

Formation 5 overlies the Main Bedded Fragmental formation with a sharp contact. This formation is composed of several lithologic units (Table 1). It is 60% pillowed lava flows, 30% massive lava flows (Figs. 3, 5, 7) and 10% bedded fragmental rocks with local intercalated flows; these bedded fragmental rocks form three lenticular members in the lower part of the formation (Fig. 3).

The lower part of the formation is composed of pillowed flows with normal-sized pillows. This is overlain by three breccia members, which are lithologically quite different although they occur at approximately the same stratigraphic level. The south member, which has a maximum thickness of 33 m is composed of breccias and tuff-breccias, lapilli-tuffs and tuffs, and intercalated pillowed flows. The central member which is only 1 m thick is composed of bedded tuffs. The northern member is 22.7 m thick with a very restricted lateral extent because the exposure is limited; it is composed of a lower 1.2 m thick basal tuff overlain by 21.5 m of tuff-breccias and breccias.

The lava flows overlying the fragmental members are lithologically diverse and there is considerable lateral variation in flow morphology. In the north, the flows are dominantly pillowed and contain 10 to 15% clinopyroxene phenocrysts and are highly amygdaloidal with well developed thermal contraction fractures. In the center, the flows contain 1 to 10% clinopyroxene and 1 to 5% plagioclase phenocrysts, and are also highly amygdaloidal but comprise both pillowed and massive types with minor occurrences of pillowed flows with megapillows and lava-lobe units containing pillow-like structures surrounded by lapilli and ash matrix. In the south, the flows are weak to moderately amygdaloidal and are composed dominantly of pillowed flows and minor massive flows. The pillowed flows in the south contain greater than 25% phenocrysts, whereas the massive flows are sparsely porphyritic (Table 1). A characteristic feature of some flows, particularly in the upper part of the formation, is epidote-rich alteration which forms globular to irregular patches within the flows.

Formation 6.

The Upper Bedded Fragmental formation overlies formation 5 with a sharp contact. This formation is lithologically similar to the Main Bedded Fragmental formation (Formation 4) being composed of approximately equal proportions of bedded fragmental rocks and intercalated pillowed flows (Figs. 3, 5, 7). Laterally, this formation has a restricted outcrop distribution: in the north, the formation has been removed by intrusion of the Mikanagan Lake gabbro; in the south, it is covered by a lake (Fig. 3). The fragmental rocks are mainly breccias and tuff-breccias in the lower part of the formation but change to lapilli-tuffs as matrix content increases upwards. In the center, the upper contact of this formation with the overlying felsic to intermediate succession is a fault; in the south, the contact is in an area of poor exposure and was not observed.

**Felsic Units.**

Felsic units occur near the upper parts of formations 1 and 2, and, to the north, in the middle part of formation 5 (Fig. 3). The three felsic units in the upper part of formation 1 (Fig. 3) range in thickness from 2 to 3 m . They have limited lateral extent due to poor exposure but appear to be concordant. However, one small occurrence in the central part of formation 1 (not shown in Fig. 3) is a 1-m thick dyke that is discordant to the mafic volcanic rocks. Two felsic units were observed in formation 2. The southern unit is 2.5 m thick and is discordant to pillowed flows. Langlois (1987) studied the northern felsic unit in the upper part of formation 2. There quartz-phyric felsic units range in thickness from 6 to 12 m and are generally concordant although discordant contacts were observed locally. Langlois (1987) concluded that these units were intrusive although he did identify minor felsic pyroclastic material at the contacts. In the north part of formation 5, there is a 6.4 m thick, quartz-phyric, felsic unit that appears to have concordant relationships with the extrusive rocks; the unit has possible flow structures and a brecciated upper margin. The genesis of this unit is uncertain.

The felsic units include definite intrusions that have both discordant and concordant relationships with the mafic flows, and concordant units of uncertain genesis that could be either lava flows or intrusions. The pyroclastic material associated with the intrusions in formation 3 is particularly important because it indicates that some, albeit minor, felsic volcanism occurred during the eruption of the mafic sequence. The intrusions have high level characteristics (Langlois, 1987) and are not necessarily related to felsic units that overlie the mafic succession (Fig. 3). They may instead be related to felsic volcanism that occurred during the eruption of the mafic succession. The only direct evidence of this volcanism is the locally preserved felsic pyroclastic rocks and intrusions. If this conclusion is correct, then the volcanism that produced the lower part of the Bear Lake succession was of bimodal basalt-rhyolite character, rather than strictly basaltic.

**Mafic Intrusions.**

A number of mafic intrusions occur in the Bear Lake mafic volcanic succession. These include small diabase dykes and sills; medium-sized gabbroic intrusions; and one large gabbroic intrusion. The small diabase dykes and sills range in width from 0.1 to 50 m with an average of about 5 m. They form 1 to 50% of outcrops with an average density of about 10% of rock outcrop surface area. Medium-sized mafic intrusions range from 50 to 500 m in thickness and can be traced laterally for over 7 km (Fig. 3). They are generally elongate in shape and concordant to the volcanic stratigraphy. Their estimated density is 5% of the mapped area (Fig. 2). The Mikanagan Lake gabbro is the largest intrusion in the area and forms the northeast limit of the study area (Fig. 3). It is about 1.2 km wide and over 15 km long (Bailes and Syme, 1987). Although the mafic intrusions are ubiquitous and relatively abundant, they have not apparently removed much of the mafic volcanic succession in the Bear Lake block area. The exception is the Mikanagan Lake intrusion which has removed much of formation 6 and parts of formation 5.

# Chapter 4

# BEDDED MAFIC FRAGMENTAL ROCKS

**Introduction.**

Bedded fragmental rocks form three sequences in the Bear Lake mafic metavolcanic succession (Fig. 8). The thickest and laterally most extensive unit is the Main Bedded Fragmental Sequence (formation 4) which forms the focus of this study; the bedded fragmental sequences in formations 5 and 6, which are more poorly exposed, and laterally restricted, will be described only briefly and compared with the Main Bedded Fragmental Sequence.

The fragmental sequences in formations 4 and 6 comprise about 60% bedded fragmental rocks and 40% intercalated, lenticular, pillowed lava flows. The fragmental sequences of formation 5 which are thinner than those of formations 4 consist of three occurrences, two of which have intercalated lava flows and one of which lacks intercalated pillowed flows. The fragmental rocks of formation 6 contain one intercalated pillowed flow.

The bedded fragmental rocks are mostly breccia and tuff-breccia although lapilli-tuff and tuff are present locally. In all three formations, fragments are basaltic in composition and have variable textural features, but most of them contain about 5 to 55% amygdules; many fragments have partial chilled rims. Fragment sizes range from 0.5 to 52 cm and occasionally are up to 1 m. The fragmental rocks are mostly matrix-

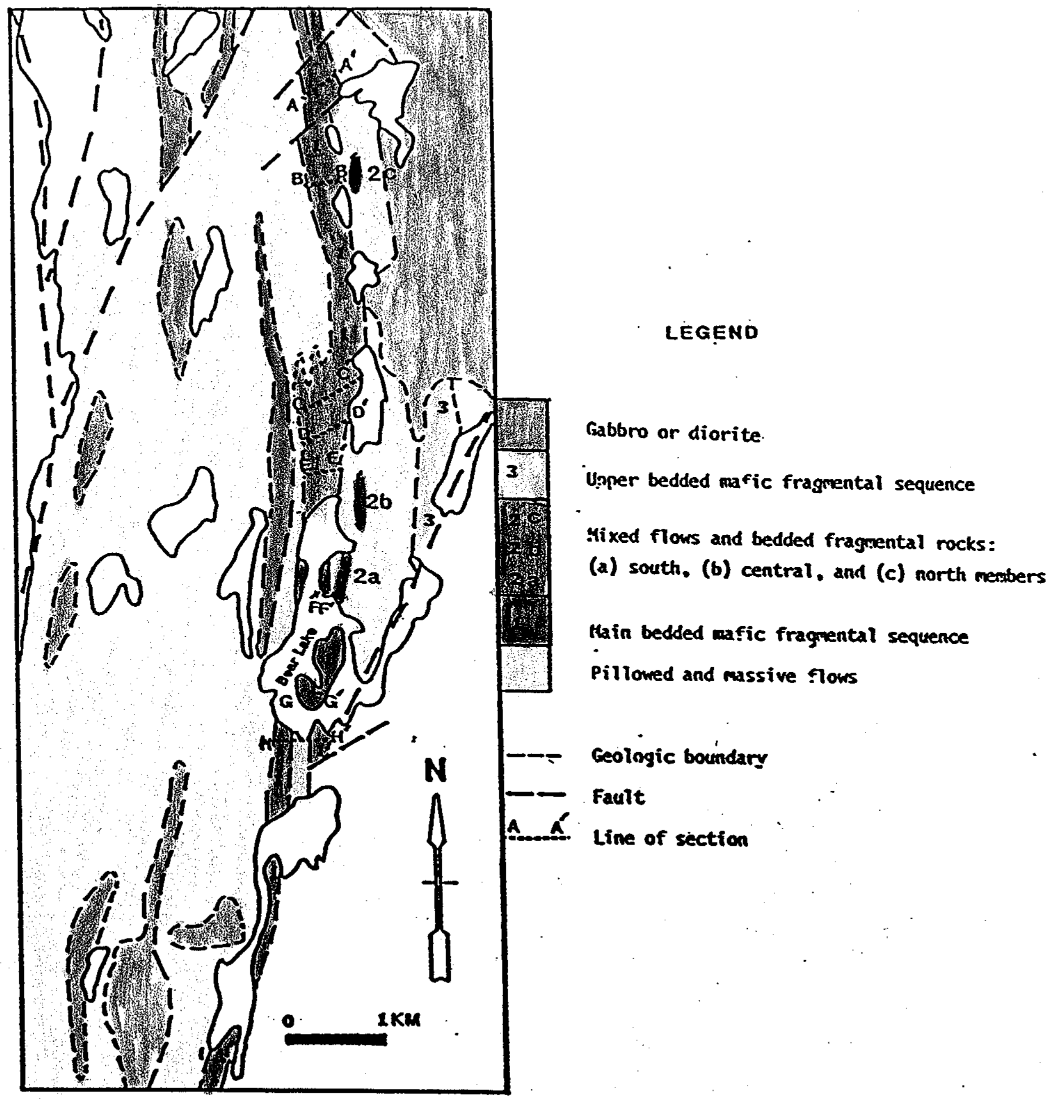



**Figure 8.** Location of bedded fragmental rock units and stratigraphic sections in the Bear Lake fault block. Geology simplified from Figure 3 and Bailes and Syme (1987).

supported with only about 7% being clast-supported. The matrix and the locally developed tuff are composed of ash and fine lapilli-size particles. Bedding in the breccia ranges in thickness from 1 to 15 m and is mostly defined by sharp contacts. About 70% of the beds are ungraded with the remaining 30% being normally or reversely graded in about equal abundance.

**Main Bedded Mafic Fragmental Sequence.**

1) General Features.

The Main Bedded Mafic Fragmental Sequence (Formation 4) is 140 to 416 m thick; it has been traced laterally for 11.2 km (Fig. 3), but its true length is not known. It is thickest near Bear Lake (Figs. 3, 8) and thins both north and south. Bedding has a northerly strike and dips are between 85° east and vertical. Several faults have caused slight displacements of the Main Bedded Mafic Fragmental Sequence, but these faults do not appear to have greatly affected lateral thickness variations (Fig. 3). The rocks are deformed but primary structures are well preserved. Although no sytematic structural analysis was done, the degree of flattening in most of the formation appears to be slight. In the south part, south of highway number 10 (Fig. 3), the rocks are relatively more deformed than they are in the rest of the study area. All the measurements presented in this study such as bed thicknesses and clast sizes come from sections A to I north of highway number 10 (Fig. 8) where deformation is weak and more or less uniform.

Formation 4 is underlain and overlain by thick successions of pillowed and massive lava flows. Both the lower and upper contacts are sharp. The main lithological constituents of this formation are: about 55% bedded fragmental rocks, 44% pillowed lava flows, and less than 1% massive flows. Based on clast size abundances (Fisher, 1966), the bedded fragmental rocks are composed of the following rock units: 1) 50% breccias and 40% tuff-breccias which occur in all sections; 2) 7% lapilli-tuffs which occur in the lower-middle parts of most sections except section B which is incomplete due to a gabbro intrusion; and 3) 3% bedded tuffs which occur in the upper parts of the sequence near sections D, E, G, H, and I (Fig. 9).

Generally, the intercalated pillowed flows do not show any significant vertical changes in abundance relative to fragmental rocks (Fig. 9). Laterally, however, there are major differences; many flow units do not appear to extend laterally for great distances and the middle part of the sequence near section E has more fragmental rocks relative to pillowed flows than adjacent parts of the sequence to the north and south (Fig. 9). The few occurrences of massive flows are in the upper parts of section E and I (Fig. 9).

The bedded fragmental sequence can be further subdivided into six subtypes on the basis of bed thickness (Ingram, 1954), clast and matrix distribution, and characteristics of

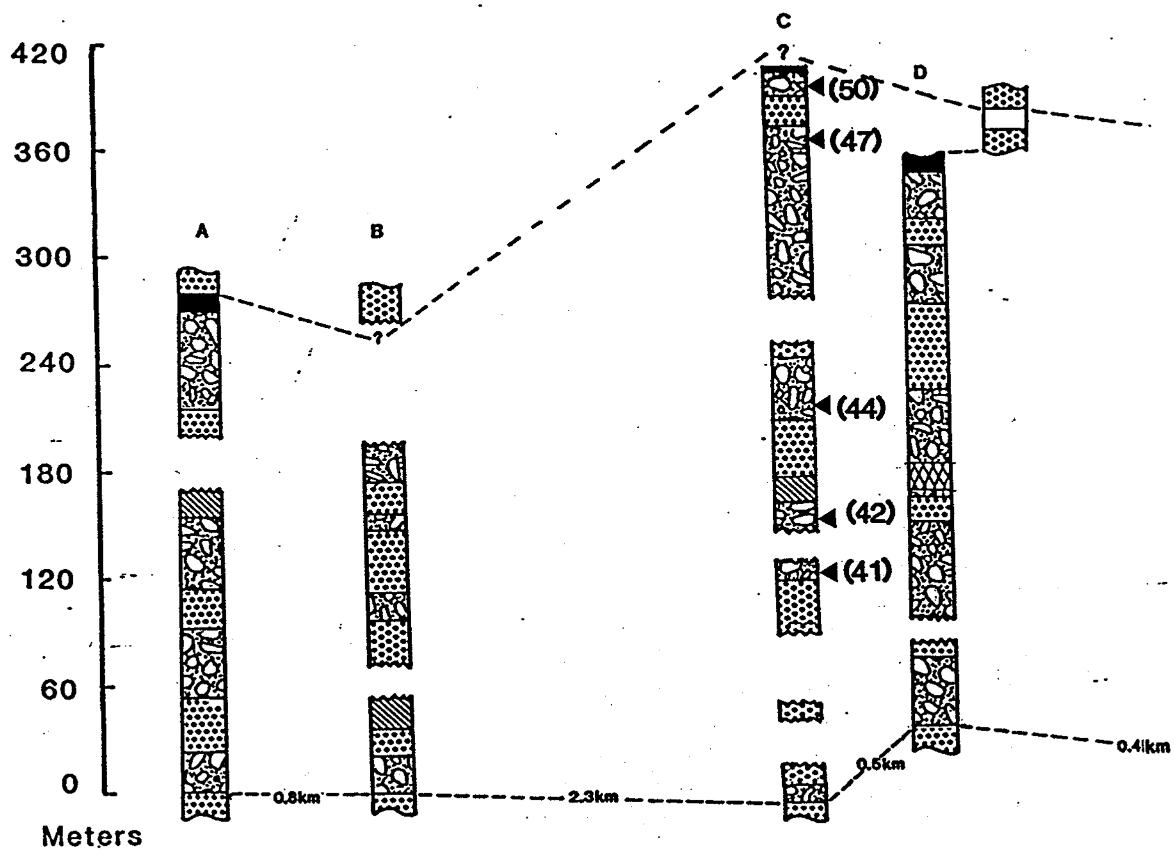
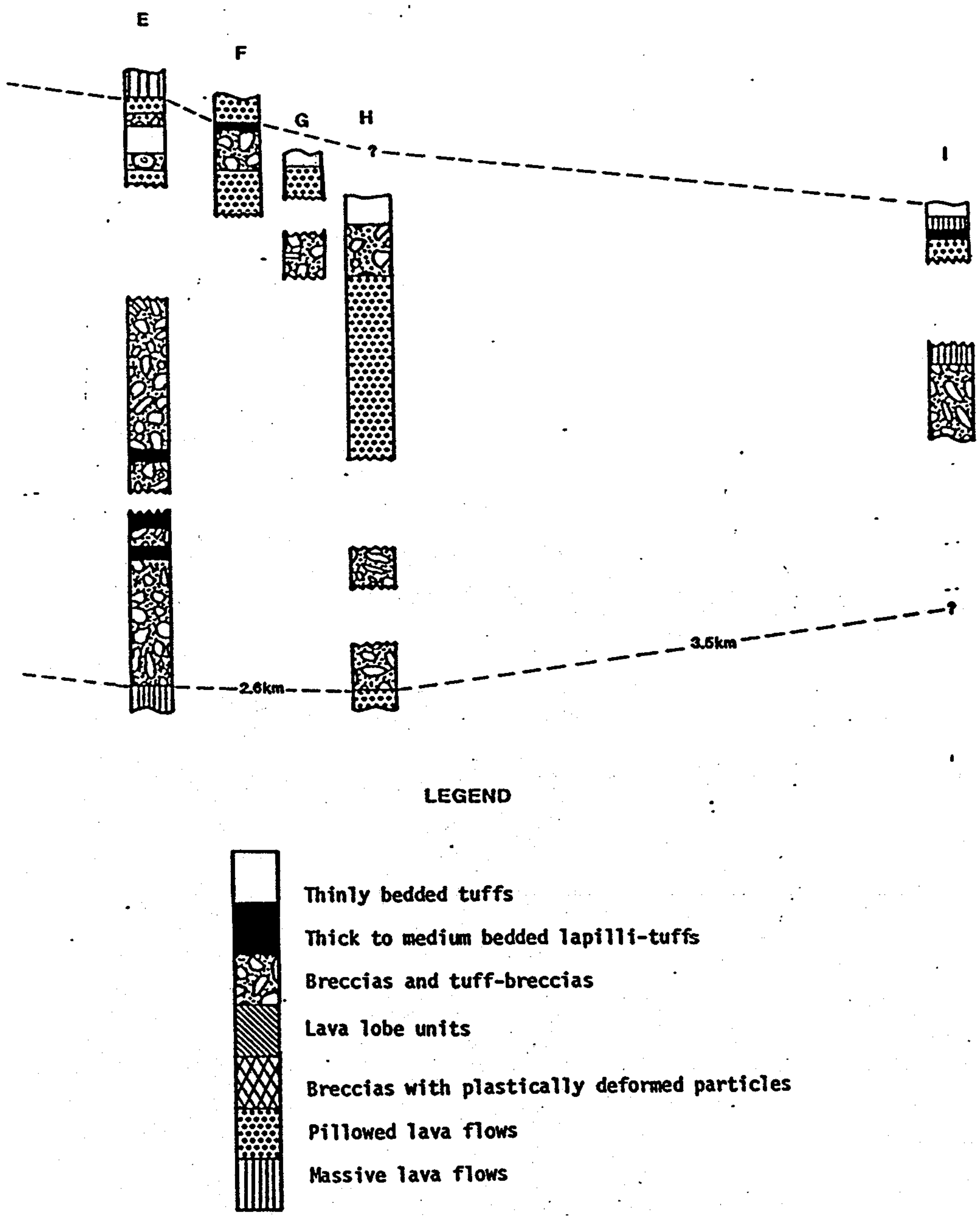



Figure 9. Stratigraphic sections across the Main Bedded Mafic Fragmental Sequence showing the major volcanic lithologic units and their lateral and vertical distributions. The base and top of the sections are indicated by the lower and upper dashed lines respectively. Locations of sections A to I are shown on Figure 8. Arrows indicate positions of Figure 49B and rock outcrop numbers are given in brackets.


E
F
G
H
I
?
?
2.6km
3.5km
LEGEND
Thinly bedded tuffs
Thick to medium bedded lapilli-tuffs
Breccias and tuff-breccias
Lava lobe units
Breccias with plastically deformed particles
Pillowed lava flows
Massive lava flows

particles. These are: 1) very thick-bedded, matrix-supported breccias, tuff-breccias, and locally lapilli-tuffs, 2) very thick-bedded, clast-supported breccias, 3) thick- to medium-bedded lapilli-tuffs, 4) lava lobe units, 5) thick- to medium-bedded tuff-breccias and breccias with plastically deformed particles, and 6) thin-to medium-bedded tuffs. The major characteristics of these units are summarized in Table 2.

The components of these bedded fragmental units such as clast and matrix types, clast and matrix distribution, clast fabric, and petrographic characteristics are generally common to several of these subtypes. Component descriptions for the subtypes are therefore presented together in the following sections.

2) Clast Size Distribution.

The longest dimensions of clasts were measured from rock outcrop exposures. In sections A to I the degree of flattening is more or less the same, hence, clast sizes can be compared from one area to another.

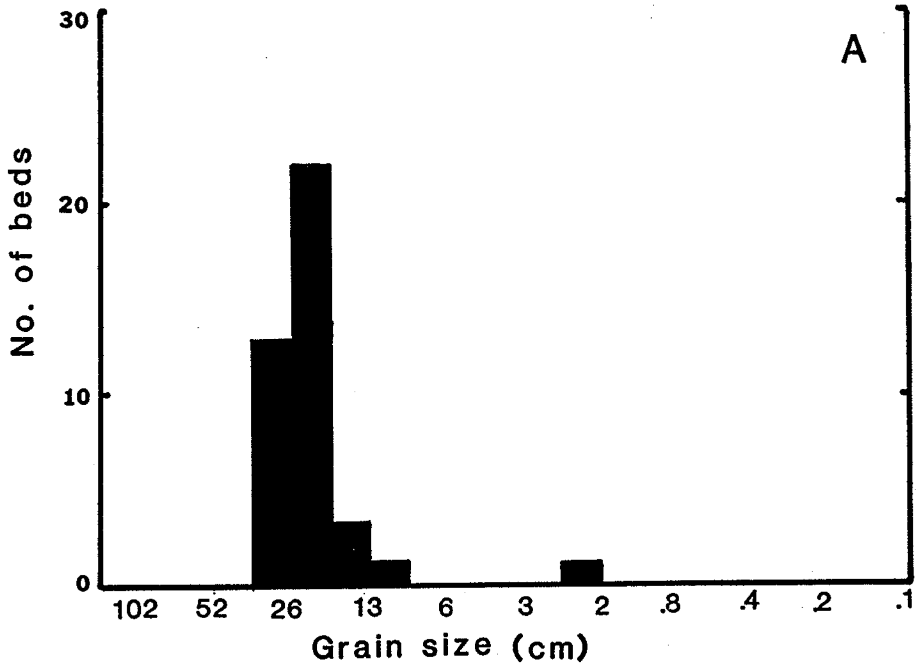
Excluding the lava lobes, maximum clast sizes measured in 259 beds range from 0.5 to 102 cm; the mean maximum particle size based on measurement of several of the largest clasts in each bed is 28.9 cm (Fig. 10). However, outside these measured sections, clasts up to 1 m were observed. The fragments occur in a lapilli-tuff matrix which is defined as particles less than 0.5 cm in size. The choice of 0.5 cm as the boundary between fragments and matrix is based on the

Table 2 Comparison of Various Subtypes of Bedded Fragmental Rock Units

| Bed types Characteristics | Very thickly-bedded matrix-supported breccia and tuff-breccia | Very thickly-bedded clast-supported breccia | Thick-to medium-bedded matrix-supported lapilli-tuffs | Lava lobes | Thick- to medium-bedded plastically deformed particle breccia and tuff-breccia | Thin- to medium-bedded tuffs |
|---|---|---|---|---|---|---|
| Sample size | n= 216 | n= 21 | n= 28 | n= 5 | n= 7 | n= 10 |
| Abundance * | 75% | 7% | 10% | 2% | 2% | 4% |
| Bed thickness | Range=0.5 to14m<br>x= 2.45m | Range=0.5 to 11.4m<br>x= 1.94m | Range=0.05 to 2.6m<br>x= 0.41m | Range=4.2 to 13.5m<br>x= 9.2m | Range=0.4 to 1.5m<br>x= 0.93m | Range=0.01 to 1.3m<br>x= 0.2m |
| Bed contacts | Lower=sharp<br>Upper=sharp | Lower=sharp<br>Upper=sharp | Lower=sharp<br>Upper=sharp | Lower=sharp<br>Upper=sharp | Lower=sharp<br>Upper=sharp | Lower=sharp<br>Upper=sharp |
| Maximum particle size | 0.5 to 52cm,rare blocks 1m<br>x= 28.7cm | 0.5 to 50cm<br>x= 14.0cm | 1 to100mm<br>x= 5mm | 1 to 5m long<br>x= 2.2m | 5 to 10cm,rare blocks 1m<br>x=3.3 cm | 1 to 5mm, rare blocks 0.5m<br>x= 2mm |
| Whole particles ** | About 10% | About 10% | About 5% | About 50% | About 80% | About 5% |
| Grading | Ungraded (72%)<br>Normal (12%)<br>Reverse (12%)<br>Reverse to normal (3%)<br>Normal to reverse (1%) | Ungraded (83%)<br>Normal (8%)<br>Reverse (4.5%)<br>Reverse to normal (4.5%) | Ungraded (90%)<br>Normal (10%)<br>Reverse to normal (<1%) | Ungradded (100%) | Ungraded (86%)<br>Crude reverse (14%) | Ungraded (30%)<br>Normal (60%)<br>Reverse to normal (10%) |
| Matrix<br>a)Abundance<br>b)Vesicular ***<br>c)Non-vesicular*** | a) x=59%<br>b) 1-70%,x=38%<br>c) 15-80%,x=62% | a) x= 14%<br>b) 10-20%,x=38%<br>c) 50-75%x=62% | a) x= 70%<br>b) 50-80%, x=71%<br>c) 65-45%,x=29% | a) x= 70%<br>b) 20-55%,x=53%<br>c) 30-55%,x=47% | a) x= 67%<br>b) 50-60%,x=65%<br>c) 25-40%,x=35% | a) x= 95%<br>b) 5-80%; x=33%<br>c) 10-80%,x=67% |

Explanations:

x = Mean
* = % of fragmental sequence
** = Maximum abundance as % of total fragment population
*** = % of matrix population



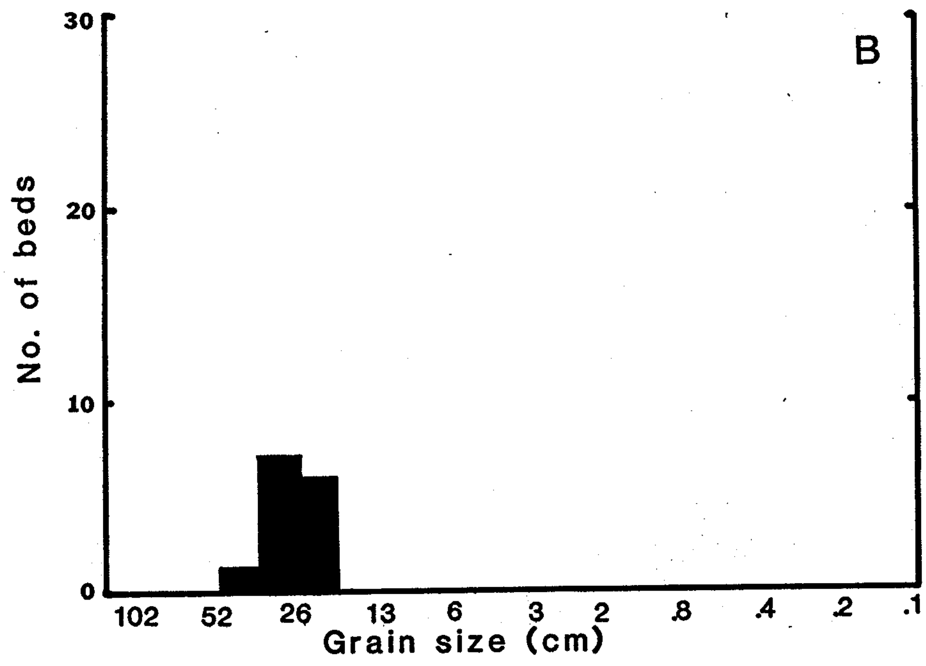




**Figure 10.** Distribution of maximum clast sizes in stratigraphic sections A, B, C, D, E, H and I of Figure 9.

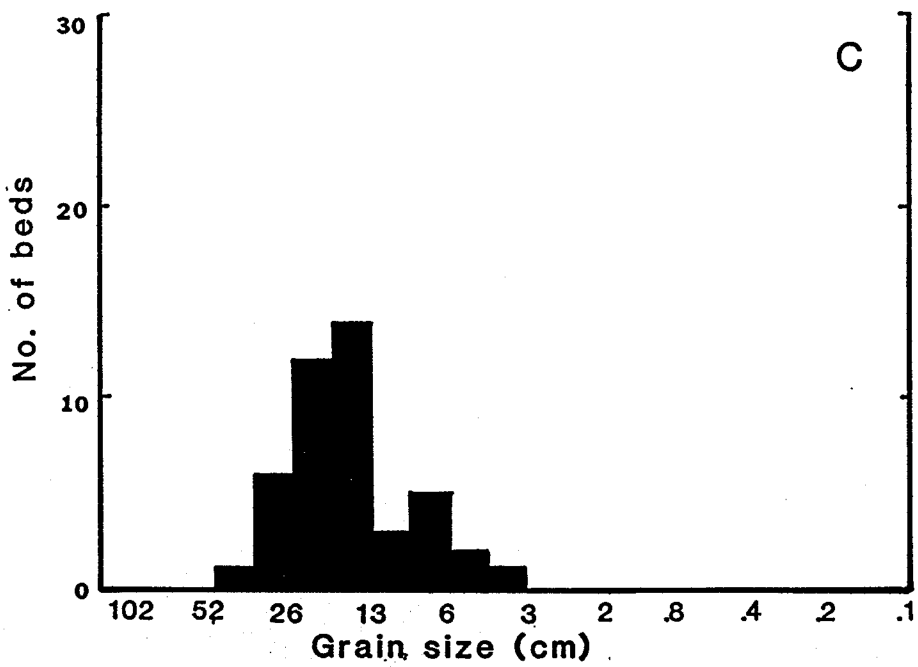
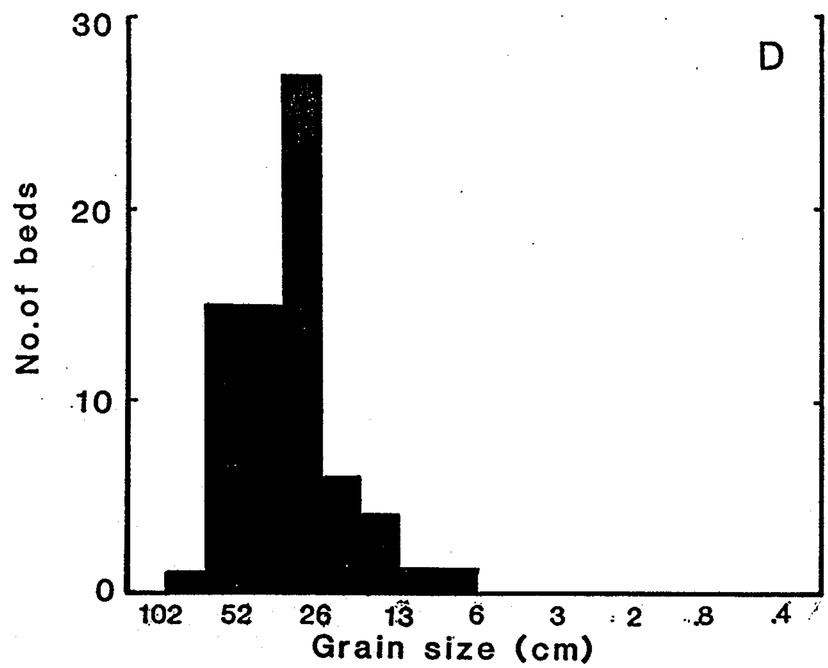
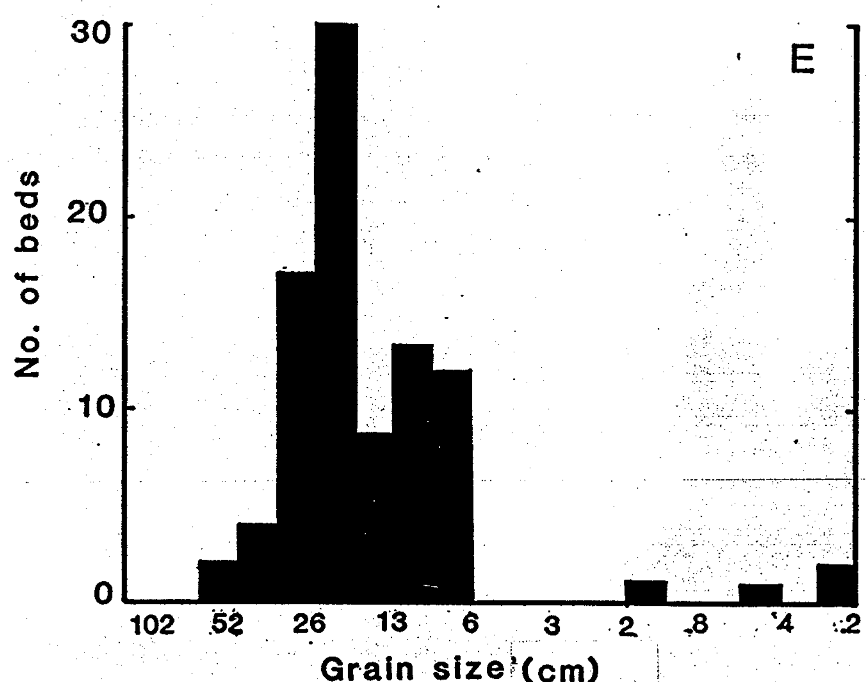



Figure 10: Continued

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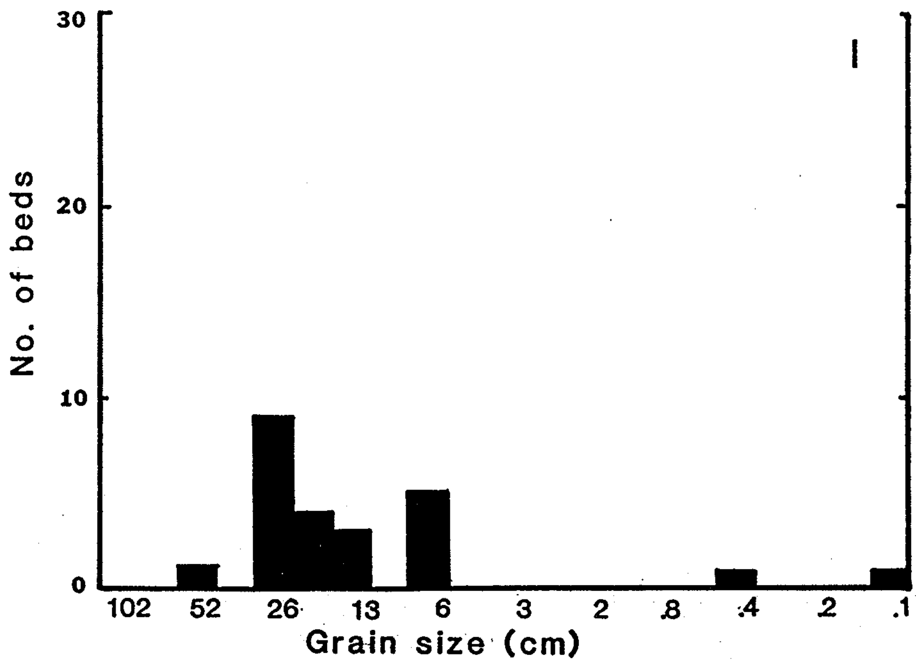


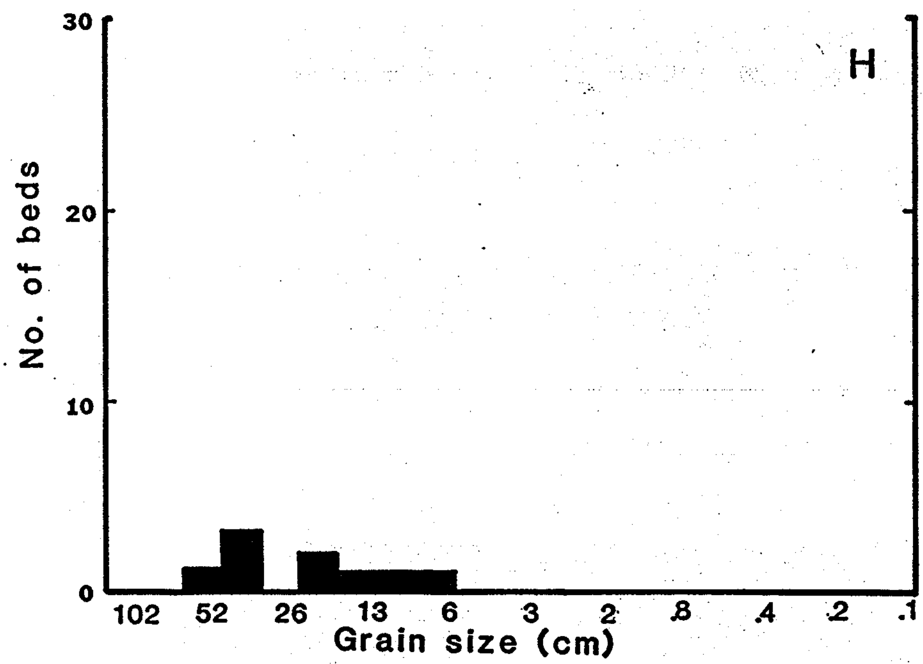


Figure 10: Continued

practical lower limit for ready recognition of particles on outcrop surfaces.

Although proper clast size analyses could not be done because of the large size of many particles and the inability to disaggregate samples, the maximum particle size appears to have a bimodal distribution which, in sections C and E (Fig. 10), corresponds to the breccia plus tuff-breccia and lapilli-tuff beds. There is no apparent lateral change in maximum clast size (Fig. 10). Vertical changes in maximum clast size are generally irregular; however, in sections D, E, H and I there are 2 to 3 intervals, each about 150 cm thick, with lower maximum clast sizes. These intervals correspond to the occurrence of the interbedded thick- to medium-bedded lapilli-tuff beds (Fig. 9).

In the coarse-grained fragmental rocks, there is a wide range in matrix abundances. Based on modal analyses of outcrops, matrix abundance of the breccia and tuff-breccia beds ranges from 5 to 95% (Fig. 11). The beds thus include both clast-supported and matrix-supported frameworks. Most authors do not give a precise boundary for the distinction between clast-supported and matrix-supported frameworks, and, where a boundary is specified, there is disagreement on the value used. For example, Pettijohn (1975) used a matrix abundance of 15%, whereas Shultz (1984) used a matrix abundance of about 40%. Empirically, it was found that, in the study area, a matrix abundance of 20% was the appropriate boundary to differentiate between beds which, in the field,

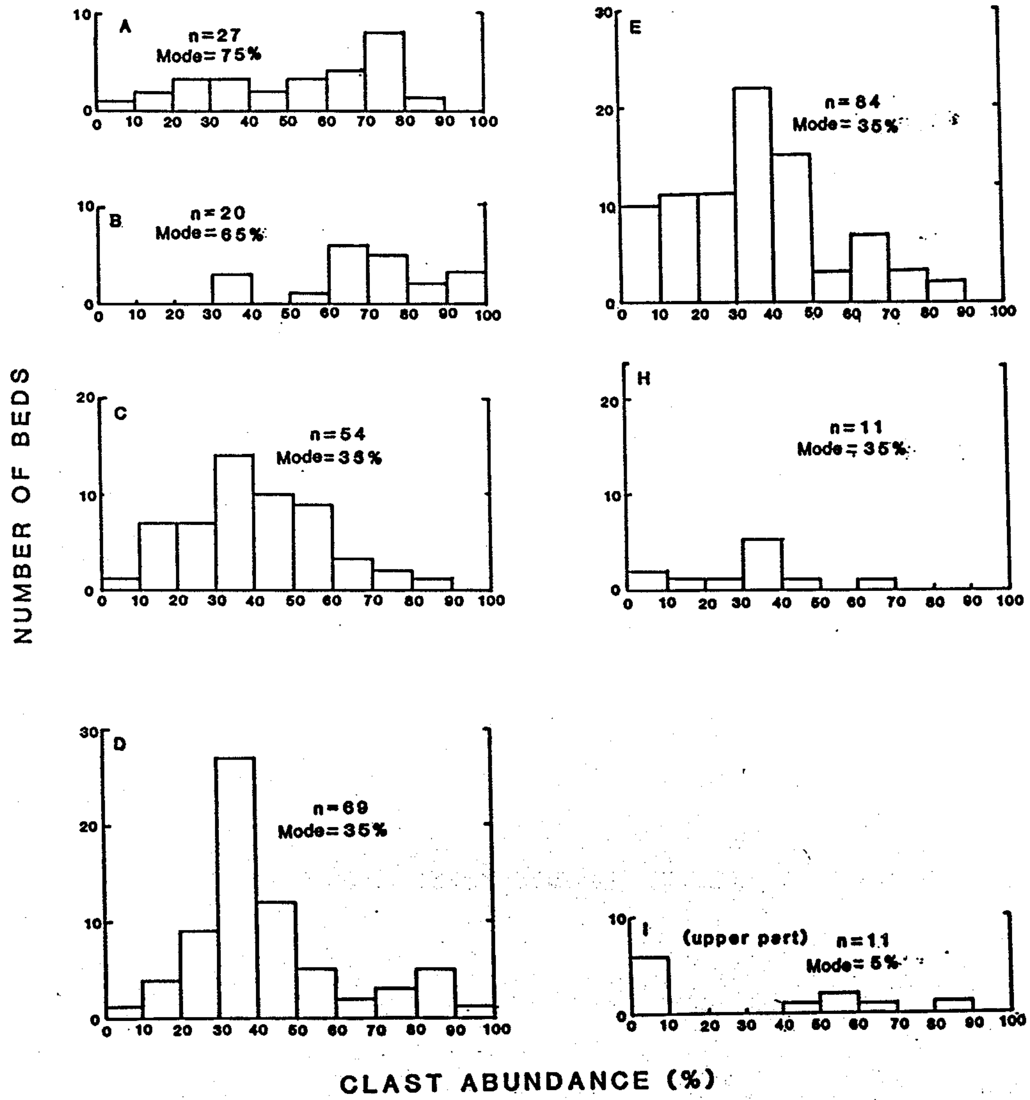


**Figure 11.** Clast abundances in bedded fragmental rocks in sections A, B, C, D, E, H, and I of Figure 9 arranged from north to south.

were classified as either matrix-supported or clast-supported. The relatively low, boundary-matrix abundance may reflect the poor sorting of the deposit (Pettijohn, 1975). Using this boundary, clast-supported beds form about 10% of the breccia and tuff-breccia component. The proportion of matrix varies from bed to bed and section to section and is lower in the northern two sections than the other sections (Fig. 11).

Clast distribution in individual fragmental beds is variable resulting in various types of grading. Out of 250 breccia and tuff-breccia beds examined, 73.2% are ungraded; 11.6% normally graded; 11.2% reversely graded; 3.6% symmetrically graded with a coarse middle zone; and 0.8% symmetrically graded with a fine middle zone (Table 3). Graded beds have slightly larger mean bed thicknesses and matrix abundances, and slightly lower maximum clast sizes than ungraded beds (Table 4).

The very thickly-bedded, poorly sorted, breccia, tuff-breccia, and locally lapilli-tuff beds are mostly ungraded although both normally and reversely graded beds are present in about equal proportions (Table 2). Occasionally, reversely graded breccia and tuff-breccia beds have a 10 to 50-cm basal tuff zone that grades rapidly upward into coarse breccia and tuff-breccia which forms most of the beds. Locally, large fragments surrounded by fine-grained matrix occur at the top of some breccia beds. Lapilli-tuff beds are moderately to poorly sorted and they are dominantly ungraded with about 10% normaly graded beds. Thin- to medium-bedded tuffs have the

Table 3

Proportions of Grading Types by Stratigraphic Section in Bedded Breccia and Tuff-Breccia

| Grading Types | Stratigraphic Sections | | | | | | | | | | | | | | All Sections | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | | B | | C | | D | | E | | H | | I | | | |
| | n | % | n | % | n | % | n | % | n | % | n | % | n | % | n | % |
| Normal | 3 | 1.2 | 2 | 0.8 | 1 | 0.4 | 3 | 1.2 | 12 | 4.8 | 5 | 2.0 | 3 | 1.2 | 29 | 11.6 |
| Reverse | 2 | 0.8 | - | - | 6 | 2.4 | 9 | 3.6 | 7 | 2.8 | 1 | 0.4 | 3 | 1.2 | 28 | 11.2 |
| Symmetric (Reverse to normal) | - | - | - | - | 1 | 0.4 | 1 | 0.4 | 2 | 0.8 | - | - | 4 | 2.0 | 8 | 3.6 |
| Symmetric (Normal to reverse) | - | - | - | - | - | - | - | - | 2 | 0.8 | - | - | - | - | 2 | 0.8 |
| Ungraded | 17 | 6.8 | 14 | 5.6 | 38 | 15.1 | 55 | 21.8 | 47 | 18.7 | 2 | 1.6 | 10 | 3.6 | 183 | 73.2 |
| Total | 22 | 8.8 | 16 | 6.4 | 46 | 18.3 | 68 | 27.0 | 70 | 27.9 | 8 | 4.0 | 20 | 8.0 | 250 | 100.4 |

Abbreviations: n = number of beds; (%) = percent abundance

Table 4

Variations of Bed Thickness, Matrix Abundance and Maximum Clast Size between Graded and Ungraded Breccia and Tuff-Breccia Beds

| Section | A | | B | | C | | D | | E | | SUMMARY | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameters | Graded | Ungraded | Graded | Ungraded | Graded | Ungraded | Graded | Ungraded | Graded | Ungraded | Graded | Ungraded |
| Bed Thickness (cm) | | | | | | | | | | | | |
| n | 6 | 20 | 2 | 10 | 7 | 43 | 13 | 53 | 16 | 45 | 44 | 171 |
| Range | 95 -950 | 60 -1420 | 430-720 | 60-1150 | 135-890 | 30-1000 | 90-360 | 30 - 700 | 50-670 | 20-640 | 50-950 | 20-1420 |
| x | 404 | 380 | 575 | 379 | 379 | 258 | 191 | 176 | 208 | 228 | 351 | 284 |
| s | 347 | 388 | 205 | 401 | 318 | 480 | 142 | 141 | 166 | 121 | 236 | 306 |
| Matrix Abundance (%) | | | | | | | | | | | | |
| n | 6 | 20 | 2 | 10 | 7 | 43 | 13 | 51 | 16 | 51 | 44 | 175 |
| Range | 20-80 | 15-85 | 37-65 | 1-67 | 20-80 | 10-86 | 13-94 | 5-81 | 50-98 | 10-85 | 13-98 | 1-86 |
| x | 50 | 40 | 50 | 24 | 56 | 58 | 61 | 56 | 73 | 57 | 58 | 47 |
| s | 27 | 20 | 18 | 21 | 20 | 19 | 18 | 22 | 20 | 17 | 21 | 20 |
| Maximum Clast Size (mm) | | | | | | | | | | | | |
| n | 6 | 20 | 2 | 10 | 7 | 43 | 13 | 51 | 16 | 51 | 44 | 175 |
| Range | 20-280 | 100-340 | 200-220 | 180-350 | 110-290 | 60-460 | 64-460 | 60-460 | 64-380 | 64-525 | 20-460 | 60-525 |
| x | 175 | 216 | 210 | 263 | 205 | 173 | 214 | 260 | 195 | 222 | 200 | 227 |
| s | 85 | 58 | 14 | 48 | 67 | 84 | 82 | 100 | 82 | 110 | 66 | 80 |

Explanations:

x = Mean
s = Standard Deviation

greatest proportion of normally graded beds (Table 2) and are generally well sorted.

3) Bedding Characteristics.

In the very thickly-bedded breccia, tuff-breccia, and locally lapilli-tuff beds are defined by variations in both clast size and matrix abundance. Most of the bed contacts are sharp and planar, although small scale irregularities are produced by slight upward projection of large clasts above the bed surface (Fig. 12). A small proportion of beds have transitional contacts and are marked by gradual changes in clast sizes over a distance of 10 to 100 cm (Fig. 13). Beds thicknesses range from 0.5 to 14 m with a mean thickness of 2.45 m.

In the thick- to medium-bedded lapilli-tuffs, beds range in thickness from 0.05 to 2.6 m and average 0.4 m (Table 2). The beds are organized in sets of 5 to 10 beds with sharp bed contacts. The bed sets occasionally contain discontinous, lenticular, coarse breccia and tuff-breccia interbeds which are 0.9 to 10 m long, and 5 to 30 cm thick; the interbeds contain clasts 5 to 20 cm in diameter.

Beds in the thinly- to medium-bedded tuffs commonly have sharp contacts defined by a change in clast size. Bed thicknesses vary from 0.01 to 1.3 m and an average of 0.2 m. Most beds are massive but in the finer grained upper parts of some normally graded beds there are 1 to 5 mm thick planar laminations (Figs. 13, 14). Rare scour-and-fill structures

**Figure 12.** Sharp bed contact between a breccia and tuff-breccia bed defined by a change in clast size. Notice the straight bed contact with minor irregularities due to upward projection of large fragments. The pointed end of the hammer head is the top of the sequence.

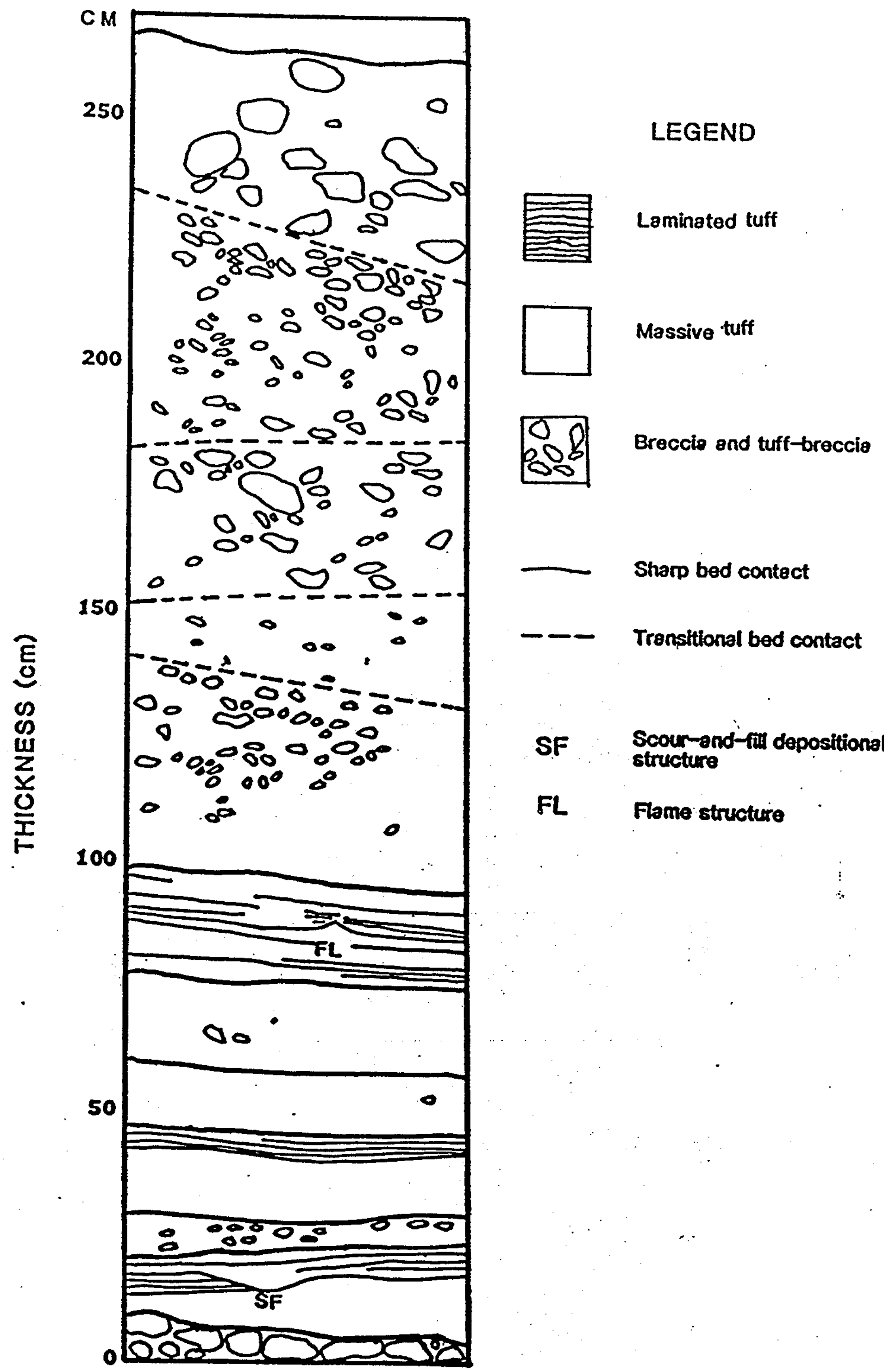


Figure 13. Bedding and clast size distribution in a selected section across bedded fragmental rocks. This is from the top of section E of Figure 9 and was traced from a series of rock outcrop photographs.

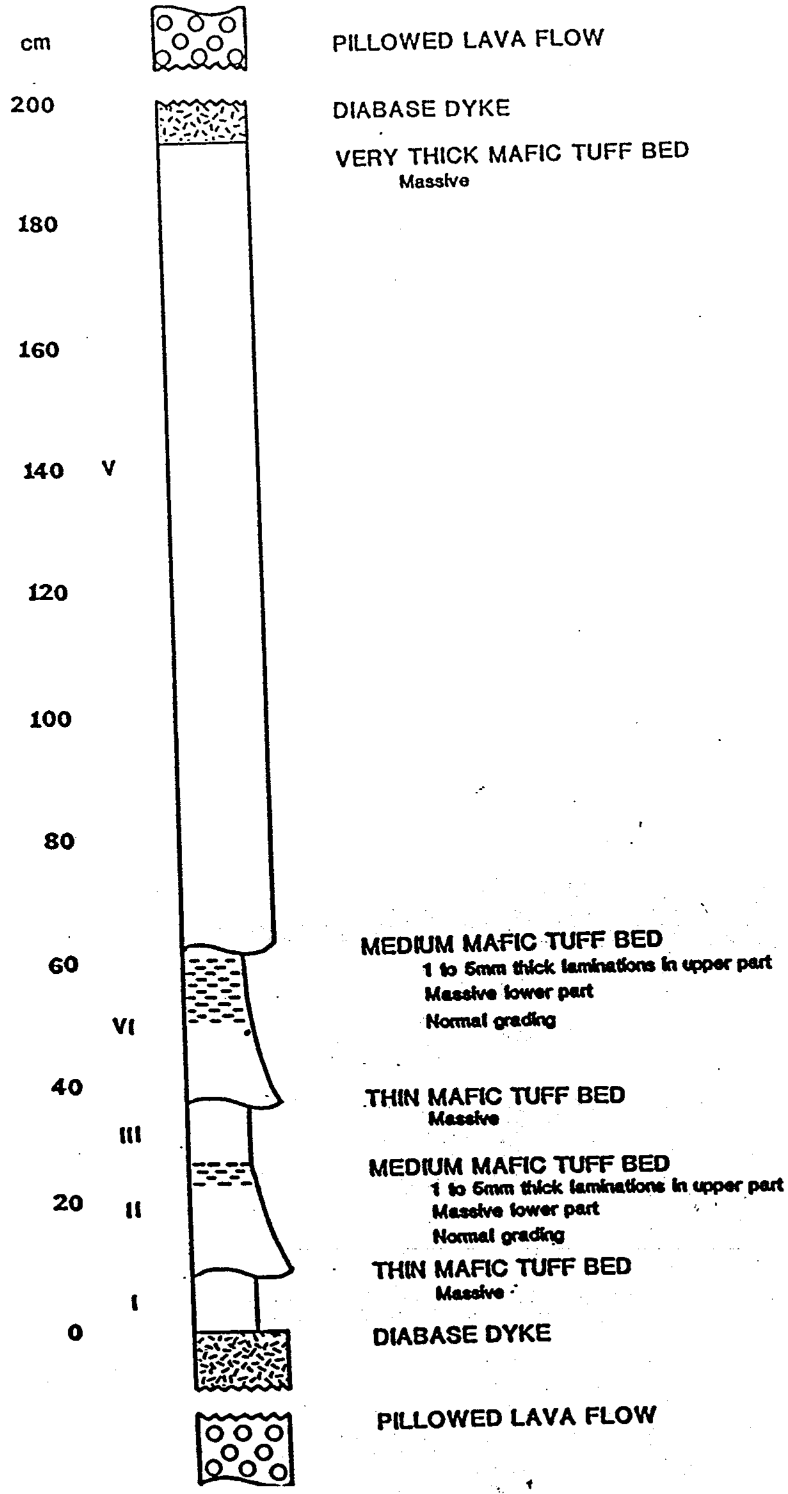


Figure 14. Section across bedded mafic tuff from the upper part of section D of Figure 9.

and flame structures are also present (Fig. 13).

When all the fragmental rocks are considered, bed thicknesses have a log normal distribution and show a slight lateral decrease in bed thickness from north to south (Fig. 15). In some sections there is a general vertical decrease of bed thickness which coincides with the occurrence of lapilli-tuff units.

Individual beds have been traced laterally for up to 500 m, but most beds can be traced for only 50 to 100 m. Correlation of specific beds from outcrop to outcrop and from section to section across areas of cover is uncertain because differences between many beds are relatively subtle. Where beds could be traced laterally for long distances, there is only a limited variation in bed thickness. No bed terminations were observed although the disparity in numbers of beds among sections (Fig. 11) and the lenticular nature of the intercalated pillowed flows (Fig. 9) indicate that many individual beds must terminate within the mapped extent of the sequence.

The relationships between bed thickness and maximum particle size (Fig. 16); bed thickness and matrix abundance (Fig. 17); and maximum particle size and matrix abundance (Fig. 18) show poor correlations for both the entire bed population and the subset of graded beds.

4) Clast Fabrics.

Clast fabrics are generally isotropic although in a few

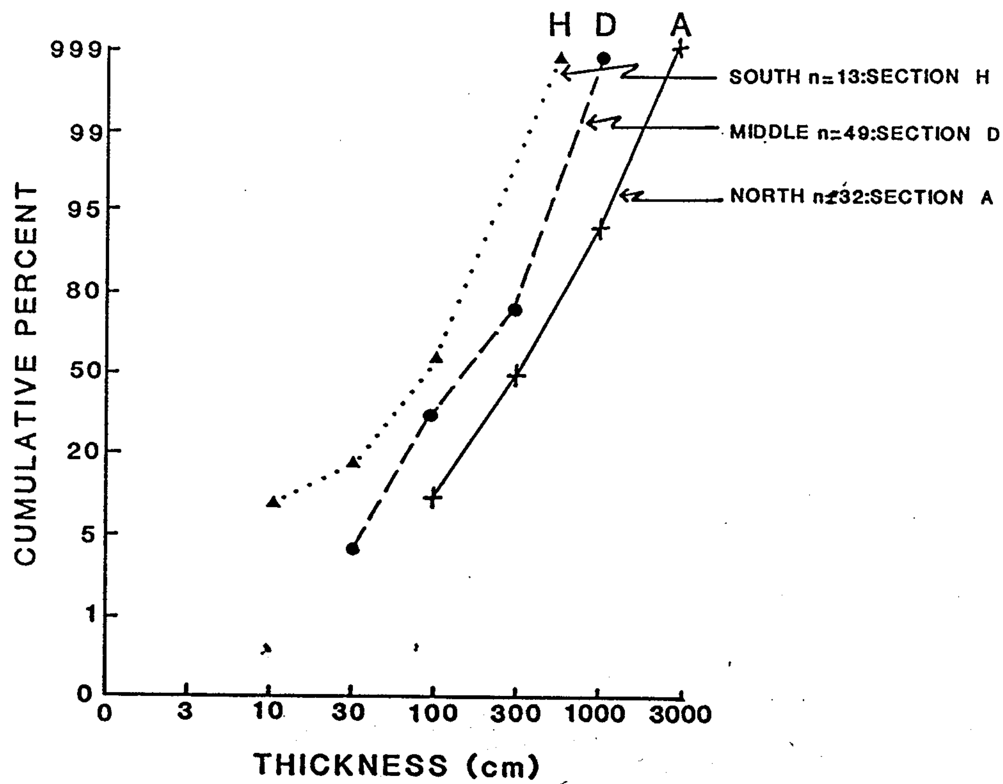


**Figure 15.** Log-normal bed thickness variation in bedded fragmental rock units (method after Ingram, 1954; Tassé et al., 1978). Location of sections as shown in Figure 9. Other sections plot within the limits of curves H and A and have been omitted for clarity.

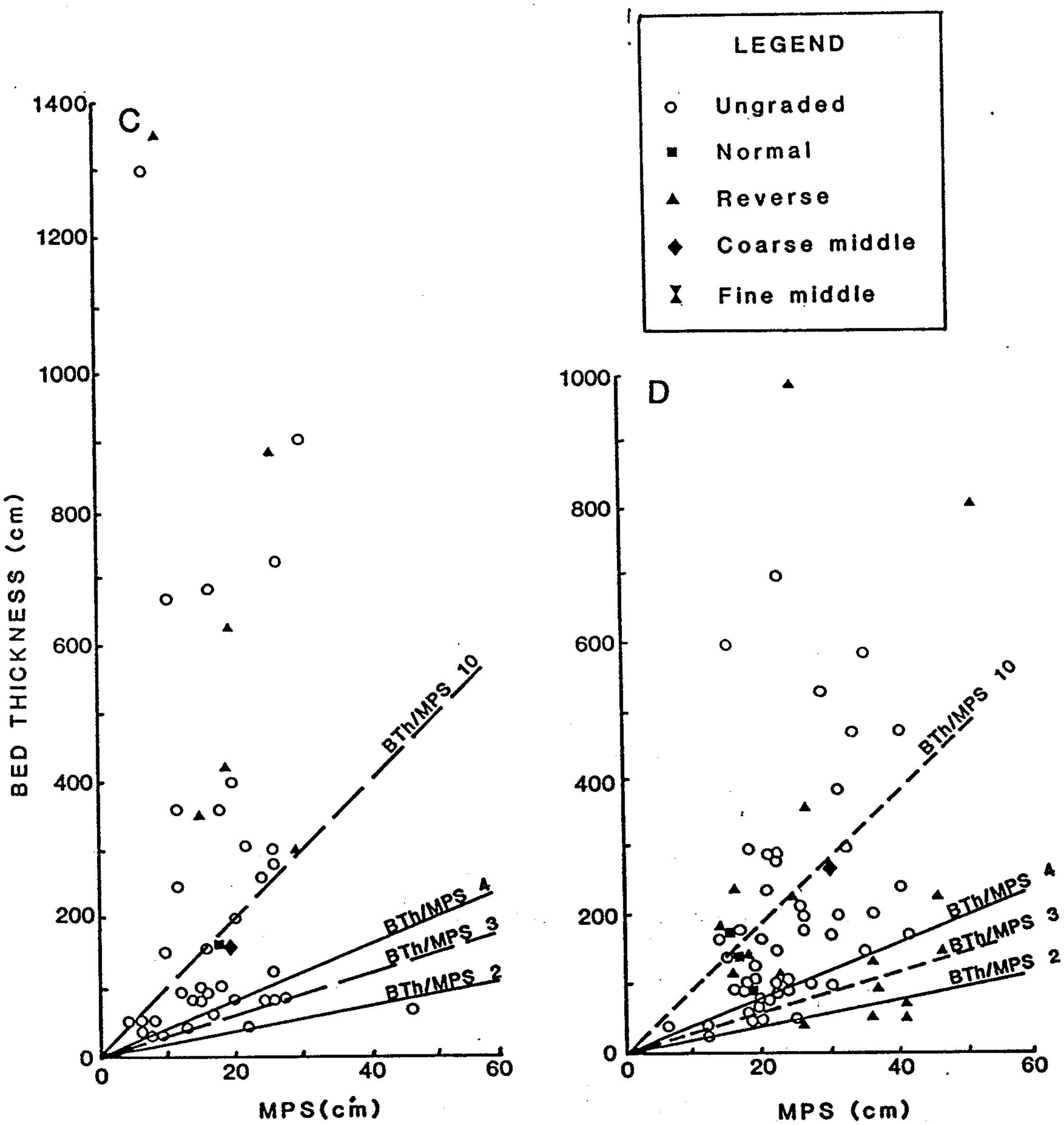


**Figure 16A.** Bed thickness (BTh) versus maximum particle size (MPS) of representative bedded fragmental rock units. Solid and dashed lines indicate various BTh/MPS ratios. According to Nemec et al., (1980) and Gloppen and Steel (1981), subaerial debris flows have BTh/MPS ratios from 2 to 4 (solid lines) and subaqueous debris flows from 3 to 10 (dashed lines).

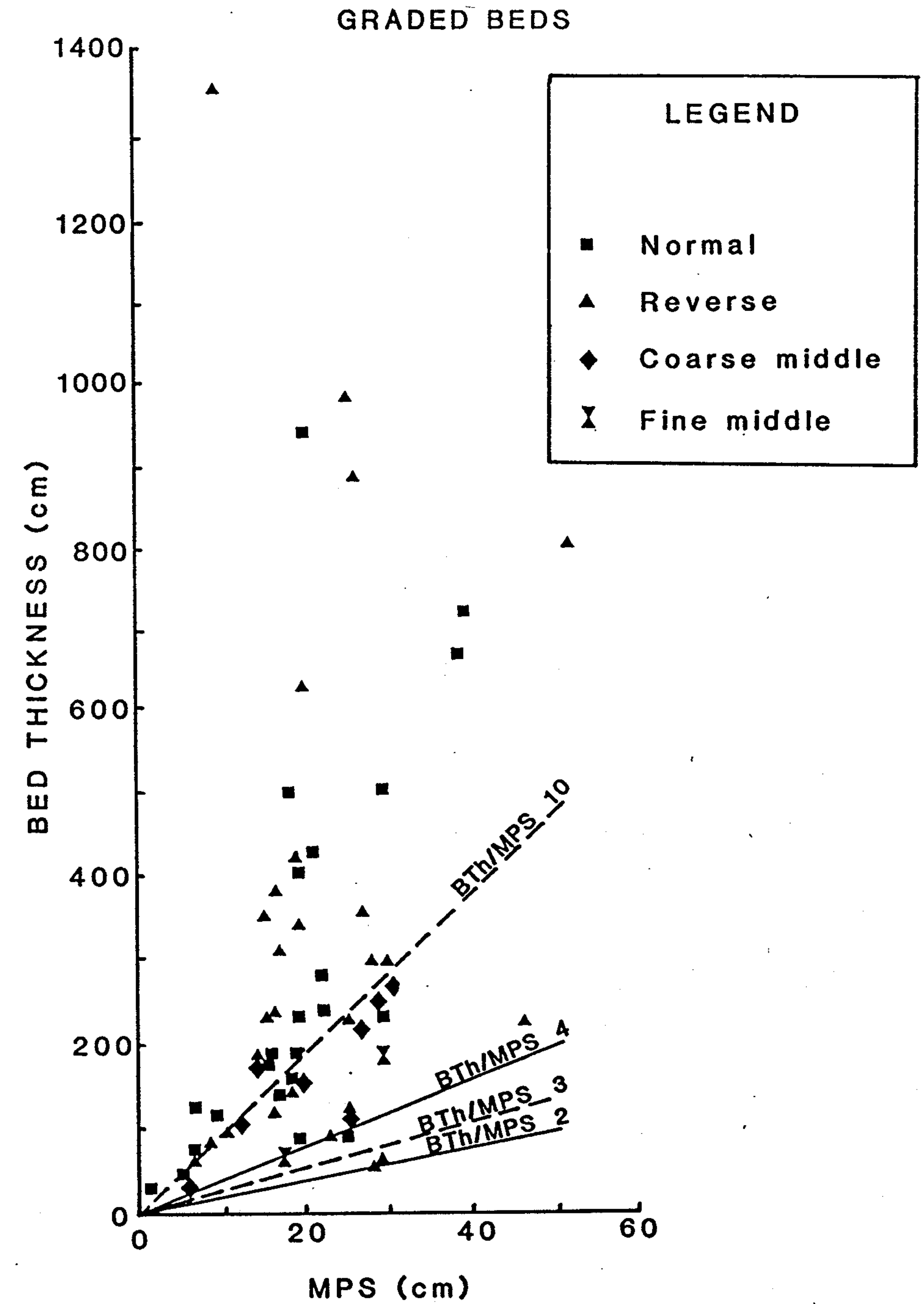


**Figure 16B.** Bed thickness (BTh) versus maximum particle size (MPS) of graded beds only for all stratigraphic sections of the Main Bedded Mafic Fragmental Sequence of Figure 9. Solid and dashed lines as defined in Figure 16A.

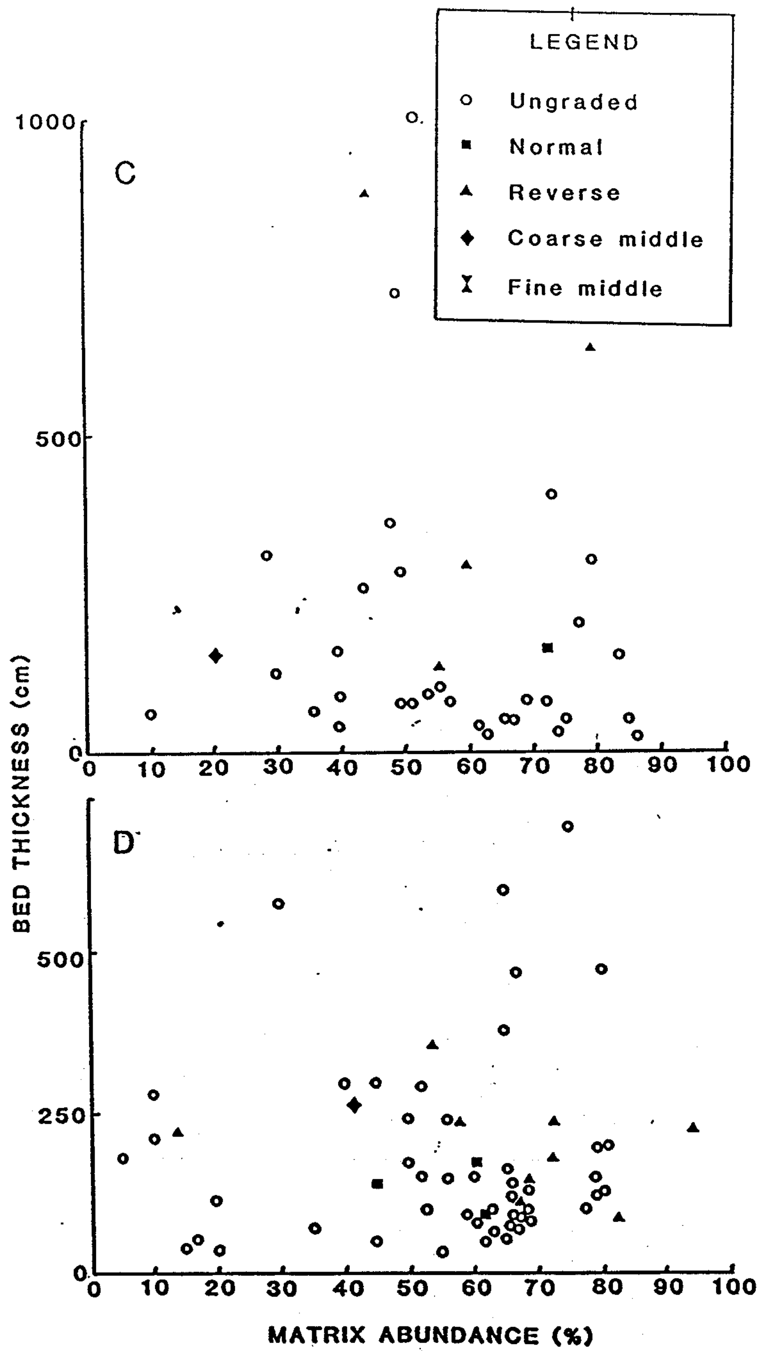


**Figure 17A.** Bed thickness versus matrix abundance of representative bedded fragmental rock units. Locations of sections as shown in Figure 9.

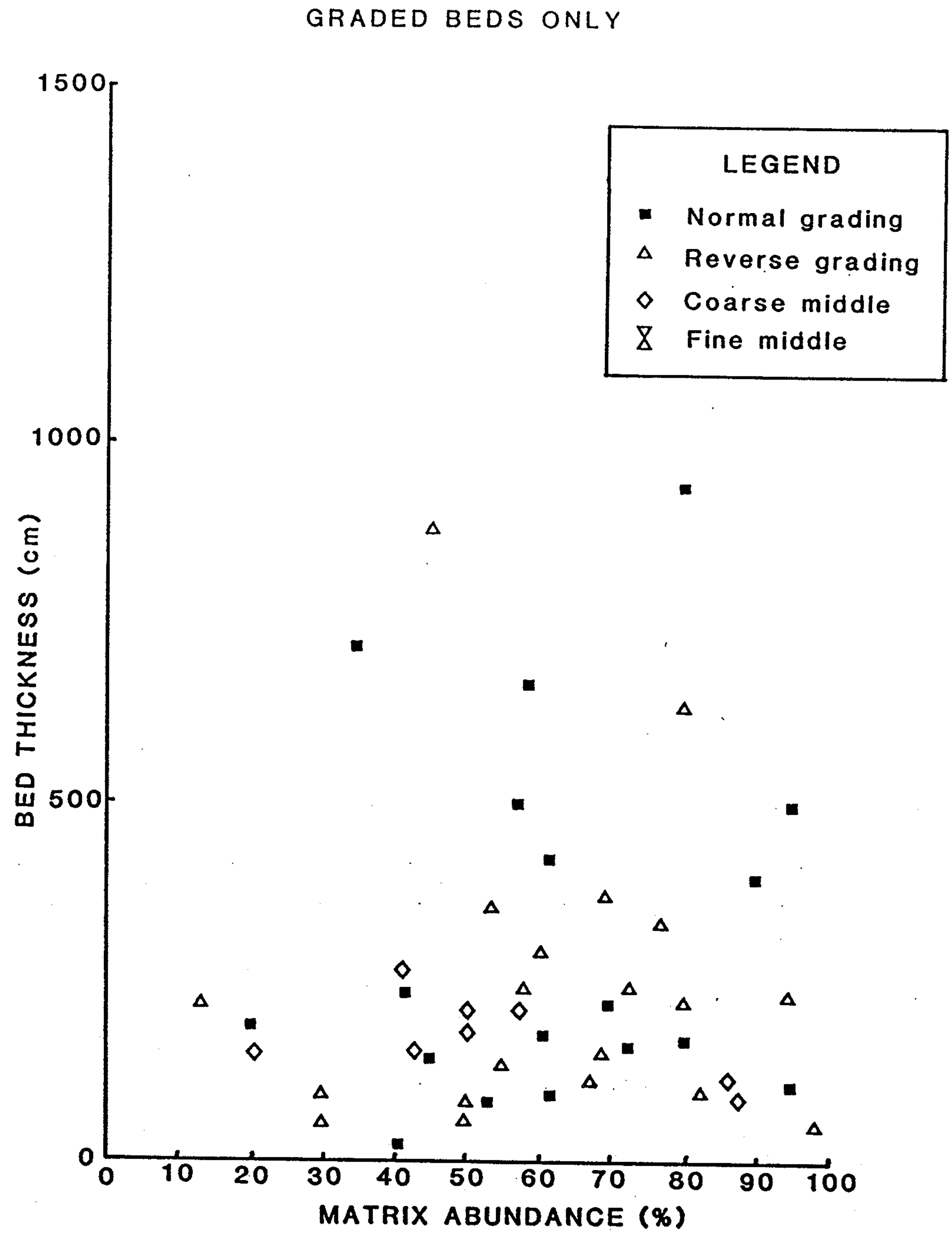


**Figure 17B.** Bed thickness versus matrix abundance of graded beds only for all stratigraphic sections of the Main Bedded Mafic Fragmental Sequence of Figure 9.

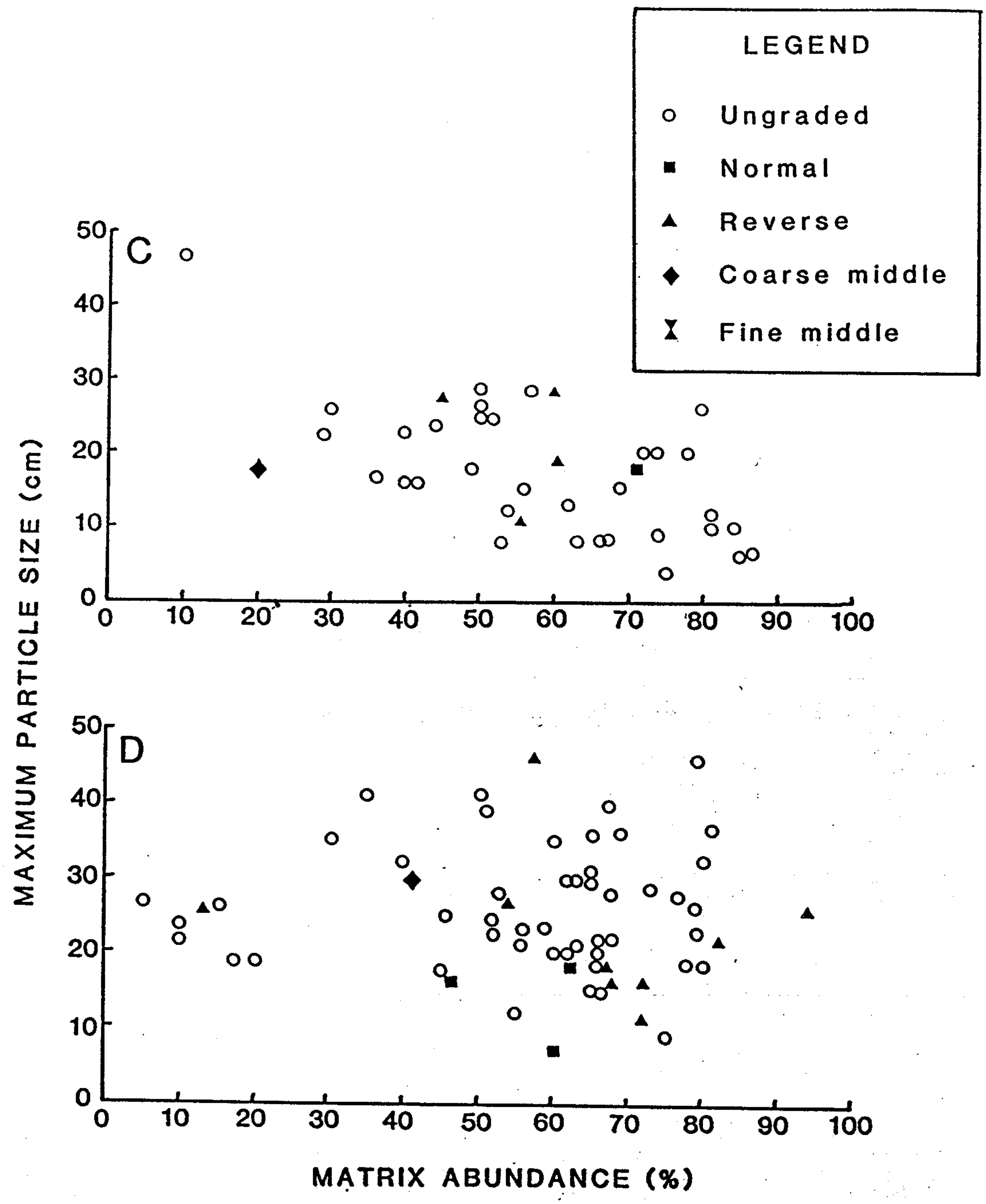


**Figure 18A.** Maximum particle size versus matrix abundance of representative bedded fragmental rock units. Locations of sections as shown in Figure 9.

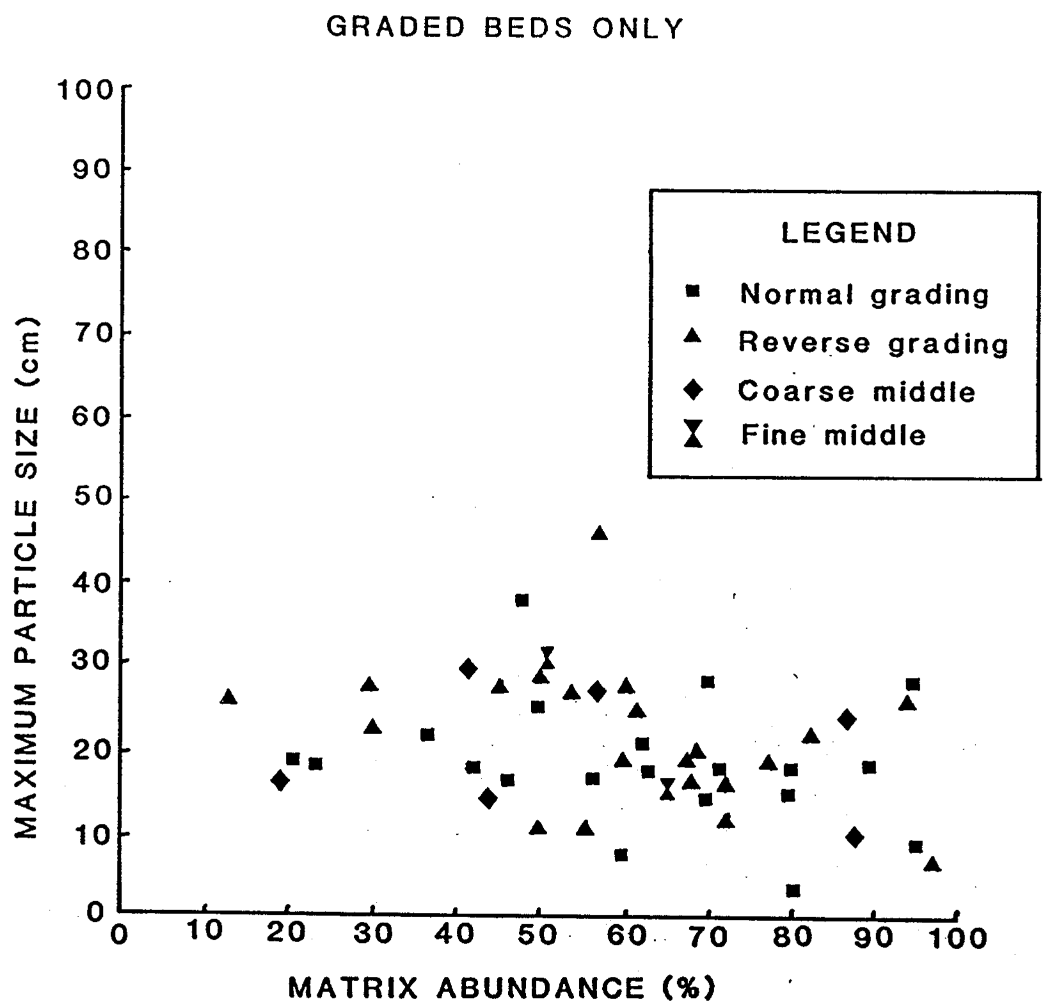


**Figure 18B.** Maximum particle size versus matrix abundance of graded beds only for all stratigraphic sections of the Main Bedded Mafic Fragmental Sequence of Figure 9.

beds elongate clasts are aligned parallel to bed contacts. Rare imbrication of clasts was also observed and indicate a southward azimuth of flow. The non-isotropic clast fabrics were observed in stratigraphic sections C and D where there is least tectonic deformation as indicated by the nearly spherical quartz amygdules.

5) Petrography.

a) Breccia and Tuff-breccia Fragments.

Breccia clasts are generally porphyritic with 1 to 15% pyroxene and/or 1 to 10% plagioclase phenocrysts in a fine-grained groundmass that is now composed of plagioclase, epidote, chlorite and minor quartz. Pyroxene phenocrysts are prismatic, and euhedral to subhedral; they range in size from 0.2 to 2.0 mm (Fig. 19). Glomeroporphyritic phenocryst clusters composed of pyroxene are relatively common, but glomeroporphyritic texture is less commonly developed with plagioclase phenocrysts. Pyroxene phenocrysts are largely replaced by pale green actinolite, chlorite, and occasionally quartz and calcite (Table 5), but relict clinopyroxene is preserved in some phenocrysts, particularly the lower parts of sections C, D, and E (Fig. 9). The prismatic shape, local preservation of relict clinopyroxene, and dominance of single-crystal actinolite pseudomorphs (Table 5) suggest that the pseudomorphs have replaced clinopyroxene phenocrysts.

Plagioclase phenocrysts are tabular, and subhedral, and range in length from 0.2 to 1.0 mm (Fig. 19). They have been

A


B

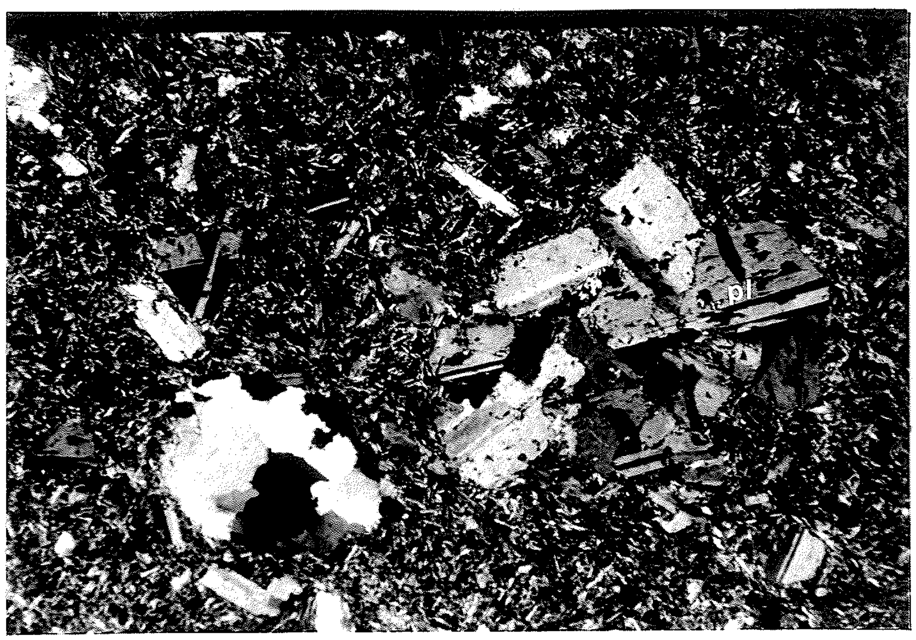


**Figure 19.** Photomicrographs (crossed nicols) of fragments in breccia showing representative mineralogic composition: A) shows clinopyroxene phenocrysts (px) now replaced by chlorite and actinolite, and B) shows plagioclase phenocrysts (pl). Both samples have groundmass clinopyroxene, now replaced by actinolite, and plagioclase microlites. Round to oval white features are quartz-filled amygdules. The field of view is 4.2 mm.

Table 5 Mineralogy of Pseudomorphs After Clinopyroxene Phenocrysts in Basaltic Fragments and Lava Flows in the Main Bedded Mafic Fragmental Sequence.

| Secondary Mineral | Habit | Abundance (% pseudomorph volume) | Size (mm) | Stratigraphic Variation |
|---|---|---|---|---|
| Actinolite | Occurs as euhedral to anhedral single-crystal replacement mineral. | Ranges from 5 to 100% with an average of 60% | Ranges from 0.2 to 2.0mm with an average of 0.5mm | Dominant in the north near sections A and B; and in the middle part near section C. |
| Chlorite | Occurs as multi-crystal aggregates. | Ranges from 0 to 75% with an average of 25% | Less than 0.1mm | Dominant in the south near sections E to I |
| Quartz | Occurs as anhedral, partial replacement of actinolite | Ranges from 0 to 50% with an average of 10% | About 0.1 to 0.5mm | Common in the north near sections A and B |
| Calcite | Occurs mostly as anhedral, multi-crystal, partial replacement of actinolite; occasional single crystal replacement | Ranges from 0 to 35% with an average of 5% | About 0.1 to 0.5mm | Occurs in nearly all stratigraphic sections except near section C and the lower part of section E. |

mainly replaced by single-crystal pseudomorphs of albite ($An_{2-5}$). In the upper part of sections A and B, plagioclase has been replaced by multi-crystal aggregates of minute sericite, and occasionally, single-crystal calcite.

Phenocryst species and abundance in randomly collected fragments and in multiple samples collected from several beds show vertical stratigraphic variations. As discussed later, the lower stratigraphic parts are generally pyroxene-phyric, whereas the upper parts are plagioclase-phyric (Fig. 48).

In most fragments, groundmass textures are relatively well preserved (Fig. 20). The groundmass is composed of 1 to 50%, 0.1 to 0.2 mm randomly oriented, tabular plagioclase laths forming a felted texture. The plagioclase has been replaced by albite and locally by epidote. Subhedral, prismatic actinolite laths that are also generally 0.1 to 0.2 mm in size form 1 to 20% of the groundmass; they have probably replaced clinopyroxene microlites as indicated by their shape and mineralogic composition. The plagioclase and clinopyroxene microlites are surrounded by very fine-grained chlorite and epidote that probably represent recrystallized basaltic glass. The abundance of microlites is therefore an indication of the crystallinity of the breccia fragments.

In many of the large fragments, there is a pronounced internal variation in microlite abundance as a function of proximity to the partial chilled rim that occurs on many fragments. However, when microlite abundance in the central part of large fragments, away from the chilled rims, are

A

B

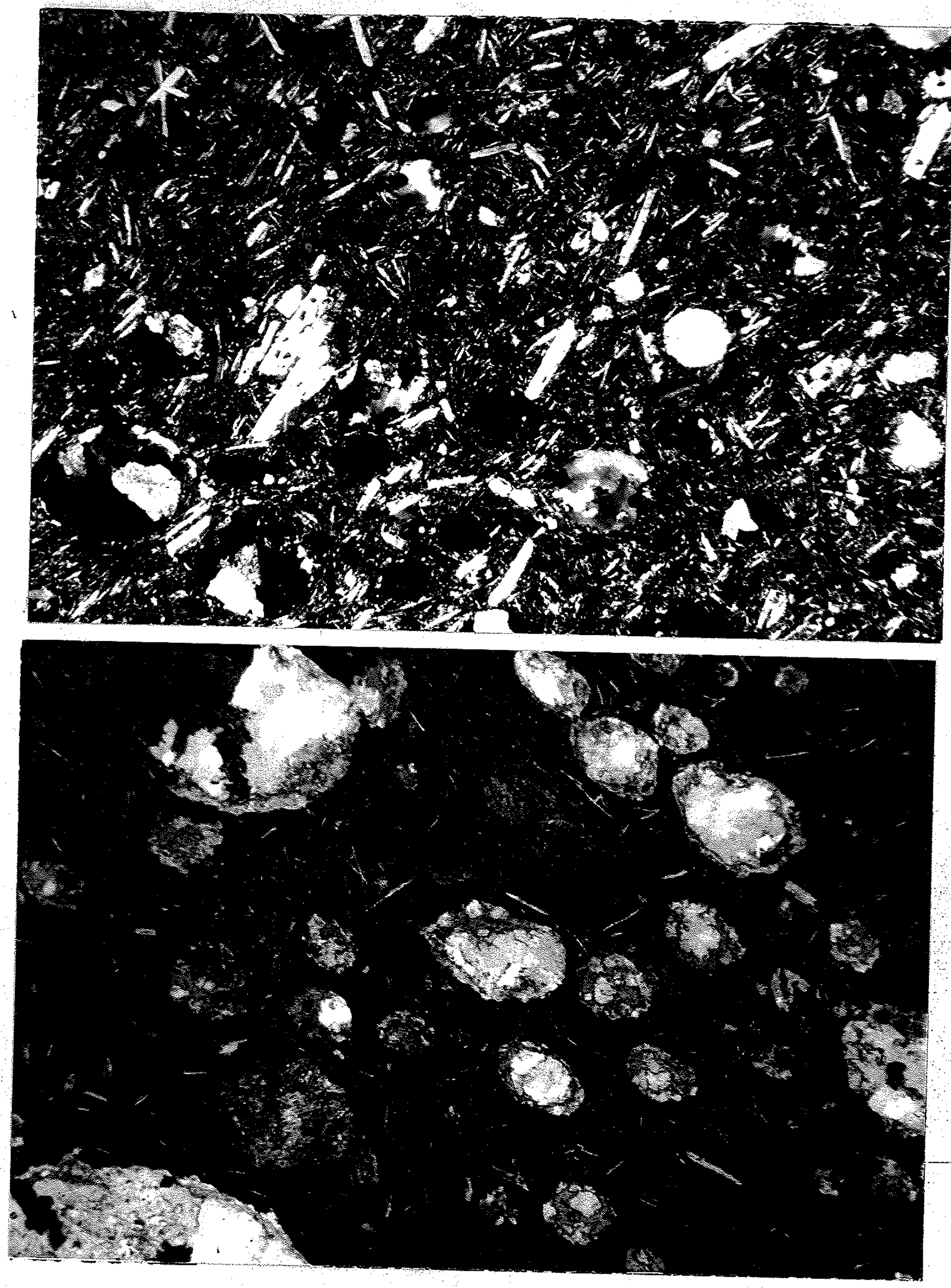

**Figure 20.** Photomicrographs (A=crossed nicols, B=plane light) of groundmass textures of large fragments showing high (A) and low (B) microlite contents. Notice the original felted textures which are well preserved in spite of metamorphic and alteration effects. The large, oval to round, white areas are amygdules. The field of view is 4.2 mm.

compared, there is also a pronounced difference among fragments. Of 29 randomly selected large fragments examined, 20% have 1 to 15% microlites; 30% have 15 to 30% microlites and 50% have more than 30% microlites (Table 6). These estimates indicate that about half of the large fragments had an original glass content of 70%, or more. In contrast, about 70% of the small fragments have less than 15% microlites. Of 14 randomly selected samples from pillowed flows, at comparable distance from the rim, 50% have 15 to 30% microlites and 50% have more than 30% microlites. This indicates that pillows have a higher crystallinity than large and small breccia fragments.

Three types of clasts can be recognized in the breccia (Table 7): 1) apparently unbroken particles that, on outcrop surfaces, are surrounded by a 5 to 25 mm thick, complete chilled rim (Fig. 21); 2) broken fragments, 0 to 30% of which have 1 to 5 mm thick partial chilled rims (Fig. 22); and 3) broken polygonal fragments with a light colour weathering rim (Fig. 23). The broken particles thus appear to have thinner chilled rims than the unbroken particles. In general, the chilled rims have less than 5 to 10% plagioclase and pyroxene microlites which are generally 0.1 to 0.2 mm in size. These are surrounded by very-fine grained chlorite and actinolite which are probably recrystallized basaltic glass (Fig. 24). There is an increase in microlite content from 5 to 10% in the chilled rims to 10 to 50+% in the interiors of the fragments indicating slower cooling.

Table 6 Estimate of Plagioclase and Pyroxene Microlite Abundance in groundmass of Breccia Fragments and Intercalated Lava Flows.

| Lithology | Number of samples | Range of microlite abundances and proportion of samples | | |
|---|---|---|---|---|
| | | 0 to 15% | 15 to 30% | above 30% |
| Breccia fragments * | 29 | 20 | 30 | 50 |
| Pillowed lava flows | 14 | ** 10 | 45 | 45 |
| Lava lobes | 4 | 0 | 50 | 50 |
| Small particles | 35 | 70 | 20 | 10 |

Explanation:

* Large breccia fragments only; taken from middle part, away from chilled zones

** Sample from pillow margin

Unbroken fragments range in size from 5 to 10 cm and have irregular, plastically deformed shapes (Fig. 21). These occur mainly in the lower-middle part of stratigraphic section D where seven successive beds with a total thickness of 7 m contain 30 to 50% of this type of fragment which forms 80% of the fragment population (Table 2).

Broken fragments range in size from 0.5 to 50 cm and are generally angular to subangular. Some of these fragments have curved partial chilled rims, and these constitute 0 to 30% of the total fragment population (Fig. 25).

Another type of particle which ranges in size from 5 to 10 cm and generally has a regular polygonal shape (Fig. 23) is characterized by a complete rim which weathers to a pale grey colour and is 1 to 2.5 cm thick with a mean of 1.3 cm. The rim has approximately the same size and abundance of microlites as the interior (Table 7), but the two zones are distinguished by the type and abundance of minerals replacing phenocrysts and microlites. In the outer rim, plagioclase is replaced by 60 to 90% multi-crystal aggregates of sericite and clinopyroxe by single-crystal actinolite. In the interior, there is 100% replacement of plagioclase by sericite and clinopyroxene is replaced dominantly by epidote. The similarity in size and abundance of microlites and the differences in the type and abundance of replacement minerals between the two zones suggests that this is an alteration rim. These particles are restricted to one outcrop in the upper part of section B. Here, in five successive beds with a total

Table 7 Textural Variations Relative to Rim Type in Large Basaltic Fragments

| Type | Zones | Crystallinity and Mineralogy | Vesicularity |
|---|---|---|---|
| 1. Complete chilled rim (Plastically deformed fragments) | Rim is dark green and 5 to 10mm thick in fragments 5 to 10cm in size. The rim is thickest where curvature of particle margin is greatest. Moderately sharp boundary between rim and inner part of fragment. | About 5% clinopyroxene microphenocrysts which are 0.5mm long. 5% tabular plagioclase microlites which are 0.25 to 0.5mm long; and 90% very fine-grained material containing 70% actinolite and 20% chlorite. | 15 to 20% amygdules which are generally round and 0.1 to 1.0mm in diameter. These are composed of 70% quartz; 25%plagioclase with characteristic albite twins and 5% epidote. |
| | Interior has pale green colour | 5 to 10% clinopyroxene microphenocrysts which are 0.5 to 1.0mm in size. 10 to 15% plagioclase microlites which are 0.25 to 0.5mm long; and 75% very fine-grained material containing 50% actinolite and 25% epidote. | 20% amygdules ranging in size from 0.1 to 5.0mm are both round and irregularly shaped. Amygdules are 80% quartz and 20% epidote. |
| 2. Partial chilled rims | Rim is dark green and 1 to 5mm thick in fragments ranging in size from 0.5 to 50cm. The rim is convexly curved and generally forms 20 to 25% of the fragment margin. The remainder of the fragment is angular to subangular with planar, broken margins. Moderately sharp boundary with inner part. | About 5% 0.2 to 0.5mm plagioclase microlites; 5%, 0.1mm dark coloured epidotized microlites possibly pseudomorphs after clinopyroxene. 90% is very fine-grained material composed of 65% chlorite, 30% actinolite and 5% epidote. | 20%, 0.5 to 0.1mm round to oval amygdules composed of 90% quartz, 5% epidote and 5% chlorite. |
| | Interior is pale green | About 50% of the fragments contain more than 30% plagioclase and clinopyroxene microlites; 5%, 0.5 to 1.0mm plagioclase and pyroxene phenocrysts. 65% is very fine-grained with more actinolite than chlorite relative to the rim. | 25 to 40%, 0.5 to 1.0mm, round, oval, and occasionally irregular amygdules consist of 85% quartz, 10% chlorite, 3% epidote, and 2% calcite. In some samples, 1 to 5% segregation vesicles are present. |
| 3. Polygonal particles with complete rim. | Rim is pale grey and 1 to 2.5cm thick around fragments 5 to 10cm in diameter. The rim is thickest at corners of particles. Sharp boundary with inner part | 5 to 10%, 0.5 to 1.0mm tabular subhedral plagioclase microphenocrysts, replaced by 60% to 90% multicrystal sericite aggregates; 3 to 5%, 0.5 to 1.0mm subhedral actinolite pseudomorphs after clinopyroxene phenocrysts; 1 to 5%, 0.1 to 0.2mm plagioclase microlites replaced by sericite; 50% to 60% 0.1 to 0.2mm actinolite and epidote microlites after clinopyroxene. The remainder is epidote and actinolite without recognizable primary textures, possibly replacing original basaltic glass. | About 30%, 0.5 to 1.0mm, round to irregular amygdules composed of 95% quartz, 3% epidote and 2% sericite. |
| | Interior is pale green | Similar in size and abundance of microphenocrysts as rim except that plagioclase is replaced by 100% sericite aggregates. Relatively more epidote microlites than rim i.e. 30 to 50% 0.1 to 0.2mm anhedral epidote after clinopyroxene microlites. The remainder is actinolite,epidote and sericite without recognizable primary textures, possibly replacing original basaltic glass. | About 40% amygdules which are 1 to 5mm in diameter and have round to irregular shape. Amygdules are 85% epidote 10% quartz, and 5% calcite. rare segregation vesicles. |

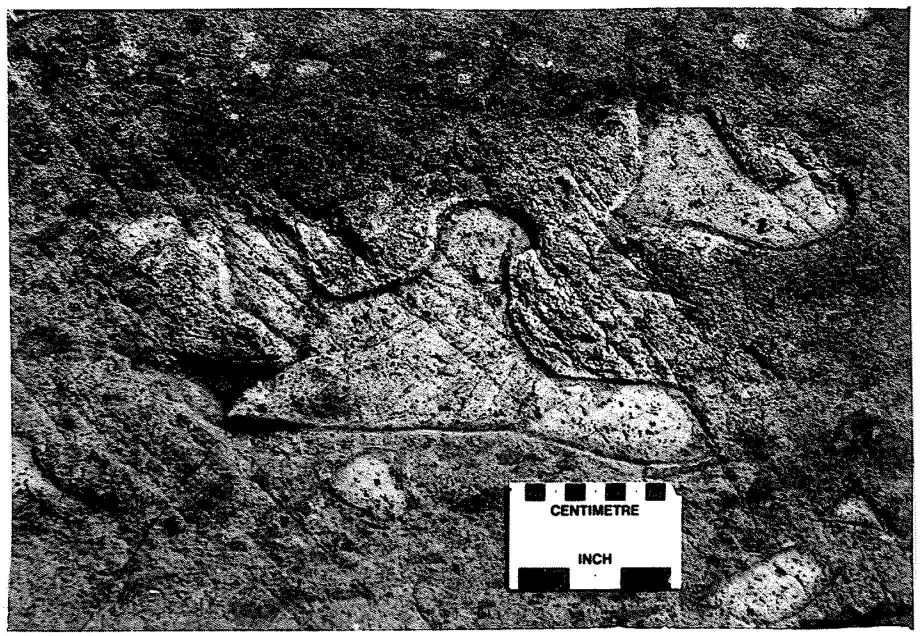


**Figure 21.** Rock outcrop photograph of plastically deformed particle with a complete chilled rim. Notice the high abundance of lapilli-tuff matrix surrounding the large particles.

A


B

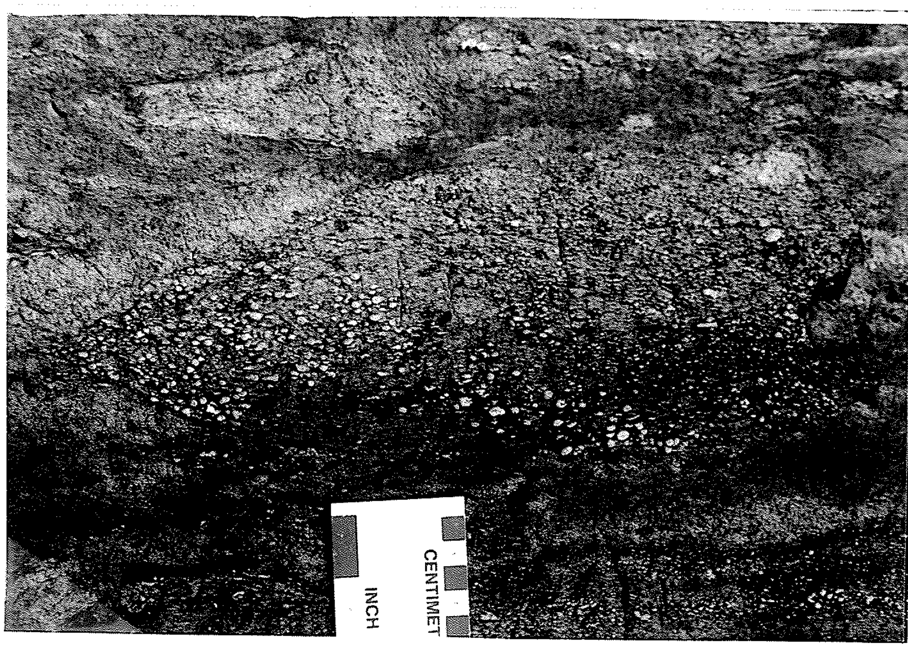


**Figure 22.** Rock outcrop photographs showing angular to subangular fragments with partial chilled rims indicated by rapid change in amygdule distribution, i.e. size-zoned (a). Fragments also show layer-zoned amygdule distribution (b), and non-amygdaloidal fragment (c).

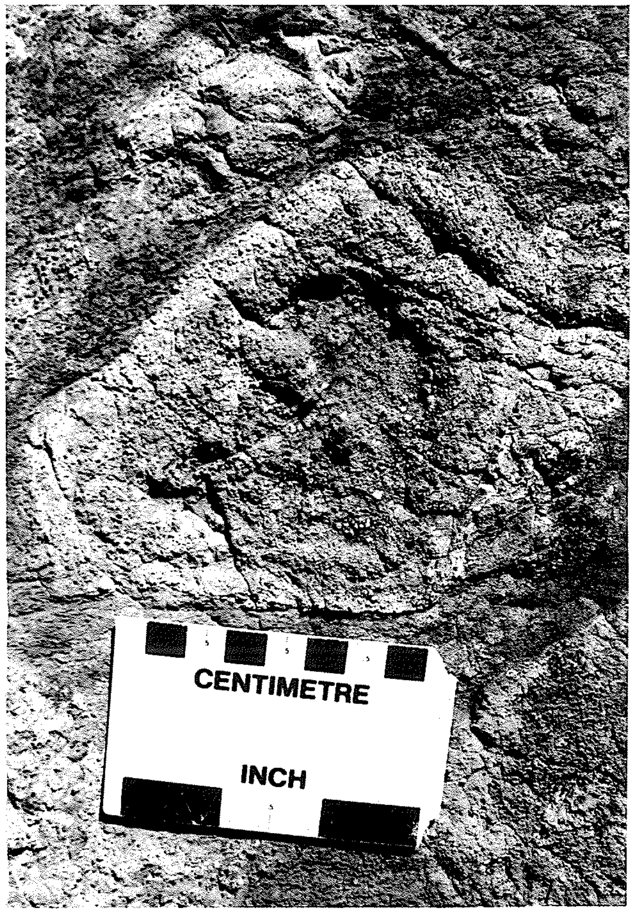


**Figure 23.** Rock outcrop photograph of a polygonal fragment with a light-coloured complete rim, surrounded by more normal, broken, vesicular fragments that lack rims.