THE UNIVERSITY OF HULL

The sedimentology of coarse grained hyperconcentrated flow deposits within modern and ancient volcaniclastic and alluvial fan sequences

being a Thesis submitted for the Degree of

Doctor of Philosophy

in the University of Hull

by

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Mount Saint Helens 1987

"A handful of sand is an anthology of the universe."

David McCord.

ABSTRACT

A minor eruption of Mount Saint Helens in Washington State U.S.A. in 1984, triggered the formation of a debris flow in the headwaters of the North Fork Toutle River. As the debris flow progressed downstream it transformed through the incorporation of water and the loss of sediment and within 34 kilometres became a muddy flood. The deposits produced by the transforming flow and associated recessional flows that followed in its wake, exhibited a coarse grained depositional continuum from debris flow to stream flow, including deposits with intermediate sedimentological characteristics termed "hyperconcentrated flow deposits".

The systematic and detailed sedimentological analysis of these deposits, combined with information concerning the characteristics of the flow, has allowed the delineation of hyperconcentrated flow deposits within the debris flow/stream flow depositional continuum and hence the establishment of criteria for the recognition of coarse grained hyperconcentrated flow deposits in the volcaniclastic environment of Mount Saint Helens. Hyperconcentrated flow deposits are generally homogeneous, matrix-supported, unstratified (except where defined by sub units), have sorting characteristics intermediate between debris flow and stream flow and can exhibit a bimodal, generally non imbricate, clast fabric as a function of clast size. Coarse-tail inverse grading may occur but it is weak, or restricted to sub units. Use of

these criteria enabled the recognition of hyperconcentrated flow deposits within depositional sequences produced earlier in the eruptive history of Mount Saint Helens.

The analysis of Permo-Triassic alluvial fan deposits on the Isle of Lewis Scotland, revealed that elements of the debris flow/stream flow depositional continuum could be recognised by the application of the criteria established in the volcaniclastic environment of Mount Saint Helens.

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I would like to acknowledge Mr Mathew Yuill who identified my first fossil find in August 1977 and in doing so started my career in geology. I would like to thank Peter and Elliot Ross without whom holidays on Iona where my interest in geology was maintained and broadened, would not have been possible. I would also like to thank Mrs Muriel Sword for her encouragement over many years.

Last, but not least, I am eternally grateful for the help, advice and support of my parents and sister.

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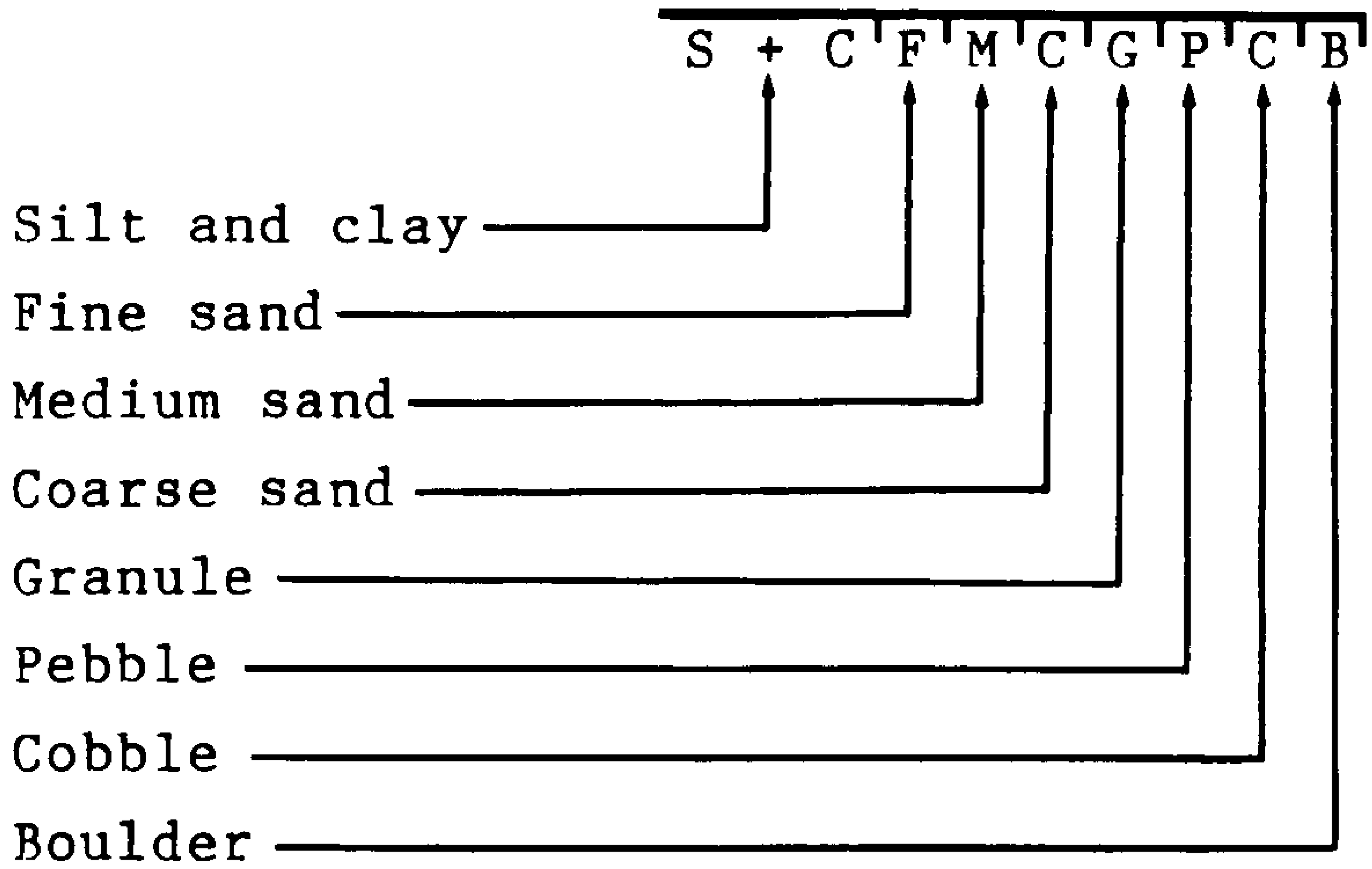

A.2. Nature of contacts between depositional units

——— Sharp

— — — Sharp to gradational

------- Gradational

B. Statistical analysis

B.1. Regression line analysis

n = number of measurements

r = linear correlation coefficient

a = correlation significance level

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n = number of measurements

$\bar{\theta}$ = mean a-axis orientation

$\bar{R}$ = mean resultant length

a = level of significance

CHAPTER 1

INTRODUCTION

1.1 SCOPE

In some regions of the world one of the most threatening natural hazards to human life and property is that of debris flow, in Japan alone ninety lives a year on average, are lost as a result of this phenomenon (Takahashi, 1981). Debris flows are not only the concern of engineers who try to develop measures to counteract the effects of this natural hazard, but they also form a focus of attention for geologists who analyse deposits attributable to debris flows.

Debris flows are described by Middleton and Hampton (1973, 1976) as types of sediment gravity flow. According to Middleton and Hampton a sediment gravity flow, which is synonymous with mass flow, consists of an intimate mixture of sediment and water that moves downslope under the action of gravity. Debris flows represent a profoundly different mechanism of sediment transport and deposition from that of water flows (Costa, 1988). Water flows can be regarded as Newtonian fluids which by definition, will flow under any applied shear stress with viscosity remaining constant, at a constant temperature (Pierson and Costa, 1987). Shear stress may be considered as a distributed force that acts parallel with a surface (Allen, 1985). Newtonian fluids lack strength, this is in contrast to debris flows which are non-Newtonian fluids: debris flows will not flow until a minimum shear stress, termed the yield strength, has been exceeded (Pierson and Costa, 1987).

Debris flows are known to be a significant sediment transport and depositional process on land (Takahashi, 1981). However, it was not until the work of Blackwelder (1928) in semi-arid regions, that the importance of debris flow became widely recognised. Prior to Blackwelder (1928) researchers, for example Gilbert (1882), presumed that alluvial fans were formed by running water only. Since the work of Blackwelder (1928), debris flows have been recognised not only on alluvial fans (Blissenbach, 1954; Hooke, 1967), but all over the world in a wide range of sedimentary environments. Deposits attributed to debris flow have been discovered within Archaean sequences in Canada (Tassē _et_ _al_., 1978), indicating that the debris flow mechanism of transporting and depositing sediment has been operational since early in the history of the Earth. The occurrence of debris flow is not restricted to this planet as volcanic associated mass flows (or lahars) have even been recognised as having formed on the surface of Mars (Christiansen, 1989).

Subaerially on Earth, debris flows have been observed in association with major fault zones (Sharpe and Nobles, 1953; Pierson, 1980), in glacial environments (Lawson, 1982) and in the sedimentary environs of stratovolcanoes (Waldron, 1967; Pierson, 1985a). The conditions required to produce these debris flows include abundant unconsolidated sediment, steep slopes and abundant amounts of water (Costa, 1984). The water sources are usually rainfall or snowmelt, but water can also be derived through glacial and volcanic associated lake bursts (Costa, 1984). The initiation of such flows either involves the production of a landslide or slump which then transfers to a debris flow (Johnson, 1970; Lawson, 1982; Pierson, 1985a) or can be the result of a purely water/ sediment interaction (Johnson, 1984; Pierson, 1985a). In the subaqueous environment, debris flows have been recognised in association with submarine fans (Walker, 1978) and can occur on a huge scale (Embley, 1976).

Johnson states that debris flows can be considered as gravity induced mass movements intermediate between land-slides and water flooding, with mechanical characteristics different from either of these processes. This continuum of flow types is not conceptual, since Bull (1962) discovered that in addition to mudflows (mudflow is a subcategory of debris flow [Lowe, 1979, 1982]), flows intermediate in character between stream flow and mudflow exist and can be found on alluvial fans. Soon after Bull's (1962) study, Beverage and Culbertson (1964) proposed a terminological scheme in which flows with intermediate sediment transport characteristics, between debris flow and normal stream flow, were termed "hyperconcentrated".

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1.2. THE DEBRIS FLOW/STREAM FLOW CONTINUUM

Beverage and Culbertson's (1964) terminological scheme was based upon observations of highly concentrated flows in the Colorado River and other American river systems. Beverage and Culbertson defined hyperconcentrated flow as occurring when the ratio of the weight of dry sediment to the weight of water/sediment mixture exceeded 40%, that is 20% by volume, however this limit is quite arbitrary. Despite the use of such arbitrary limits, Beverage and Culbertson's graph of sediment concentration versus volume of water per unit volume of water/sediment mixture, (figure 1.1), is a good pictorial illustration of the mud flow (or debris flow) to normal stream flow continuum.

The basic characteristics of hyperconcentrated flow have been observed in the field. Turbulence, the primary support mechanism of sediment in a clear water flow, is damped in hyperconcentrated flow, with the flow having the appearance of flowing concrete, with a smooth oily surface (Beverage and Culbertson, 1964). Within highly concentrated sediment flows laminar flow may develop with the formation of plug flow (Johnson, 1970; Lawson, 1982). A plug is a zone within a highly concentrated flow in which there is little or no internal deformation and the yield strength is generally not exceeded (Johnson, 1970). Despite their highly concentrated nature, such flows can travel at between 0.5 and 20 m/s (Takahashi, 1981; Costa, 1984). Observations of flows

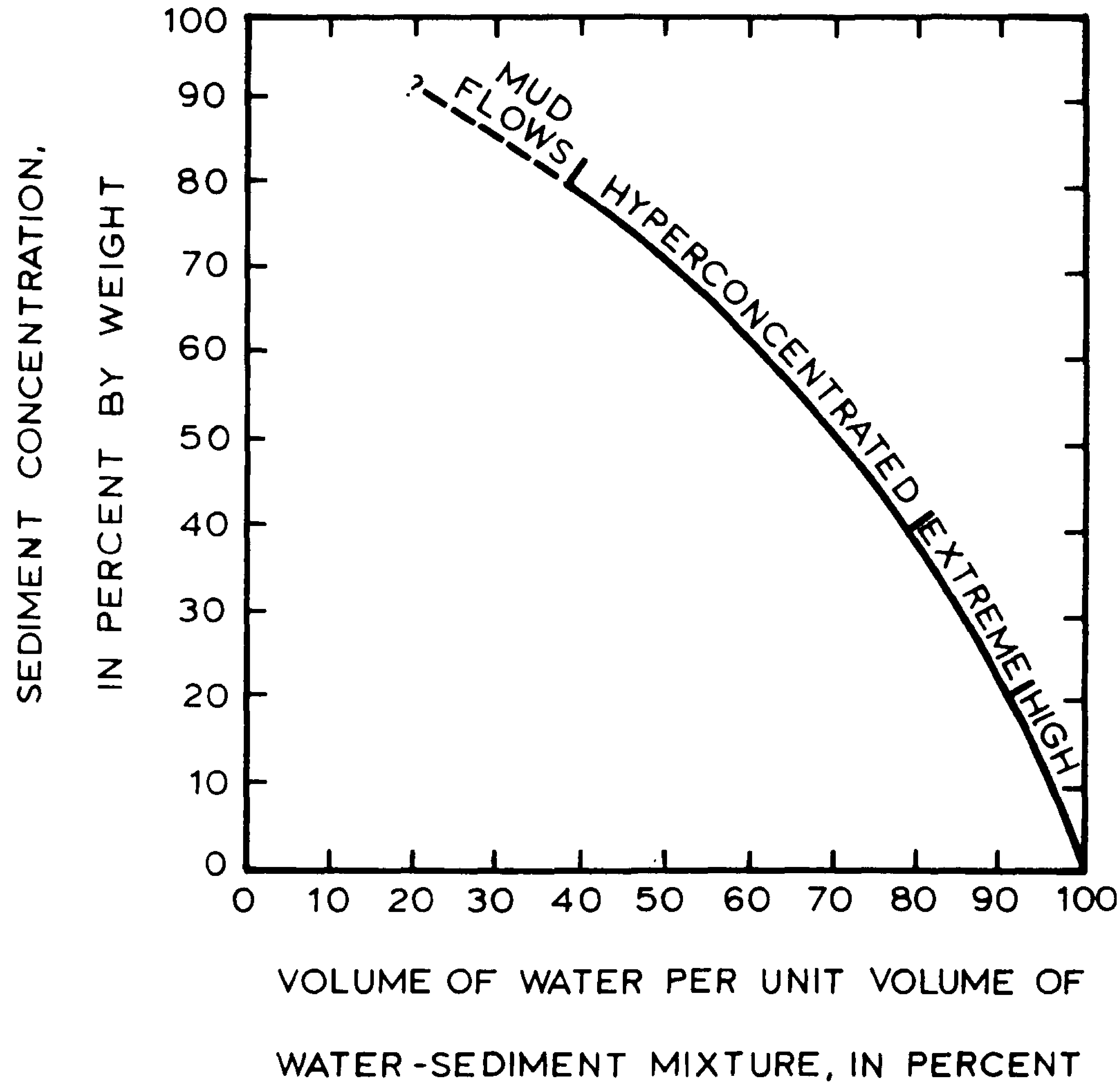


Figure 1.1. The relation between sediment concentration and volume of water per unit volume of the water-sediment mixture, with suggested terminology (from Beverage and Culbertson [1964]).

in the field have been supplemented by laboratory analysis, which has been conducted by researchers mainly in China and America. This has yielded much information on the mechanics of sediment transport and deposition in flows with high concentrations of sediment. The experimental investigations conducted using fine grained sediment have shown that with increasing sediment concentration in a flow, the fluid density and viscosity of the water/sediment mixture increases (Simons et al., 1963; Dai et al., 1980; Wan, 1982). This causes clast fall velocity to decrease and hence sediment transport rates to increase (Nordin, 1963; Simons et al., 1963; Howard, 1966; Graham and Bradley, 1982; Wan, 1985). Turbulence as observed in the field becomes damped and can be totally eliminated (Hino, 1963; Howard, 1966; Dai et al., 1980; Itakura and Kishi, 1980; Qian et al., 1980; Wang et al., 1983; Wan, 1985). This results in the decrease of bedform height and the eventual cessation of bedform formation (Wan, 1985; Bradley, 1986). Eventually, with increasing concentration a non deforming rigid "plug" region may develop, below which there is laminar shear (Wang, et al., 1983).

With increasing sediment concentration as described above the absolute concentration limits at which a flow attains yield strength and eventually becomes homogeneous exhibiting plug flow, varies according to the composition of the water/sediment mixture. A flow with increasing clay concentration acquires yield strength at a lower concentration than a flow with increasing concentration of coarse particles (figure 1.2). This variation has been used by Pierson and Costa (1987), to produce a classification scheme based upon both sediment concentration and mean velocity (deformation rate), rather than having sediment concentration as the only variable, as in Beverage and Culbertson's (1964) suggested terminological scheme. The divisions between different flow types, represent major rheological boundaries being crossed as sediment concentration increases (figure 1.3). The stream flow, hyperconcentrated flow boundary represents the transition from Newtonian to non-Newtonian behaviour, with the acquisition of yield strength. Pierson and Costa (1987) define debris flow as occurring in a sediment/water mixture when the yield strength rapidly increases. This corresponds to the bends in the graph of yield strength versus sediment concentration (figure 1.2).

The term "hyperconcentrated", as used by Pierson and Costa (1987), after Beverage and Culbertson (1964), has been used by several other researchers to describe sediment/water mixtures in which the ratio of the weight of dry sediment to the weight of sediment/water mixture is high. It has been used mostly in association with experimental investigations (Howard, 1966; Wan, 1982, 1985; Qian *et al.*, 1983; Wang *et al.*, 1983; Qian and Wan, 1986). In addition, Nemec and Muszyński (1982); Fisher and Schminke (1984); Pierson and Scott (1985) Smith (1986, 1987, 1988) and Scott (1988a), have

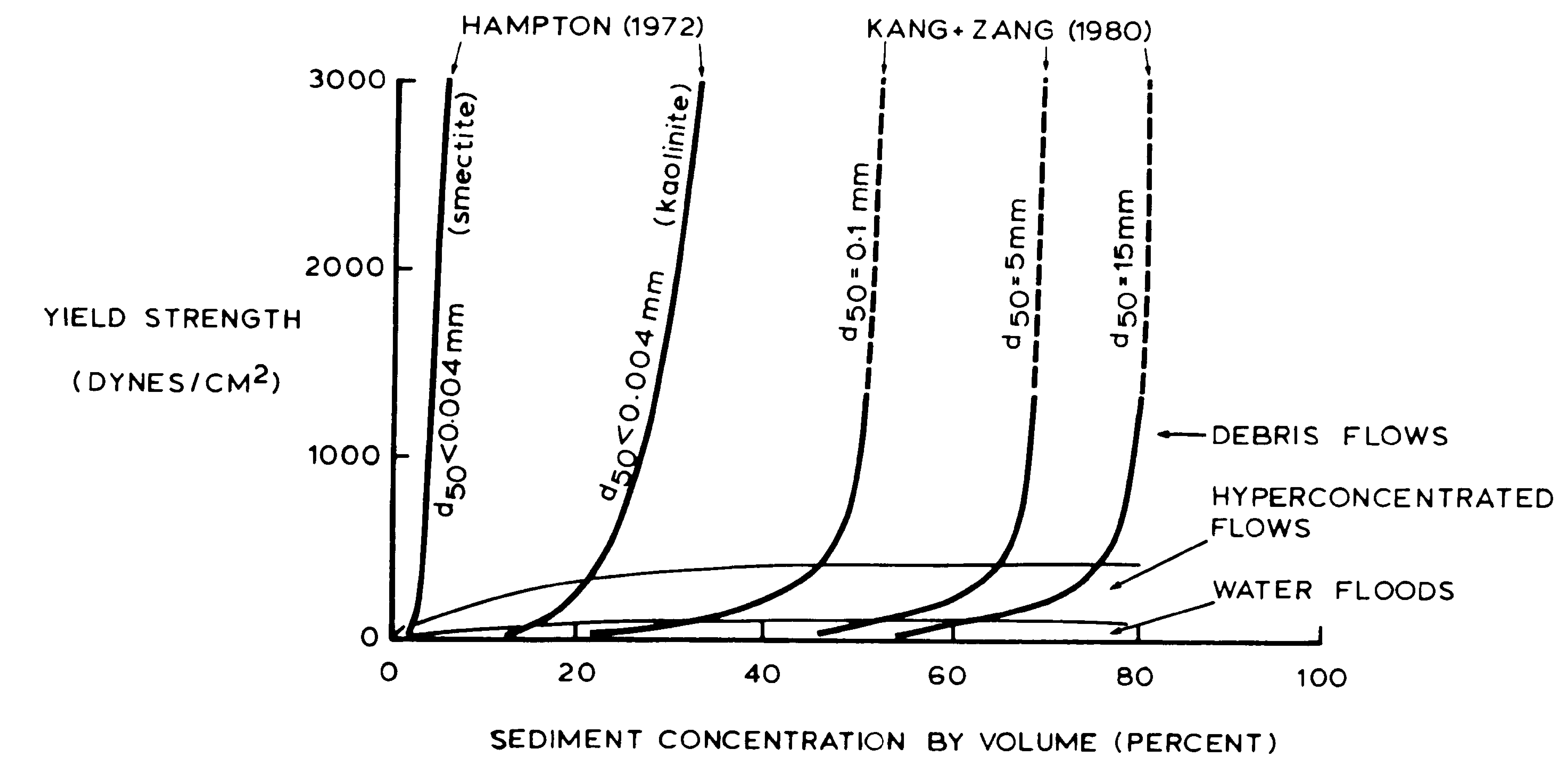
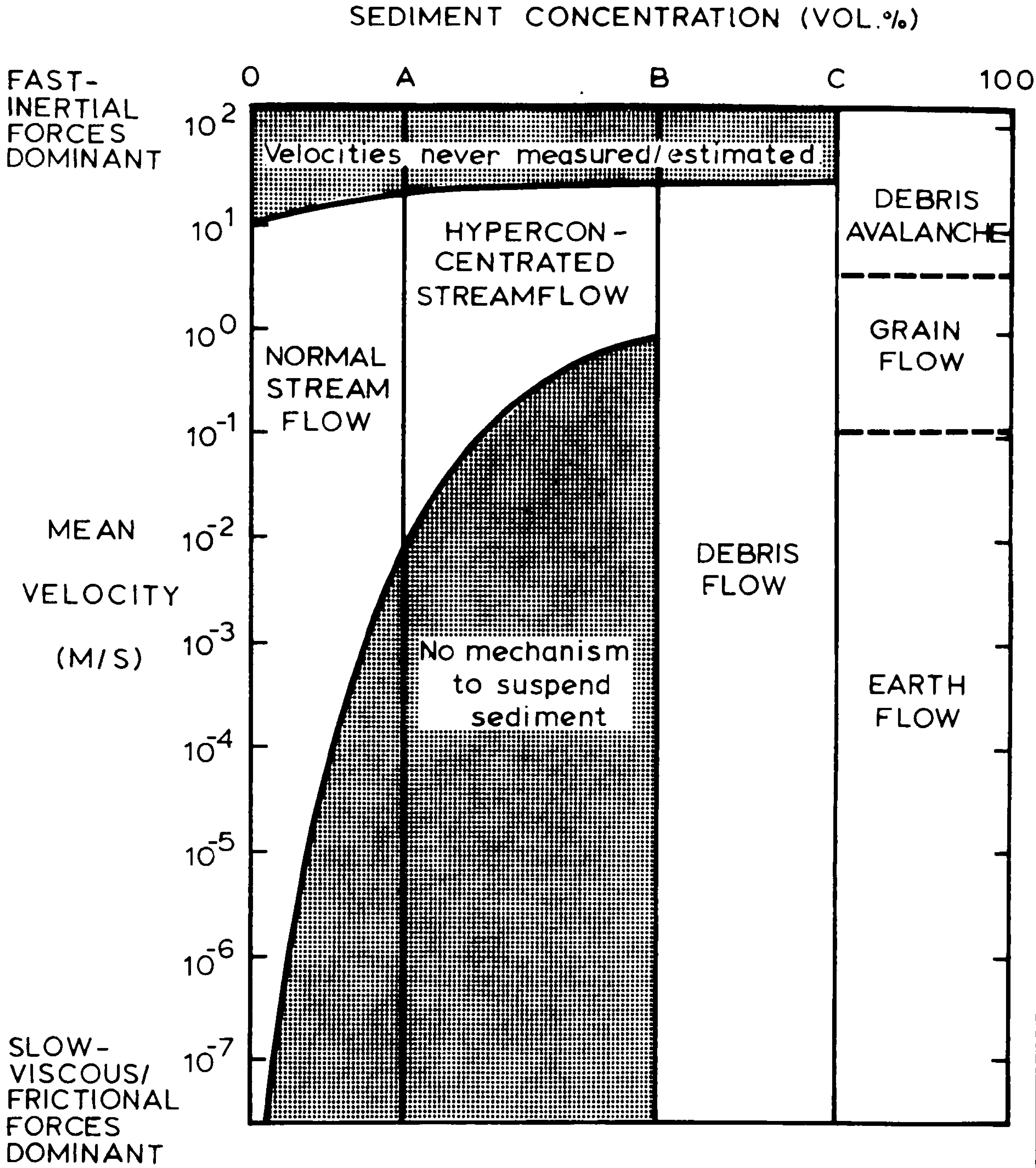


Figure 1.2. A classification of sediment laden flows based on shear strength and sediment concentration from Costa (1988), data from Hampton (1972) and Kang and Zhang (1980). Note that the flows with coarser particles acquire yield strength at higher concentrations than flows with finer particles, in particular, the clay-water mixtures. The intersection of each curve with the abscissa marks the transition from normal stream flow to hyperconcentrated flow (boundary A, figure 1.3). Abrupt steepening of the slope in each curve marks the approximate transition from hyperconcentrated flow to debris flow (boundary B, figure 1.3).



FLUID TYPE	NEW-TONIAN	NON-NEWTONIAN	
INTERSTITIAL FLUID	WATER	WATER + FINES	WATER + AIR + FINES
FLOW BEHAVIOR	LIQUID	PLASTIC	

Figure 1.3. Pierson and Costa's (1987) proposed rheologic classification of subaerial sediment-water flows. It is based upon sediment concentration and mean velocity (deformation rate), the boundaries A, B and C represent major rheological boundaries being crossed, see figure 1.2.

all used "hyperconcentrated" to describe highly concentrated sediment/water flows or deposits attributable to them.

1.3. THE STATEMENT OF THE PROBLEM

As seen in the last section, Beverage and Culbertson's (1964) general classification and terminology have been adopted by several researchers and in particular by investigators concerned with experimental studies of high concentration fluids. However, deposits attributed to hyperconcentrated flow as defined by Beverage and Culbertson are rare. This is despite the considerable number of sedimentological studies conducted in contemporaneous sedimentary environments where highly concentrated flows occur. The bulk of researchers attempt to classify coarse grained deposits as being produced for example from either some sort of mud flow, debris flow, or by stream flow processes (eg. Schultz, 1984) and not by flows termed hyperconcentrated, or indeed by flows described as having intermediate characteristics between debris flow and stream flow. Some researchers have used rather ambiguous terms to describe sediment/water flows: for example Larsen and Steel (1978) who use the term "low concentration debris flow". Hence, the reality of a flow continuum, as defined by Beverage and Culbertson (1964), does not appear to have been fully realised and utilised and thus intermediate or hyper-concentrated flow deposits have been largely unrecognised. Notable exceptions are the studies of Bull (1962, 1963, 1964), Lawson (1982) and Nemec and Muszyñski (1982) who have studied deposits which they infer as being produced from flows intermediate between debris flow and normal stream flow.

A major breakthrough in the investigation of hyperconcentrated flow deposits occurred following the 1980 eruption of Mount Saint Helens in the U.S.A., where a number of sedimentological investigations were conducted on the eruption associated mass flow deposits. Researchers realised that within the mass flow depositional sequences, deposits attributable to hyperconcentrated flows were discernible and attempts were made at their characterisation (Pierson and Scott, 1985; Scott, 1988a). In addition to these advances, Smith (1986), also working on volcaniclastic mass flow deposits in the north west U.S.A., produced some criteria for the recognition of hyperconcentrated flow deposits, based largely upon deposits in the geological record. These criteria include bimodal orientation of clast a-axes and non or horizontal stratification but no cross stratification.

Although these works represent a major contribution in the understanding of hyperconcentrated flow deposits, they lack detailed systematic sedimentological analysis, of inferred hyperconcentrated flow deposits and the precise delineation of hyperconcentrated flow deposits within the debris flow/stream flow deposit continuum. In addition, the results of these investigations on volcaniclastic hyperconcentrated flow deposits have not been applied to other sedimentary environments: for example, on alluvial fans where it can be suggested from the work of Bull (1962, 1963, 1964), that analogous deposits may occur.

1.4. THE OBJECTIVES

It has been shown in the preceding sections that there exists a continuum between debris flow and stream flow. Flows from this continuum occur in a wide range of different subaerial sedimentary environments and fine grained corollaries have formed the focus of laboratory investigations, yielding the flow characteristics of flows in the continuum. However, despite advances made through the examination of inferred hyperconcentrated flow deposits, in particular at Mount Saint Helens, there are gaps in our knowledge of the deposits produced from hyperconcentrated flows, especially the delineation of hyperconcentrated flow deposits within the debris flow/stream flow deposit continuum. Hence the primary objective of this study is to delineate hyperconcentrated flow deposits within the debris flow/stream flow deposit continuum through detailed sedimentological analysis, with the production of a set of criteria for their recognition. This major part of the study is based on depositional sequences in the volcaniclastic environment, where research on hyperconcentrated flow deposits has been centred. The secondary objective of this study is to use the criteria established in the volcaniclastic environment, in order to recognise hyperconcentrated flow deposits within depositional sequences of an other sedimentary environment.

1.5. THE ORGANISATION OF THE THESIS

The results of a detailed investigation of deposits produced at Mount Saint Helens in 1984, from a mass flow that underwent flow transformation, forms the basis of chapter two. These deposits are characterised and related to the original flow properties, in order to delineate hyperconcentrated flow deposits within the debris flow/stream flow deposit continuum. The results of that investigation, together with the results obtained from the examination of deposits produced by a mass flow in 1982, were then used in the study of mass flow deposits produced in the last 40,000 years at Mount Saint Helens, the findings of which are presented in chapter three.

Chapter four presents the conclusions of chapters two and three and assesses the applicability of these conclusions to other sedimentary environments. The sedimentological investigations conducted in Permo-Triassic alluvial fan deposits, where the results of chapters two and three were applied, are presented in chapter five. Chapter six is a summary of the complete work and presents suggestions for further research.

CHAPTER 2

THE DELINEATION OF HYPERCONCENTRATED FLOW DEPOSITS WITHIN A VOLCANICLASTIC MASS FLOW SEQUENCE PRODUCED IN 1984, AT MOUNT SAINT HELENS

2.1. INTRODUCTION

2.1.1. Sedimentological setting

Mount Saint Helens in south west Washington State U.S.A. is one of the Cascade Range of Quaternary stratovolcanoes that occur in a 1000 km arc between northern California and British Columbia (Figure 2.1). The Cascade Range has been an active continental margin volcanic chain from the Eocene to the present day and represents the surficial expression of the subduction of the Pacific plate beneath the North American plate (Riddihough, 1977).

The eruptive history of Mount Saint Helens, which has been dominated by andesitic and dacitic volcanism, began approximately 40,000 years ago. However, much of the pre-1980 volcanic cone formed during the last 2,500 years (Mullineaux and Crandell 1981). Prior to the recent phase of volcanic activity which began in March 1980, eruptions of Mount Saint Helens have produced many lahars. The deposits of these lahars, together with fluvial sediments, have formed the valley fills in the Mount Saint Helens drainage systems

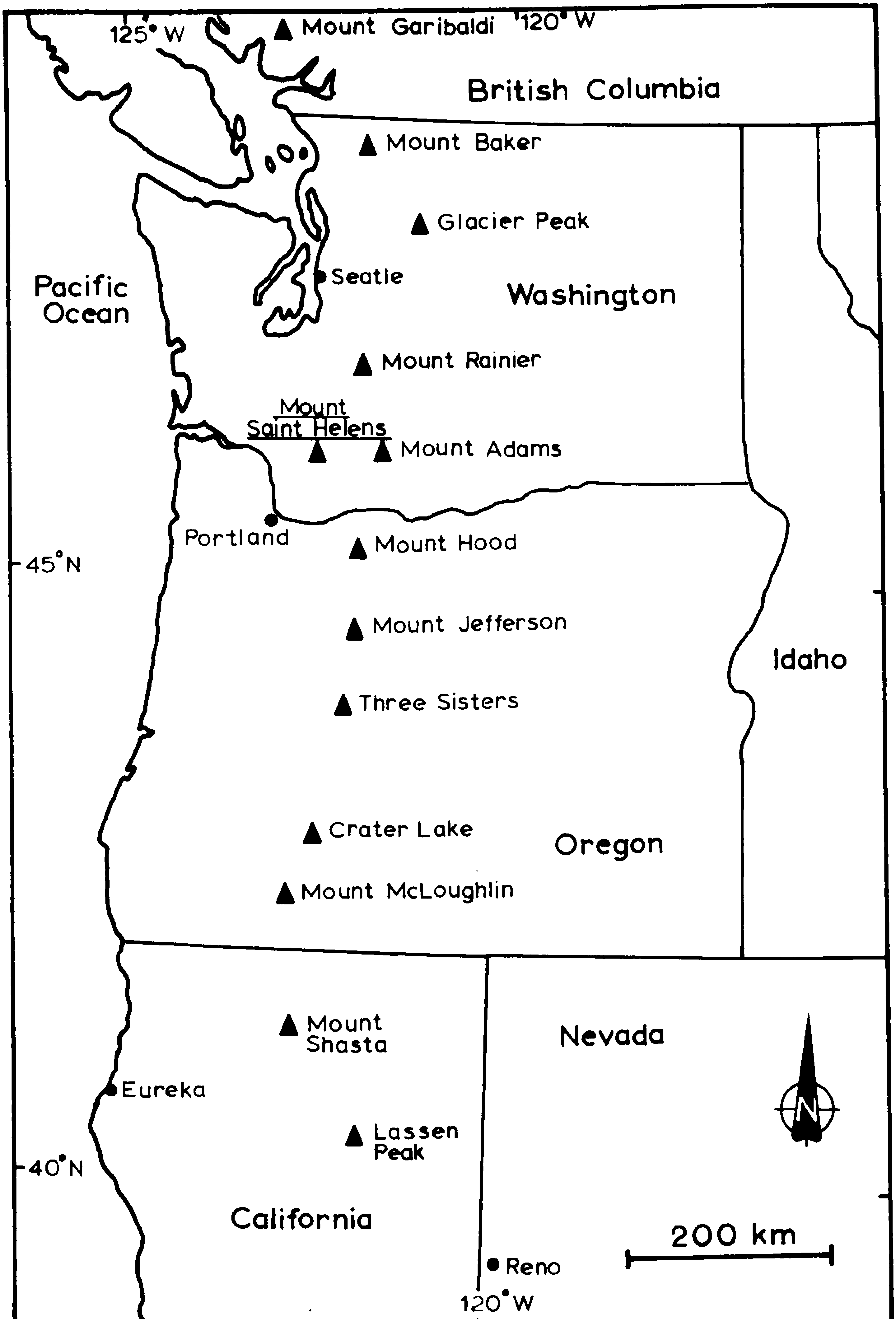


Figure 2.1. Map of the north west U.S.A. showing the location of Mount Saint Helens within the Cascade Range of volcanoes.

(Mullineaux and Crandell, 1962). The 1980 volcanic activity of Mount Saint Helens culminated in the May 18th eruption which devastated a large area north of the volcano with the passage of a blast induced pyroclastic flow. In addition, the eruption removed a large portion of the north side of the mountain which avalanched into the upper North Fork Toutle River (figure 2.2). From water saturated parts of the avalanche a voluminous mass flow was produced, which flowed down the North Fork Toutle River and eventually entered the Columbia River over 80 km downstream. The eruption also triggered mass flows in the South Fork Toutle River, on the volcano's south west flank and in the river systems to the south east (Janda et al., 1981), (Figure 2.2).

2.1.2. Previous studies on modern Mount Saint Helens mass flows and their deposits

Following the major eruption of Mount Saint Helens in 1980, there have been several investigations concerning the eruption-triggered mass flows and their deposits. Janda et al. (1981) presented a general review of all the mass flows that occurred as a result of the 1980 eruption. Brief reference is made to the velocity of the flows, which varied from 40 m/s near the cone to 1.5 m/s further downstream, in addition to the thickness (a few cm up to 4 m) and extent of the deposits produced from the mass flows, but there is no detailed sedimentological characterisation of the sequences.

Figure 2.2. Mount Saint Helens and the surrounding area, showing the 1980 debris avalanche and the river systems draining the cone. The inset map shows Mount Saint Helens in relation to the Columbia River and south west Washington State. Maps are derived from U.S.G.S Professional Paper 1250.

Fairchild (1985) describes the initiation of the most voluminous mass flows which were produced in the North and South Forks of the Toutle River on the west side of Mount Saint Helens. The North Fork Toutle River lahar was initiated through slumping of water saturated parts of the debris avalanche into the river system, at the same time as the South Fork Toutle River lahar was initiated through snow melt associated with a pyroclastic flow. Fairchild (1985) presents undetailed generalised descriptions of the deposits produced by these two lahars (which show a downstream decrease in mean grain size) and in addition presents some grain size distribution analyses which indicate a clay component of less than 1%. Gilkey (1983) also described the North and South Fork Toutle River lahars and their associated deposits, and also found a downstream decrease in mean grain size of the deposits in a downstream direction. In an analogous study to that of Fairchild (1985), Pierson (1985b) examined the initiation and flow behaviour of the Pine Creek and Muddy River lahars that occurred on the south east side of Mount Saint Helens and calculated lahar velocities from superelevated mudlines around bends. Major (1984) presents an account of the formation and flow behaviour of lahars on the south west flank of Mount Saint Helens and describes deposit texture and fabric. A notable find was that a preferred planar clast fabric was developed with respect to the bedding surfaces of the lahar deposits.

Janda et al. (1981), Fairchild (1985), Gilkey (1983)

Pierson (1985b) and Major (1984) together present a good introduction to the 1980 Mount Saint Helens mass flows and their deposits. However, due to their wide non specific approach, detailed and systematic analysis of the deposits is lacking. Other works have been conducted that are more specific to certain aspects of the mass flows or their deposits. Fink et al. (1981) and Pierson (1985a) concentrate on flow dynamics and rheological behaviour. Fink et al. (1981) reconstructed the flow rheology of "mudflows" from the examination of deposits which involved the reconstitution of "mudflow" matrix. Pierson (1985a) measured the velocities and depths of actual flows that occurred between 1981 and 1983 on the south side of the volcano and determined their grain size distribution. Pierson noted that the fronts of debris flows were steep and that they had "hyperconcentrated" tails. The only other specific studies were concerned with the analysis of clast fabric within the mass flows, Mills (1984), Fritz and Ogren (1984) and, Major and Voight (1986). These three studies all found parallel to flow clast a-axis orientations with upstream dips in addition to clast a-axes orientations transverse to flow. Major and Voight (1986) also found a strong planar orientation of clasts parallel to bedding surfaces. No precise mechanism is presented by Mills, Fritz and Ogren or Major and Voight to explain the production of these clast fabrics. The fabric studies of Mills (1984) and Fritz and Ogren (1984) were not conducted in conjunction with a systematic sedimentological analysis of the host deposits.

In 1982 a minor eruption of Mount Saint Helens triggered a mass flow which entered the North Fork Toutle River. The flow is described and its deposits are noted by Pierson and Scott (1985) and Scott (1988a). Although much smaller than the 1980 North Fork Toutle River flows, the 1982 flow illustrated well the principle of flow transformation, where in a 15 km reach of the North Fork Toutle River, the mass flow diluted from a debris flow to "hyperconcentrated stream flow" with the production of a coarse to fine depositional sequence. An outline of the depositional sequence is given by Pierson and Scott (1985) with a fuller characterisation presented by Scott (1988a). The 1982 depositional sequence is composed of a fine grained, often stratified unit, with an inversely graded, coarser unit on top, which thins progressively downstream. The superimposed fine and coarse units are thought by Pierson and Scott (1985) and Scott (1988a), to document the downstream dilution and transformation of a debris flow to hyperconcentrated flow. This deduction was made by Pierson and Scott (1985) and Scott (1988a) although they did not actually observe the flow in the reach where the transformation took place. Pierson and Scott (1985) and Scott (1988a) do not present any analyses of clast fabric from the 1982 mass flow deposits.

The most recent eruption of Mount Saint Helens occurred in 1984 and triggered the formation of a mass flow which was much smaller in volume than any other eruption associated post-1980 mass flow (Pringle and Cameron, in press). The 1984 mass flow also travelled down the North Fork Toutle River and like the 1982 flow underwent flow transformation. Pringle and Cameron (in press) described the general flow characteristics and noted the coarse to fine nature of the deposits produced along the reach.

The 1982 and 1984 mass flows both exhibited a downstream continuum of flow processes from debris flow to stream flow with the production of a spectrum of depositional facies. However, detailed sedimentological characterisation of the deposits is lacking and their relationship to the processes of sediment transport and deposition within the transforming flows is minimal. Pierson and Scott (1985) produced a model (expanded by Scott [1988a]) which attempts to explain how the 1982 flow transformed through the incorporation of water from the channel in conjunction with the deposition of sediment. However, the transformation was not actually observed and hence the model produced must be largely conjectural.

Although some good work has been accomplished regarding the initiation of mass flows (eg. Fairchild, 1985), flow behaviour (eg. Fink <u>et al</u>., 1981) and the orientation of clasts in mass flow deposits (eg. Major, 1984), there is no unifying publication that incorporates systematic and detailed logging and deposit characterisation with clast fabric and granulometric analysis, together with the determination of sediment transport and depositional processes. In addition studies have been retarded by the adoption of confusing and misleading terminology with terms such as "lahar": Janda _et al_. (1981), Gilkey (1983), Mills (1984), Fairchild (1985), Pierson (1985a), Pierson and Scott (1985), Major (1984), Scott (1988a) and Pringle and Cameron (in press) and "lahar runout", Janda _et al_. (1981), Pierson and Scott (1985), Scott (1988a) and Pringle and Cameron (in press). These terms represent in a genetic sense, flows of volcanic debris and water, the latter being derived from the former through flow transformation. "Lahar" and "lahar runout" are also used to denote the deposits produced from these flows. From these works it appears that the whole stream flow to debris flow continuum is encapsulated by the term "lahar" with the sub-division, "lahar runout". However, there is no strict adherence to these terms as they are used interchangeably with terms such as debris flow, mud flow and hyperconcentrated flow, where hyperconcentrated flow is synonymous with lahar runout and debris flow with lahar or mud flow, (Pierson and Scott, 1985; Pringle and Cameron, in press). This confused situation with regard to terminology present in all publications related to Mount Saint Helens mass flows has led to the oversimplification and generalisation of deposit interpretation and has consequently tended to ignore the subtle variation in deposits through the debris flow/hyperconcentrated flow/stream flow continuum.

any sequential differences present in deposit characteristics in a downstream direction, which could indicate the evolution of the transforming flow.

2.2. THE 1984 MASS FLOW

2.2.1. The origin and observation of the flow

On May 14th, 1984 a volcanic explosion within the crater of Mount Saint Helens sprayed hot rocks and gases onto the snow covered west crater wall. This produced a mixture of rock debris, snow and ice which flowed from the crater into the headwaters of the North Fork Toutle River (figure 2.3 and plate 2.1A). Pringle and Cameron (in press), describe the mixture as an "avalanche slush-flow". The progress of the flow as it passed down the Toutle was observed by Pringle and Cameron in a helicopter and by other eyewitnesses. However, it is important to note that most of the observations were of the recessional flow phase which followed after the main flow and only once did Pringle and Cameron observe the oncoming main flow.

The detailed observations of Pringle and Cameron (in press) will be discussed in relation to the findings of this study in section 2.5. in the latter part of this chapter when the rheological behaviour of the flow is considered. However three key observations are worthy of note at this stage: 1) the "avalanche slush-flow" evolved into a "debris flow" in the headwaters of the North Fork Toutle River through the erosion and incorporation of material from the debris avalanche produced in the 1980 eruption, 2) the debris flow underwent flow transformation and dilution eventually forming

Figure 2.3. The crater of Mount Saint Helens and the 1980 debris avalanche. The path of the 1984 mass flow along the North Fork Toutle River, is marked. 0.0 and 9.2 denote the localities along the reach where the most proximal and the most distal deposits occur respectively. The circled X and Y with arrows, indicate the locations where the views in plate 2.1A and 2.1B were photographed. The base map and the path of the 1984 mass flow are from Pringle and Cameron (in press).

a "muddy flood" 24 km from the crater, 3) the flow had both precessional and recessional flood phases.

2.2.2. Channel characteristics

The Upper North Fork Toutle River system that drains the Mount Saint Helens cone is actively incising a channel system in the 1980 debris avalanche deposit. The headwaters proximal to the cone occur in a system of steep narrow channels (plate 2.1A) but these eventually coalesce to form a broad floored channel, about 9 km from the crater, which winds its way among the hummocks of the debris avalanche (plate 2.1B). The channel along the reach where the 1984 flow deposits remain, is broad floored, normally braided and varies from 100 to 250 m in width with a slope of generally less than 2°. The channel margins are terraces which were formed from normal fluvial activity in the early 1980's as the Toutle established and incised a channel in the unconsolidated debris avalanche.

2.2.3. The remaining deposits

The 1984 flow engulfed the normal fluvial system of the North Fork Toutle River with deposition occurring on the river terraces as well as in the channel (Pringle and Cameron in press). However, at the time of this study in the summer of 1987, most of the deposits produced from the flow had been

PLATE 2.1 [OVER]

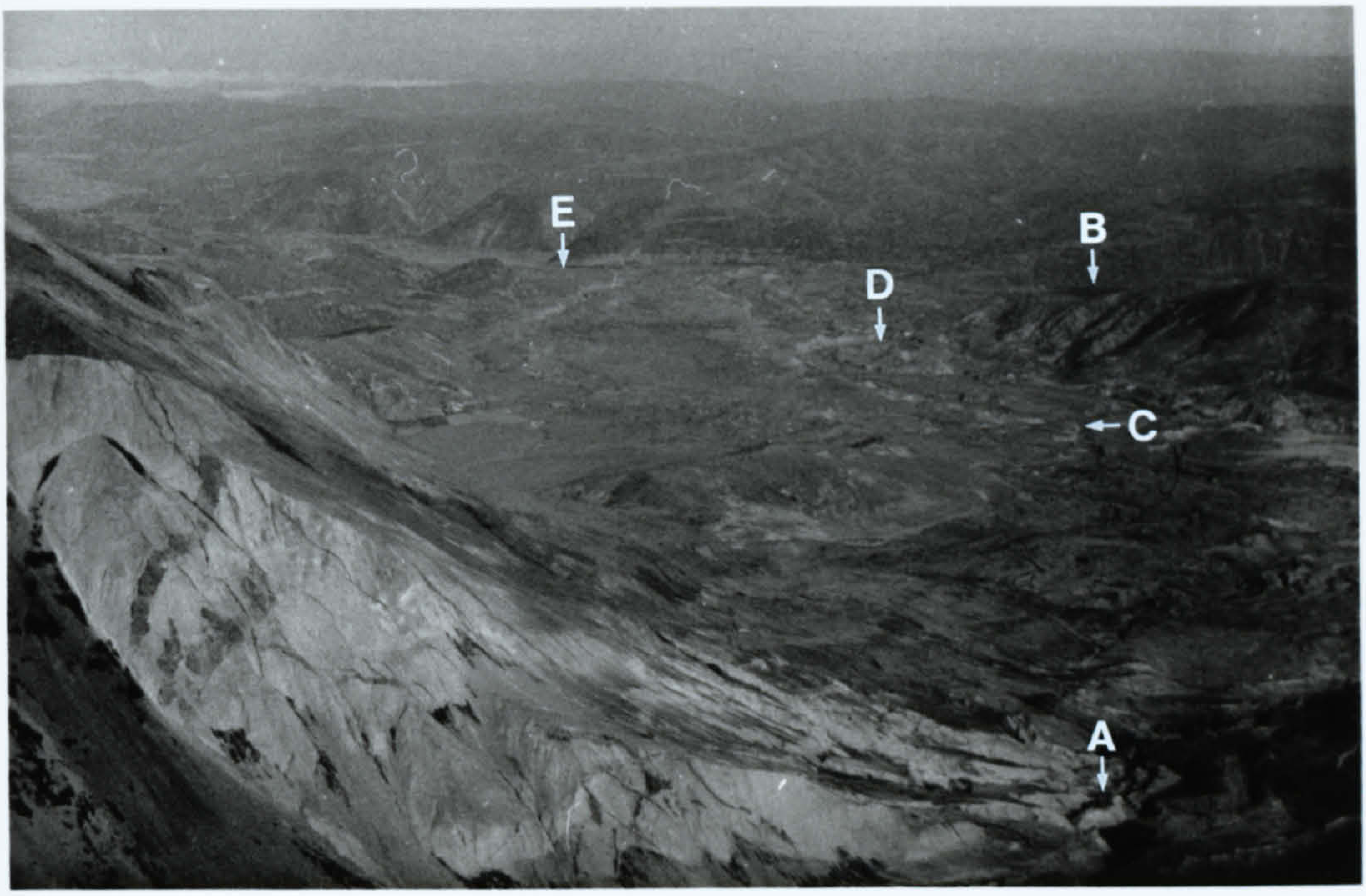
PLATE 2.1

A

View from above the crater of Mount Saint Helens looking north west along the North Fork Toutle River, within the 1980 debris avalanche. The west crater wall occupies the bottom left third of the view. Arrow A indicates the headwaters of the North Fork Toutle River, arrow B indicates the location of Coldwater Lake (figure 2.3) and arrows C, D and E refer to localities 0.0, 3.4 (plate 2.1B) and 9.2 respectively.

B

The North Fork Toutle River within the 1980 debris avalanche looking south west. The arrow indicates locality 3.4. The peak in the lower centre right of the view, is approximately 60 m above the level of the river.


E
B
D
C
A

eroded, with the only remaining deposits occurring in a 9.2 km reach of the Toutle River between 9 and 18.2 km from the crater (figure 2.3).

The deposits generally occur as single, bipartite or tripartite sequences in channel margin areas and occasionally on the river terraces (plate 2.2A and 2B). However, no mid channel deposits were in existence at the time of study. Since no other deposits from previous mass flow events were present in the 9.2 km reach, there was no confusion regarding the differentiation of the 1984 flow event sequences, which in all cases rested upon the pre-1984 flow fluvial sands and gravels.

PLATE 2.2 [OVER]

PLATE 2.2

A

Typical deposits (bounded by lines) at the channel margin in the vicinity of locality 0.0. The 30 cm scale bar is arrowed and the distance between the lines is 1.6 m. Flow was from left to right.

B

Typical deposits (bounded by lines) on the river terrace at locality 5.2. The thickness of the deposit between the lines is 35 cm. The direction of flow is away from the observer.

2.3. DESCRIPTION OF THE DEPOSITIONAL SEQUENCE

2.3.1. Introduction

The deposits of the 1984 flow are located along a 9.2 km reach of the North Fork Toutle River which starts 9 km from the crater of Mount Saint Helens. Figure 2.4 shows this reach within the debris avalanche, the location of the study sites which document the only remaining deposits and the downstream length of the exposures. The study sites have been labelled 0.0 to 9.2 according to their position in terms of distance in kilometres along the reach.

The deposits within the channel are mostly bipartite and are composed of a lower thick, coarse grained and generally inverse graded unit which is overlain by a much thinner, finer unit. The contact between these two varies in character from being sharp to gradational. The deposits on the terraces are, by contrast, predominantly single depositional units, directly comparable to the top unit within the bipartite channel sequence. However a few bipartite sequences with a lower coarser unit and a finer grained capping do occur occasionally on the terraces. The basal contacts of both the channel and terraced deposits are planar, never scoured and blanket the underlying pre-1984 flow fluvial deposits. Along the length of the reach there is a very profound change in the character of the lower thick units. These deposits which consist of polymodal boulder

LOCALITY		DEPOSIT LENGTH (m)	BANK	LOCALITY		DEPOSIT LENGTH (m)	BANK
0.0	C	14	S	3.7	C	7	N
0.7	C	35	S	4.3	T	35	N
1.0	C	20	N	4.5	T	10	N
1.7	C	40	S	5.2	C/T	40	N
2.0	C	15	N	6.5	C	38	N
2.7	C	20	N	7.3	C	35	N
3.0	C	5	S	8.0	C	8	S
3.4	C	10	N	8.5	C	16	S
3.4	T	30	N	9.2	C	12	N

C = CHANNEL DEPOSIT, T = TERRACE DEPOSIT
C/T = DEPOSIT ON SLOPING CHANNEL MARGIN
S = SOUTHERN BANK N = NORTHERN BANK

Figure 2.4. The studied reach of the North Fork Toutle River, showing the locations of the remaining 1984 flow deposits. The table details deposit position and extent. The outline of this section of the river was derived from an unpublished U.S.G.S. map.

conglomerates in the proximal part of the 9.2 km reach, become progressively finer grained downstream with the occurrence of a stratified pebbly granule sand deposit at the most distal part of the reach. The boulder conglomerates are matrix to clast-supported and have a polymodal matrix which is uniform throughout the reach, even though the grain size of the unit may change in a vertical sense through coarse-tail inverse grading of the larger clasts.

The following descriptions were made from sections of deposits parallel to the channel along the reach from proximal to distal. In order to avoid constant repetition, a representative suite of deposits from among those indicated on figure 2.4, is described that illustrate the sedimentological variation downstream. Each description is based upon a detailed annotated log and is accompanied where necessary with a plate. The sorting and size distribution estimates used in the descriptions are based upon those suggested by Walker (1975a), and the grain size scale used in this section and subsequently is the Udden-Wentworth Grade Scale from Folk (1980). The scale bar used in all the plates is 30 cm in length and is marked off at centimetre intervals. The descriptions do not include grain size distribution data from sieve analysis or bed thickness and maximum particle size relationships and the distribution of fragile clasts, as these sets of data are best discussed separately in context with the findings of the other localities as a whole.

In several depositional units there is a well developed fabric indicated in general by pebble or cobble sized clasts, which may for example, show an a-axis parallel to flow orientation. However, in most of the described units, clasts display no visually apparent fabric. This does not necessarily indicate that there was no fabric development within the unit and so statistical analyses were conducted upon the clast orientation data the results of which are presented later in this chapter.

2.3.2. Descriptions of the depositional units along the reach

LOCALITY 0.0

General synopsis: a bipartite sequence in the channel margin composed of a lower non-graded, matrix to clast-supported, polymodal conglomerate, with a finer grained basal zone. The upper unit in the sequence represents a fine grained capping to the lower unit, (figure 2.5A, plate 2.3A).

Description of the lower unit: A tabular bed that varies in thickness from 1.5 to 1.6 m which contains boulder sized clasts. It is unstratified, structureless and has no visually apparent fabric. The matrix phase of this unit has a sharp to gradational contact with a well defined finer grained zone at the base which is devoid of cobbles. This basal zone, which varies from 5 to 12 cm in thickness, has no visible fabric or structure and blankets the pebble and gravel surface of the channel floor.

Description of the upper unit: a thin (up to 10 cm)

Figure 2.5. Representative logs of the depositional sequences at: A. locality 0.0, B. locality 3.0.

PLATE 2.3 [OVER]

PLATE 2.3

A

The depositional sequence preserved at locality 0.0. Note the lower thick matrix to clast-supported boulder conglomerate unit, overlain by a much thinner and finer grained capping. Flow was from left to right.

B

The depositional sequence, the base of which is marked, preserved at locality 3.0. Note the coarse-tail inverse grading in the lower thick matrix to clast-supported unit and the contrast between it and the lower unit at locality 0.0 (plate 2.3A). The lower unit is overlain by a thinner and finer grained unit, with which it shares a sharp to gradational contact (arrowed). Flow was from left to right.

laterally discontinuous, ungraded and unstratified pebbly granule sand bed that has no visually apparent fabric. The contact with the matrix phase of the lower unit below is sharp and planar. Large clasts embedded in the lower unit protrude through this upper unit.

LOCALITY 3.0

General synopsis: a bipartite sequence in the channel margin that has a lower matrix to clast-supported polymodal conglomerate, with basal inverse grading and an upper structureless finer grained capping (figure 2.5B, plate 2. 3B).

Description of the lower unit: a tabular bed that varies from 70 to 80 cm in thickness and contains clasts up to boulder size, it is unstratified with an inversely graded base and has no visually apparent fabric. The inversely graded base which grades into the rest of the unit above, lacks cobble sized clasts, stratification and any visually apparent fabric. Cobbles occur above 8 cm from the base and this marks the first well defined coarse-tail inverse grading along the reach.

Description of the upper unit: a 20 to 30 cm thick tabular, ungraded and unstratified pebbly granule sand bed which has a sharp to gradational contact with the unit beneath. It has no visually apparent fabric.

LOCALITY 3.4

Description: a stratified granule sand unit blanketing the river terrace (figure 2.6, plate 2.4A), which represents the on-terrace extension of the upper fine grained unit in a bipartite sequence in the channel margin. It varies from 30 to 50 cm in thickness and is composed of several thin laterally discontinuous sub units. The lowermost of these units (apart from locally developed thin sand and silt layers) are pebbly granule sands which show coarse-tail inverse grading and lateral variability in thickness over a minor pre-flow stream channel incised into the terrace (compare logs A and B on figure 2.6). The contacts between these inversely graded sub units are gradational and not sharp, in addition pebble sized clasts within the upper inversely graded unit in log A, figure 2.6, are orientated with a-axes orientated parallel to both flow direction and the bedding surface (not imbricated), (plate 2.4B and 2.4C). These lowermost units are cut out by a sequence of faintly laminated granule sand units above, which are separated by laterally discontinuous very thin layers composed of fine sand and silt. The laminae in the granule sands are horizontal and do not persist laterally for more than 60 cm. They vary from several grain diameters up to a few millimetres in thickness and are defined by horizons rich in sand and silt. Some of the laminae are subhorizontal and merge with other laminae at very low angles in a downstream sense. In association with the stacked inversely graded sub units at

Figure 2.6. Representative logs of the depositional sequence on the terrace at locality 3.4.

PLATE 2.4 [OVER]

PLATE 2.4

A

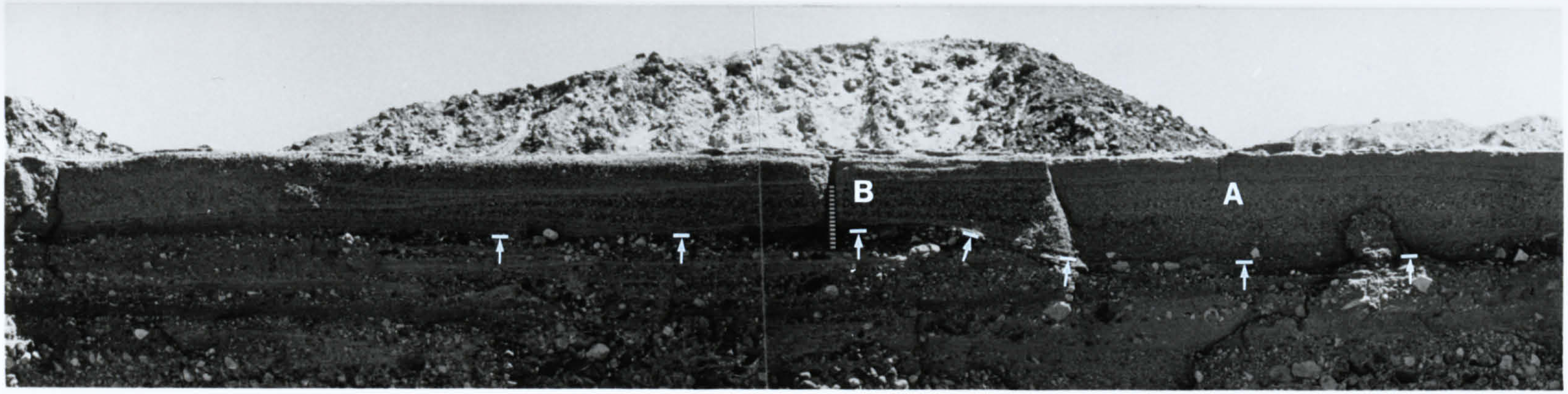
Pebbly granule sands on the terrace at locality 3.4, that represent an extension of the upper unit in a bipartite sequence in the channel. The deposits blanket a minor channel system cut into the terrace, the base of which is marked. Flow was from the right toward the viewer. Log sites A and B (in figure 2.6) are marked.

B

A section of a block from the upper inversely graded sub unit from log A, showing the inverse grading and preferential orientation of pebble sized clasts, with a-axes orientated parallel to the base of the unit. Flow was from left to right.

C

A bedding parallel section of the block described in B, showing the a-axes of pebble sized preferentially orientated parallel to flow. Flow was from left to right.


B
A

the base of the sequence there are completely homogeneous granule sand sub units with no laminae, clast grading or visually apparent fabric.

LOCALITY 3.7

General synopsis: a tripartite sequence at the channel margin which has three distinct superimposed units (figure 2.7A). These are: 1) a lowermost matrix to clast-supported polymodal conglomerate with inverse grading at the base, 2) a massive finer grained middle unit, 3) a fine grained laminated unit on top. Some large clasts project from the lower into the middle unit.

Description of the lower unit: a tabular bed that varies in thickness from 70 to 80 cm and which contains clasts up to boulder size. It is unstratified with an inversely graded base that contains no cobble sized clasts in the lowermost 12 cm and there is no visually apparent fabric. The basal zone is also unstratified, with no visually apparent fabric and grades into the matrix of the bulk of the unit above (plate 2.5A).

Description of the middle unit: a 15 to 20 cm thick tabular, unstratified and ungraded pebbly granule sand unit with no visible fabric (plate 2.5B). It has a sharp contact with the matrix phase of the lower unit.

Description of the upper unit: a 5 to 10 cm thick laterally discontinuous granule sand cap to the depositional sequence below, with which it shares a sharp to gradational

Figure 2.7. Representative logs of the depositional sequences at: A. locality 3.7, B. locality 4.5.

PLATE 2.5 [OVER]

PLATE 2.5

A

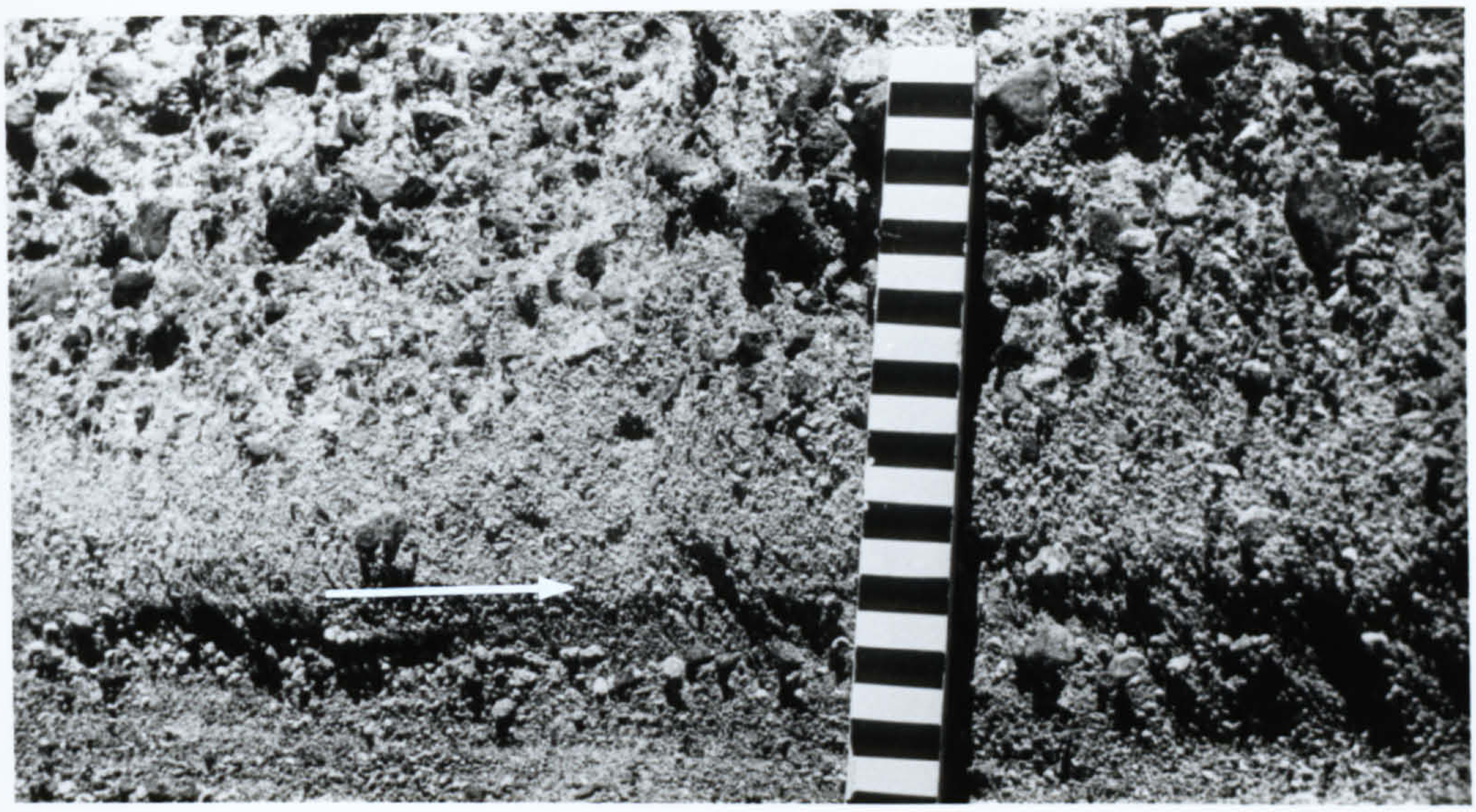
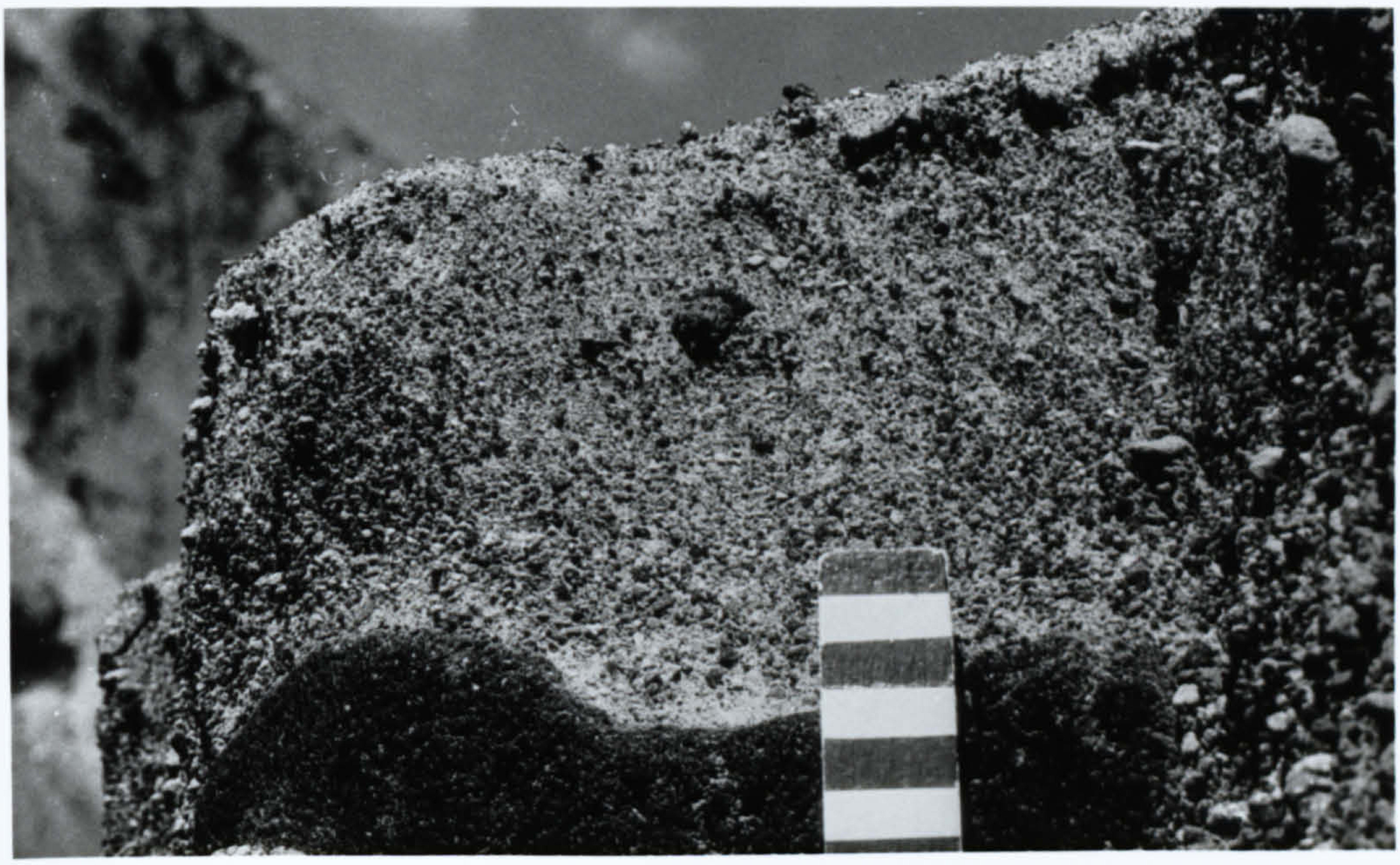
The basal zone of the lower unit at locality 3.7. The arrow marks the division between the unit and the unscoured underlying pre flow fluvial gravels. Of note is the coarse-tail inverse grading and the unstratified nature of the unit. Flow was from right to left.

B

The middle unit at locality 3.7, which in the centre of the view rests upon a cobble that projects from the lower unit. Note the homogeneous and unstratified nature of the unit. This unit is the direct lateral extension of the deposit below the laminated granule sand featured in C below. Flow was from left to right.

C

Laminated granule sand which forms the top unit in the tripartite sequence at locality 3.7, it was not present above the unit shown in B above. Note the sharp to gradational contact with the homogeneous unit below. The laminae are defined by vertical grain size variation and some of them merge in a downstream sense. Flow was from right to left.


contact. It has faint horizontal laminae which are defined by horizons rich in sand and silt (plate 2.5C). The laminae, which cannot be traced for more than 1.8 m (the length of the eroded exposure), vary from a few grain diameters, up to a few millimetres in thickness and show no discernible inverse or normal grading between them. Rare subhorizontal laminae merge at very low angles, in a downstream sense.

LOCALITY 4.5

General synopsis: a bipartite sequence on the terrace composed of a thick lower matrix to clast-supported polymodal conglomerate with basal inverse grading and a thinner fine grained unit on top. Within the lower unit there are several outsized clasts (figure 2.7B, plate 2.6A).

Description of the lower unit: an unstratified tabular bed which varies in thickness from 18 to 30 cm and has no visually apparent fabric. There are several outsized clasts that occur above the basal one third of the bed which is inversely graded. This inversely graded portion of the unit is unstratified and continuous with the matrix phase of the rest of the unit above. However, unlike the bulk of the unit above, pebbles and cobbles in the basal zone are clearly orientated with a-axes parallel to both flow direction and to the base of the unit (not imbricated).

Description of the upper unit: a laterally discontinuous and unstratified granule sand unit up to 7 cm in thickness, that has no visually apparent fabric. The sharp

PLATE 2.6 [OVER]

PLATE 2.6

A

The depositional sequence, the base of which is marked, on the terrace at locality 4.5. Note the coarse-tail inversely graded lower unit with a much thinner finer grained discontinuous capping on top. The boulder sized clast rests within the lower unit but above the basal zone of inverse grading. Flow was from right to left.

B

The depositional sequence, the base of which is marked, preserved at locality 5.2. Note the well developed coarse-tail inverse grading of the lower unit and the homogeneous nature of the upper finer grained unit. Some cobble sized clasts (arrowed) are preferentially orientated with a-axes parallel to flow with no imbrication. Flow was from right to left.

contact with the lower unit is broken by the protrusion of the outsized rafted clasts.

LOCALITY 5.2

At this locality, deposits extend over the channel margin which is gently sloping and thin onto the terrace. This represents the most voluminous deposit remaining in the entire reach.

Deposits at the channel margin

General synopsis: a bipartite sequence composed of a lower matrix to clast-supported unit with strong inverse grading, overlain by a finer grained capping (figure 2.8A, plate 2.6B).

Description of the lower unit: a laterally extensive tabular and unstratified polymodal conglomerate bed, that varies in thickness from 50 to 60 cm. Boulder sized clasts occur above the strongly inversely graded basal portion and project into the overlying unit. Discoid cobbles within and above the basal zone are orientated with a-axes parallel to the flow direction, with a/b planes parallel to the base of the bed.

Description of the upper unit: a laterally extensive, 15 to 20 cm thick, unstratified pebbly granule sand horizon which forms a cap with a sharp contact to the lower unit. Locally it contains orientated outsized clasts with poorly defined a/b planes that are orientated parallel to deposit

Figure 2.8. Representative logs of the depositional sequences at locality 5.2: A. in the channel, B. on the terrace.

base, and a-axes orientated transverse to flow direction.

At this locality on the sloping channel margin a 90 cm diameter boulder rests within and protrudes from the lower unit (plate 2.7A). Behind it there are four stacked boulders, producing a boulder jam. The large leading boulder in the jam appears to be "floating" within the matrix of the lower unit. However, on investigation it was revealed that the base of the boulder extends beyond the basal zone of the lower unit and has scoured a shallow trough in the pre-flow channel deposit where it rests. On the downstream side of the boulder there is a wedge of debris resting with a sharp contact on the boulder containing debris (plate 2.7A). This is a polymodal cobble conglomerate unit which is up to 18 cm thick but thins to less than 5 cm over the leading clast in the boulder jam. It is ungraded, unstratified and discoid clasts present are orientated with crude a/b planes parallel to the base of the deposit and a-axes orientated parallel to flow direction.

Deposits on the terrace

These deposits represent the direct lateral continuation on the terrace of the channel margin deposits described above. General synopsis: a bipartite sequence composed of a lower matrix to clast-supported inversely graded unit with a fine grained top (figure 2.8B, plate 2.7B).

Description of the lower unit: a tabular polymodal

PLATE 2.7 [OVER]

PLATE 2.7

A

A boulder jam within the depositional sequence (the base of which is marked) at locality 5.2. The lead boulder is fully 90 cm in height and penetrates the pre-flow gravels. Flow was from right to left. On the downstream side a wedge of coarse material (its sharp contact with the unit below is arrowed) thins against the boulder and represents a local repetition of the lower unit at this locality. A relatively thin, fine grained homogeneous upper unit caps the sequence.

B

The on-terrace extension at locality 5.2 of the channel depositional sequence in A above and in plate 2.6 B. Note the coarse-tail inverse grading and the lack of preferred clast orientation or stratification. The pen top marks the junction between the sequence and the pre-flow gravels. The lower unit has a gradational contact with a finer grained upper unit. Flow was from right to left.

pebble and cobble conglomerate that varies in thickness from 18 to 20 cm. It is ungraded, unstratified and has no visually apparent fabric. The lack of pebble sized clasts in the basal one third of the unit has produced coarse-tail inverse grading. This basal zone lacks stratification and visible fabric and rests with an almost gradational contact upon the pre-flow fluvial deposits.

Description of the upper unit: this is a 4 cm thick, laterally discontinuous, granule sand bed, that has a gradational contact with the lower unit. There is no visually apparent clast fabric.

LOCALITY 6.5

General synopsis: a bipartite sequence in the channel margin that is composed of a lower matrix to clast-supported polymodal conglomerate with basal inverse grading and an upper finer grained capping (figure 2.9A, plate 2.8A).

Description of the lower unit: a laterally extensive tabular bed varying in thickness from 55 to 60 cm. The largest clasts, which are cobbles, occur above the basal one third of the unit producing coarse-tail inverse grading. Discoid cobbles have a/b planes parallel to the base of the deposit, but a-axes are not preferentially orientated either parallel or transverse to flow.

Description of the upper unit: a tabular granule sand bed varying in thickness from 15 to 20 cm, resting with a sharp contact on the unit below. Faint horizontal laminae

Figure 2.9. Representative logs of the depositional sequences at: A. locality 6.5, B. locality 7.3.

PLATE 2.8 [OVER]

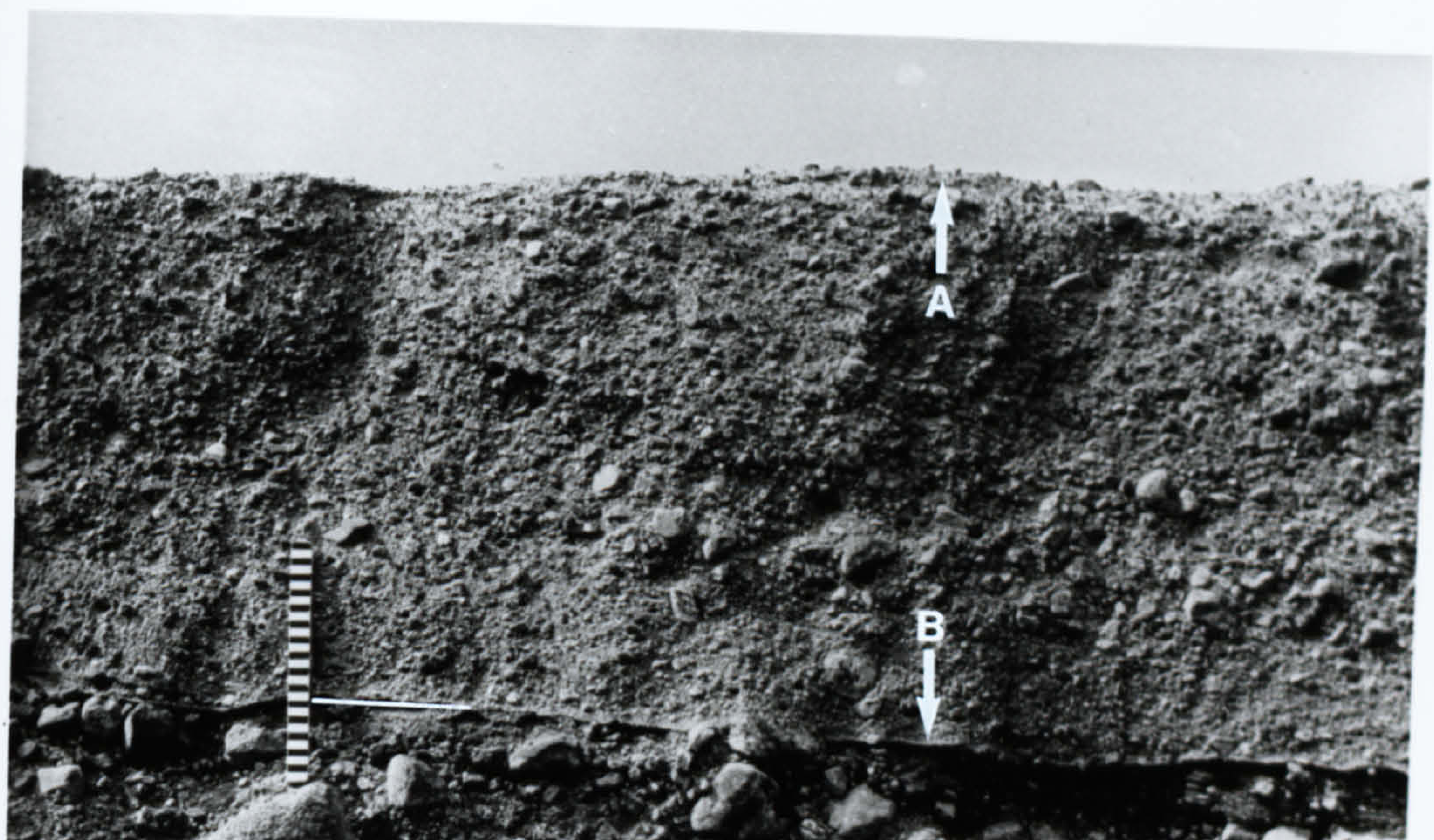
PLATE 2.8

A

The depositional sequence preserved at locality 6.5. Note the marked difference between the sequence (above the line) and the pre-flow fluvial deposits. The lower coarse grained matrix to clast-supported unstratified unit is coarse-tail inversely graded. Discoid cobbles (arrowed) are orientated with their a/b planes parallel to the deposit base. The finer grained horizontally laminated upper unit rests with sharp contact on the lower unit. Flow was from right to left.

B

The depositional sequence, the base of which is marked, preserved at locality 7.3. The lower unit dominates the sequence with the upper unit (arrowed A) restricted to a few centimetres at the top. The unstratified lower unit is a matrix-supported pebble and cobble conglomerate. The cobbles are restricted to the lower central portion of the bed. At the base of the bed there is a thin layer of sand and silt (arrowed B). Flow was from right to left.


A
B

are defined by silt rich horizons a few grain diameters to a few millimetres in thickness. The laminae do not merge in a downstream sense and grading relations between individual laminae are not discernible.

LOCALITY 7.3

General synopsis: a bipartite sequence in the channel margin that is composed of a lower matrix-supported polymodal conglomerate with basal inverse grading and a thin, unstratified, fine grained upper unit (figure 2.9B, plate 2.8B).

Description of the lower unit: a laterally extensive matrix-supported tabular bed varying in thickness from 60 to 70 cm. A coarse grained discontinuous horizon occupies the bottom one quarter of the unit. This grades with the rest of the lower unit, producing coarse-tail inverse to normal grading. The horizon more often occurs as a matrix to clast-supported cluster of coarse clasts which have no visually apparent fabric. At the base of the sequence a very thin layer of sand and silt blankets the pre-1984 flow fluvial surface and grades with the matrix of the lower unit of the bipartite sequence above.

Description of the upper unit: a laterally discontinuous and structureless granule sand bed which has a gradational contact with the lower unit. Despite the thin nature of the unit which is up to 7 or 8 cm in thickness, a boulder sized discoid clast rests within it without penetrating the lower unit (plate 2.9A).

LOCALITY 8.5

General synopsis: a bipartite sequence in the channel margin that is composed of a lower matrix-supported polymodal conglomerate bed with slight inverse grading and a very thin fine grained layer on top (figure 2.10A, plate 2.9B).

Description of the lower unit: a tabular bed varying in thickness from 45 to 50 cm. It is unstratified, has no visually apparent fabric and has poorly developed coarse-tail inverse grading, with few pebbles occurring in the lower few centimetres of the unit.

Description of the upper unit: A very thin laterally discontinuous, polymodal unstratified cap to the lower unit with which it has a sharp contact. Unorientated pebbles and small cobbles occur, embedded locally within the unit.

LOCALITY 9.2

At this locality a very disjointed exposure of pebbly granule sand within the channel documents the most distal sequence preserved from the 1984 flow event. The sequence is composed of widely separated isolated tabular beds which vary in thickness from 50 to 55 cm and are horizontally stratified revealing stacked coarse-tail inversely graded sub units (figure 2.10B, plate 2.10A and 2.10B). The inverse grading within several sub units is intermittent in a lateral sense

PLATE 2.9 [OVER]

PLATE 2.9

A

A view of the depositional sequence, the base of which is marked, at locality 7.3, showing the occurrence of a boulder sized clast within the upper unit which shows lateral variability in thickness and a sharp to gradational contact with the lower unit. Flow was from right to left.

B

The depositional sequence, the base of which is marked, at locality 8.5, showing a lower thick matrix-supported and weak coarse-tail inversely graded unit overlain by a thin pebbly granule sand upper unit with cobbles. Flow was from left to right.

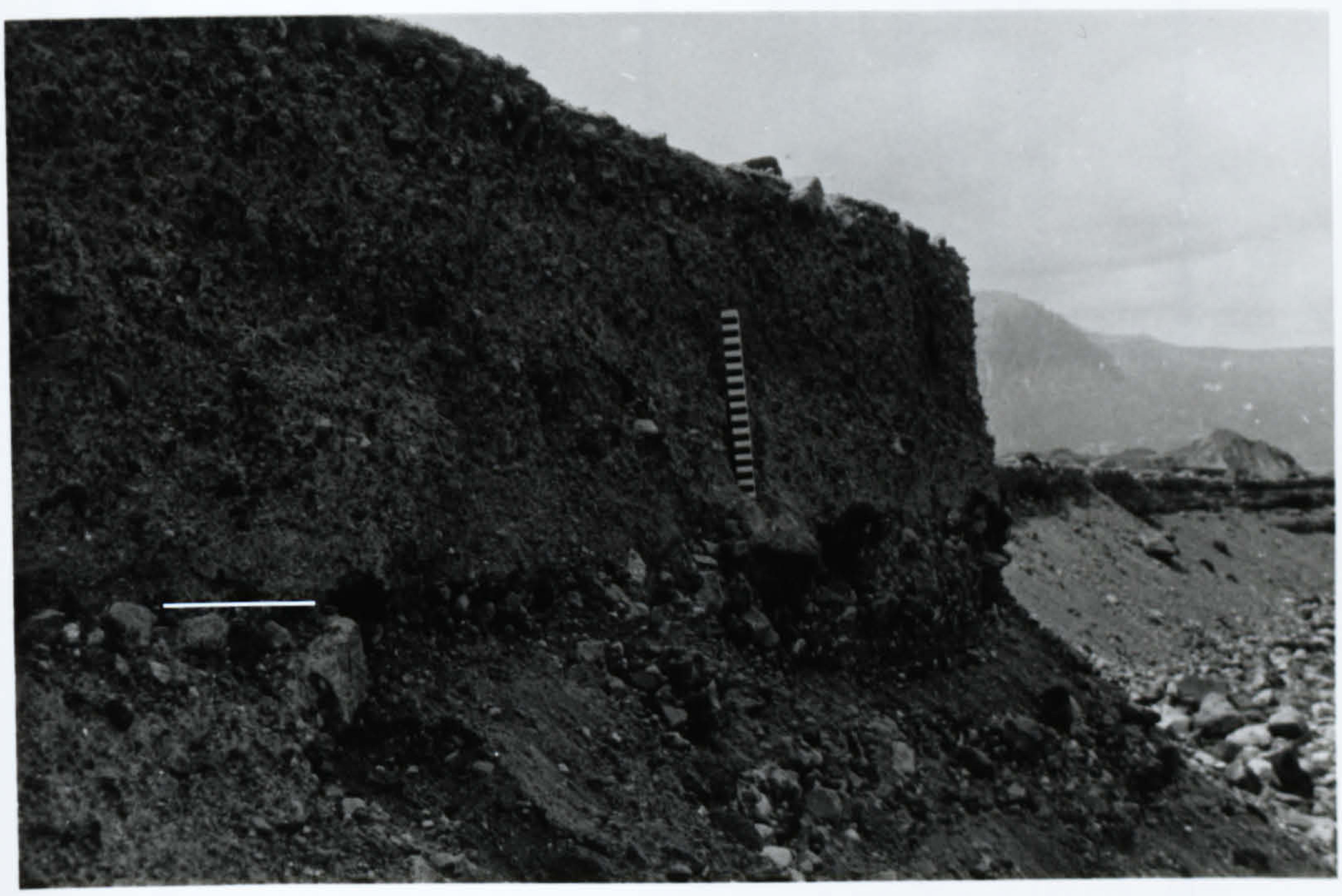


Figure 2.10. Representative logs of the depositional sequences at: A. locality 8.5, B. locality 9.2.

PLATE 2.10 [OVER]

PLATE 2.10

A

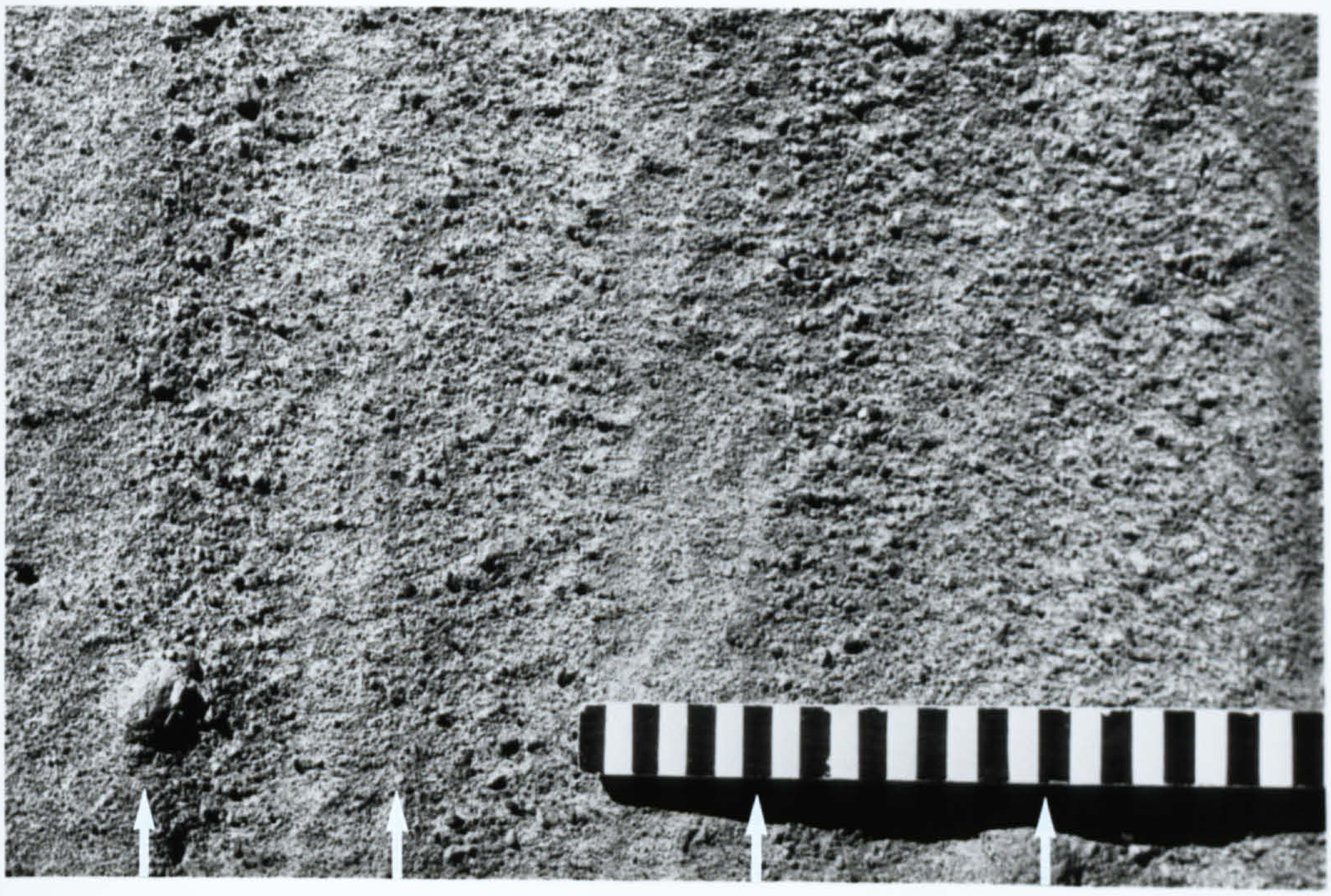
The depositional sequence at locality 9.2. The deposits consist of pebbly granule sands that form a stack of generally inversely graded sub units. Flow was from right to left. The material above the bed was emplaced through bank collapse.

B

Detail of the inversely graded sub units at locality 9.2. Note the gradational contacts between sub units (arrowed) and the occurrence of a pebble sized clast at the top of one sub unit. Flow was from right to left.

C

The most distal exposure at locality 9.2, which consists of a single homogeneous coarse grained unstratified unit, the upper and lower boundaries of which are marked. There is no well defined grading or preferred clast orientation. Flow was from right to left.



and thus these particular sub units are locally homogeneous. The longest continuous inversely graded unit is 2 m in length, this is a minimum value as the sequence was eroded. The contacts in a vertical sense between sub units are diffuse (gradational) and are only discernible due to vertical grain size variation. The inversely graded sub units exhibit a general decrease in thickness upward through the stack, which is accompanied by an upward decrease in pebble sized clasts. The pebbles, which are the largest sized clasts in the sub units, are clearly orientated with a-axes parallel to both flow direction and the base of the deposit (not imbricated).

The most distal unit of this eroded exposure occurs 50 m downstream from the beds consisting of sub units (in direct lateral continuity). It is homogeneous, unstratified, coarse grained, poorly sorted and contains randomly orientated pebble sized clasts (plate 2.10C).

2.3.3. Preliminary interpretation of the depositional units

In order to place the field descriptions of the deposits into context and to produce a base upon which the following sections are built, some preliminary interpretation is required at this stage. It has been shown in section 2.3.2 that along a 9.2 km reach of the North Fork Toutle River there is a spectrum of deposits that are generally bipartite or tripartite sequences and which occur in both channel margin and terrace settings. The lower thicker unit in each sequence was deposited by the main 1984 mass flow or lahar, whilst the upper unit(s) represent deposition from the recessional flow phase that followed in the wake of the main flow (Pringle and Cameron, in press). It is important to note that deposits described at locality 3.4 represent an exposure of recessional flow deposits which are an extension onto the terrace of the upper unit in a bipartite sequence at the channel margin. References to recessional flow phases or deposits that follow, or have followed in the wake of a debris flow are quite common, (Takahashi, 1981; Lawson, 1982; Johnson, 1984; Wells, 1984). In addition to recessional flow deposits, evidence of precessional flood flow deposition occurs at locality 7.3 where there is a thin sand and silt horizon that caps the pre-flow fluvial deposits. A precessional flood was observed by Pringle and Cameron (in press) at this locality, such floods occurring prior to mass flows, have been recorded elsewhere (eg. Lawson, 1982).

A schematic summary of the 1984 flow deposits in general, is displayed in figure 2.11. This diagram outlines the basic interpretation of the depositional sequence and presents the terminology used when referring to deposit types in subsequent sections of this chapter. The precessional flow deposit present only at locality 7.3, is represented on figure 2.11. Although this thin deposit is significant as representing depositional evidence from a precessional flood phase, it is not dealt with further, because of its very

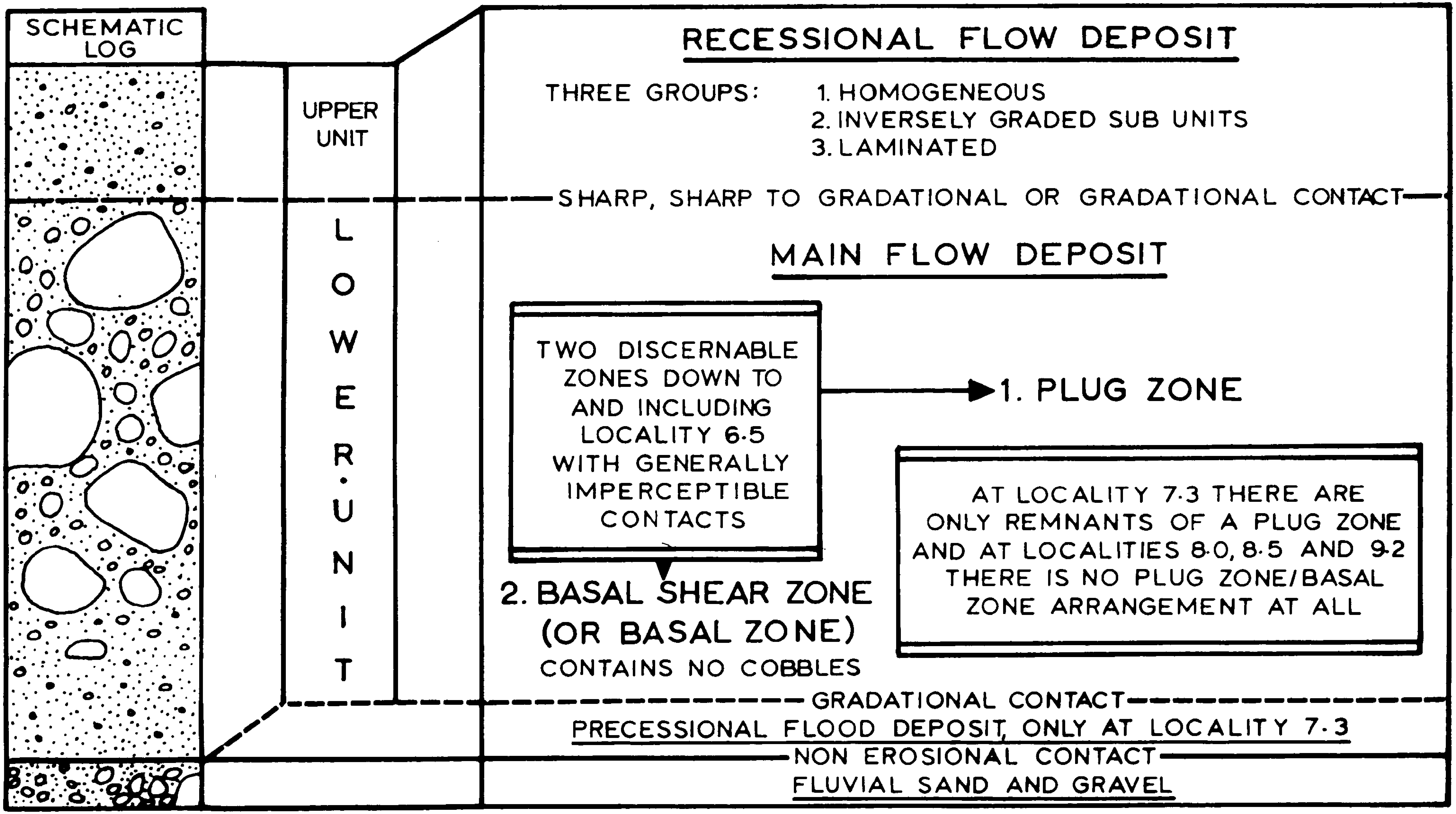


Figure 2.11. Generalised facies diagram of the 1984 flow depositional sequence with the basic interpretation of the depositional units and the terminology adopted for use throughout this work.

limited extent.

It is within the lower unit that the greatest downstream change occurs within the depositional sequence. There is a decrease in the number of large clasts, the development of strong coarse-tail inverse grading and fabric, with the most distal exposure consisting of stratified granule sands. The most proximal main flow deposits (lower units) described at locality 0.0 are very coarse grained matrix to clast-supported polymodal conglomerates, which lack internal stratification or fabric and have a fine grained basal zone that is devoid of cobbles. These features are typical of deposits from a debris flow, (Johnson, 1970, 1984; Fisher, 1971, 1984; Middleton and Hampton, 1976; and Nemec and Steel, 1984). Johnson (1970, 1984) and Pierson and Costa (1987) describe debris flow as a non-Newtonian fluid with yield strength, bulk density and viscosity that are much greater than that of clear water. Johnson (1970), through laboratory experimentation developed a rheological model that describes the fluid behaviour and sediment transport mechanisms of debris flow. This "Coulomb-viscous model" predicts that in a debris flow the resistance to flow results from the shear strength of the debris and viscosity. Shear strength originates from cohesion produced by the presence of clay (even in small amounts) and internal friction from sliding friction and particle interlocking. Cohesion and internal friction constitute the shear strength of the debris that must be exceeded before any flow occurs: viscosity affects flow resistance in the moving debris flow. Johnson's (1970) model leads to the conclusion that a mass of debris flowing in a channel will move mainly by laminar shear within a basal or circumferential zone where the shear strength of the debris has been exceeded. At the top centre of the flow a rigid plug exists where the shear strength of the debris has not been exceeded (figure 2.12).

Johnson (1970, 1984) states that the Coulomb-viscous model explains many features of debris flow deposits including the tendency for the surfaces of debris flow deposits to be smoother than the surfaces over which the debris flowed (an effect of the "raft" of relatively rigid debris) and the ability of the debris to transport large blocks. The latter feature is clearly demonstrated by the proximal 1984 main flow deposits (lower units) where a plug zone/basal zone model can be applied based on the descriptions.

The mechanisms which support sediment in debris flows are fundamentally different from those in water flows (Costa, 1988) where turbulence is acknowledged to be an important component of sediment support and transport (Collinson and Thompson, 1982). Fisher (1971) states that the primary factors that influence the properties of debris flow include absolute grain size, grain size distribution and the sediment concentration. It is from the consideration of these primary factors that the mechanisms for supporting sediment in debris flows have been suggested.

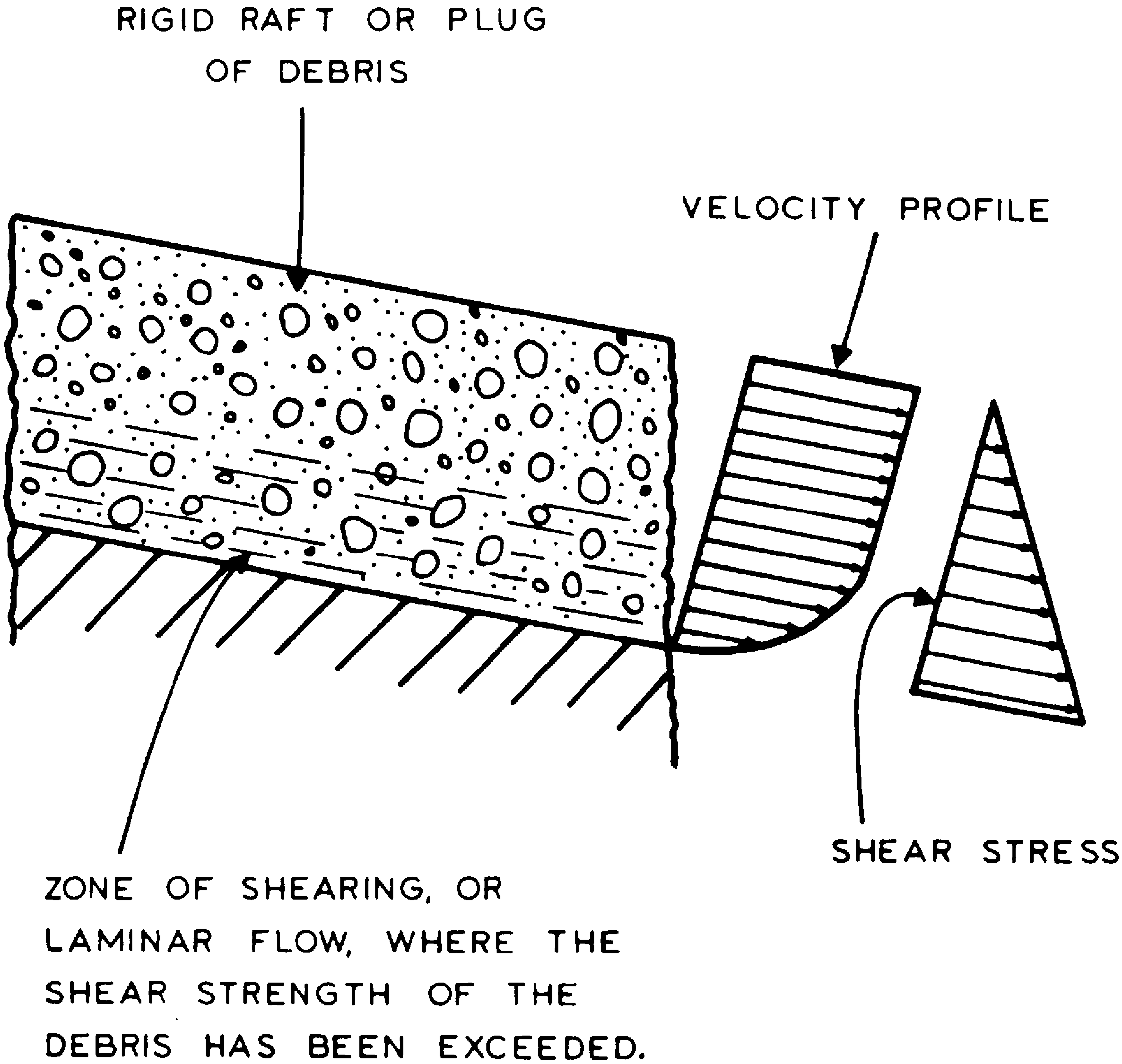


Figure 2.12. Theoretical model for a Coulomb-viscous mass flow in a channel, after Johnson (1970, 1984) and Middleton and Hampton (1976). At the left there is a profile of the debris showing the rigid plug and the zones of flow with the corresponding velocity profile. On the right there is a representation of the internal shear stress distribution.

Cohesive matrix strength has been proposed as a major particle support mechanism by several authors (Johnson ,1970; Hampton, 1975, 1979; Middleton and Hampton, 1976; Rodine and Johnson, 1976) and depends upon the amount of clay present within the debris. This is illustrated by clay-water slurries which can indefinitely suspend medium and very coarse sand (Kuenen, 1951). Particles coarser than sand require another mechanism of support in debris flows; buoyancy is considered to be such a mechanism (Johnson, 1970; Hampton, 1975, 1979; Middleton and Hampton, 1976; Rodine and Johnson, 1976; Lowe, 1979). Buoyancy of clasts which works in conjunction with cohesive strength, arises through the density difference between submerged particles and the fluid. This effect is enhanced by the transfer of the weight of the submerged particles in the flow to the pore fluid. The fine grained matrix prevents rapid loss of this pressure, thus bringing about an increase in buoyancy (Hampton, 1979). This also causes a reduction in shear strength of the debris and hence increases its mobility (Pierson, 1981; Costa, 1984).

Another important sediment transport mechanism was experimentally demonstrated by Bagnold (1954), this is dispersive pressure and results when forces are transmitted between particles in collisions or near collision as one is sheared over another in the flow. Where a flow contains a mixture of grain sizes undergoing shear, the larger grains tend to drift to the zone of least shear strain. This mechanism of particle support has been used by many authors to explain the presence of inverse grading in debris flows (Hampton, 1972; Carter, 1975a; Middleton and Hampton, 1976; Lowe, 1979; Nemec and Steel, 1984; Scott, 1988a).

Turbulence, although important in the support and transport of sediment in clear water, is of minor importance in debris flows (Costa, 1988). A full discussion of this and other mechanisms in relation to the 1984 flow as it moved along the North Fork Toutle River, cannot be conducted at this stage, as critical information is required regarding the silt and clay content of the deposits and the rheological properties of the flow presented in the following sections.

It is evident from the descriptions that the main flow deposits change profoundly downstream along the reach. The number of large clasts decreases, there is a decrease in bed thickness, the development of strong inverse grading and fabric, with the most distal exposure consisting of a stratified pebbly granule sand deposit. This indicates a corresponding fundamental change in flow processes from what is indicated to be debris flow processes exhibited by the most proximal deposits. This may involve a sequential downstream change in the relative importance of each support mechanism as briefly outlined above.

The aim of the subsequent sections of this chapter is to make distinctions between deposits in the depositional spectrum produced by the 1984 flow, through sedimentological analysis and by the consideration of flow properties.

2.4. DETAILED DEPOSIT CHARACTERISATION

2.4.1. Grain size distribution characteristics and clast composition

2.4.1.1. Introduction and techniques

Grain size distribution quantification is a most important addition to this study in two major respects: firstly, it aids in distinguishing different depositional units within a sequence and secondly it provides information on vertical and lateral changes within these units. Grain size analysis was conducted in order to permit the detection of serial changes between the deposits along the reach. A description of the clast composition although not crucial to the understanding of the depositional processes, is included in this section in order to complete the characterisation of the depositional sequence.

Thirty two samples were taken from the 1984 flow deposits for granulometric analysis, these included plug zone, basal zone and recessional flow deposits. In addition, two samples of stream flow deposits produced in 1987 were also removed to allow a comparison with the mass flow deposits (figure 2.13). Although the lower unit (main flow deposit) at locality 7.3 only had the remnants of a plug zone, the samples collected from it were labelled as plug zone and basal zone samples. Since there was no plug zone or

DEPOSIT SAMPLES AND LOCATIONS				
LOCALITY	PLUG ZONE AND MID DEPOSIT (AT 8.0, 8.5 + 9.2)	BASAL ZONE	RECESSIONAL FLOW DEPOSITS	STREAM FLOW DEPOSITS
0.0	1	13	19 (H)	
0.7			20 (L)	
1.0	2		21 (H)	
1.7			22 (H)	
2.0	3			
2.7			23 (H)	
3.0	4	14	24 (H)	
3.4			25 + 26 (IG)	
3.7	5	15		
4.3			27 (L)	
4.5	6		28 (H)	
5.2	7	16	29 (H)	33
6.5	8	17	30 (L)	
7.3	9	18	31 (H)	
8.0	10		32 (L)	
8.5	11			
9.2	12			34

KEY

1,2,3... REFER TO THE NUMBERS GIVEN TO EACH SAMPLE THE GRAIN SIZE DISTRIBUTION ANALYSES OF WHICH ARE IN APPENDIX 1A.

H = HOMOGENEOUS DEPOSIT

IG = INVERSELY GRADED SUB UNIT

L = LAMINATED DEPOSIT

Figure 2.13. The 1984 flow depositional units sampled for grain size distribution analysis and the sample locations.

basal zone arrangement evident in the deposits at localities 8.0, 8.5 and 9.2, samples of sediment for analysis were taken from the middle of the depositional unit (middle sub unit at locality 9.2), which can be regarded as being in direct lateral continuity with the plug zones of the deposits further upstream. These samples are referred to subsequently as mid-deposit samples. The grain size distribution for 3 of the 1984 flow deposit samples was supplemented by point count analysis of the whole unit sampled, in order to include large clasts within the analysis. Details of the sampling techniques and subsequent analysis are outlined as follows-

Deposit sampling: Spot samples were taken from representative areas within single depositional units by the method outlined by Folk (1980). If the unit contained clasts up to granule in size, a sample in the order of 100 to 150 g was taken. If a unit contained pebbles or cobbles, several kilograms of sediment were collected in order to obtain a representative sample.

Point counting: With units containing exceptionally large clasts a spot sample would be biased, as the large clasts would be neglected. In order to alleviate this bias, point count sampling was conducted in the following way, after the method developed by Kellerhals and Bray (1971). A tape measure was positioned along the length of the coarse unit, or if the length of the deposit section was short, at two or three levels within the unit. The size of the b-axis of cobbles and larger clasts occurring at the end of every 30 cm interval was then measured (used the scale bar pictured in all the plates). Kellerhals and Bray (1971) actually suggest a spacing of one footstep for point counting on a horizontal surface. However on the vertical sections examined in this study a footstep spacing was impracticable and hence the use of the 30 cm spacing (used in the plates). If the clast was smaller than cobble size (less than 6.4 cm) it was counted as matrix, this limit was chosen as it represented a convenient break in the Udden-Wentworth Grade Scale. Approximately 100 data points were derived along the length of the tape. These point counts were combined with the results of dry sieve analysis of the matrix, (clasts smaller than cobble size), as grid by number analysis is directly equivalent to bulk sieve analysis (Kellerhals and Bray, 1971). The result was an overall grain size distribution for the coarse unit at a particular locality.

Sample Preparation for grain size analysis: As the sediment samples were unconsolidated they did not require mechanical disaggregation. However, before sieving, the samples were examined for aggregates after being air dried, following the method outlined by Folk (1980).

Sieving: The grain size distribution of the collected sample was determined using a Ro-tap machine with sieves at 1 phi intervals. If the sample was large and contained cobbles it was passed through coarse mesh and split before before sieving.

Analysis of silt and clay: Pipette analysis was conducted on four samples to obtain a representative measure of the silt and clay fraction of the depositional units, using the method outlined by Folk (1980). A sample of 5 g of sediment collected in the pan below the 62 µm sieve was added to distilled water to produce a 1 litre suspension of uniform concentration and a few drops of sodium hexametaphosphate was added to prevent flocculation. 20 ml volumes were then withdrawn from 10 and 20 cm depths in the suspension, on a time scale determined by calculations based on Stoke's law. The dry weight of these samples was then used to calculate the grain size distribution of the original sample.

2.4.1.2. Grain size distribution data analysis

The results of the grain size analyses (appendix 1A), were plotted as cumulative percent against the appropriate size classes to produce cumulative curves. A variety of statistical parameters can be defined which illustrate some of the basic properties of the sample grain size distributions. The grain size parameters were calculated by the methods outlined by Folk (1980), using grain sizes read off cumulative curves on probability paper. The calculated grain size parameters are: mean size, M_z; the degree of sorting, σ_I; skewness, Sk_I; and kurtosis, K_G. The formulae used for the calculation of these parameters are given in appendix 1B and the calculated parameters for all the groups of depositional units are presented in appendix 1A.

Great variability in the grain size distribution of the samples is illustrated by the spread of their M_z and σ_I values, which, although when plotted show considerable overlap (figure 2.14), do display readily apparent trends. A clear distinction can be made between the plug zone samples and the laterally equivalent mid-deposit samples at localities 8.0, 8.5 and 9.2, by which the latter group are finer grained and better sorted than the former. This shows the downstream evolution of the main flow in terms of sediment sorting. In a vertical sense within the depositional sequence there is a clear distinction between the plug zone samples and the finer grained and better sorted basal zone samples. The recessional flow deposit samples, which are divided into three groups (figure 2.11), have similar mean grain size and sorting values and apart from the homogeneous deposits are quite distinct from either the plug zone or basal zone samples. However, the recessional flow deposits share a similar range of values with the mid-deposit samples at localities 8.0, 8.5 and 9.2. The stream flow deposit samples taken from the Toutle River channel which are unrelated to the 1984 flow sequences represent the most evolved in the entire reach. They have the lowest mean grain

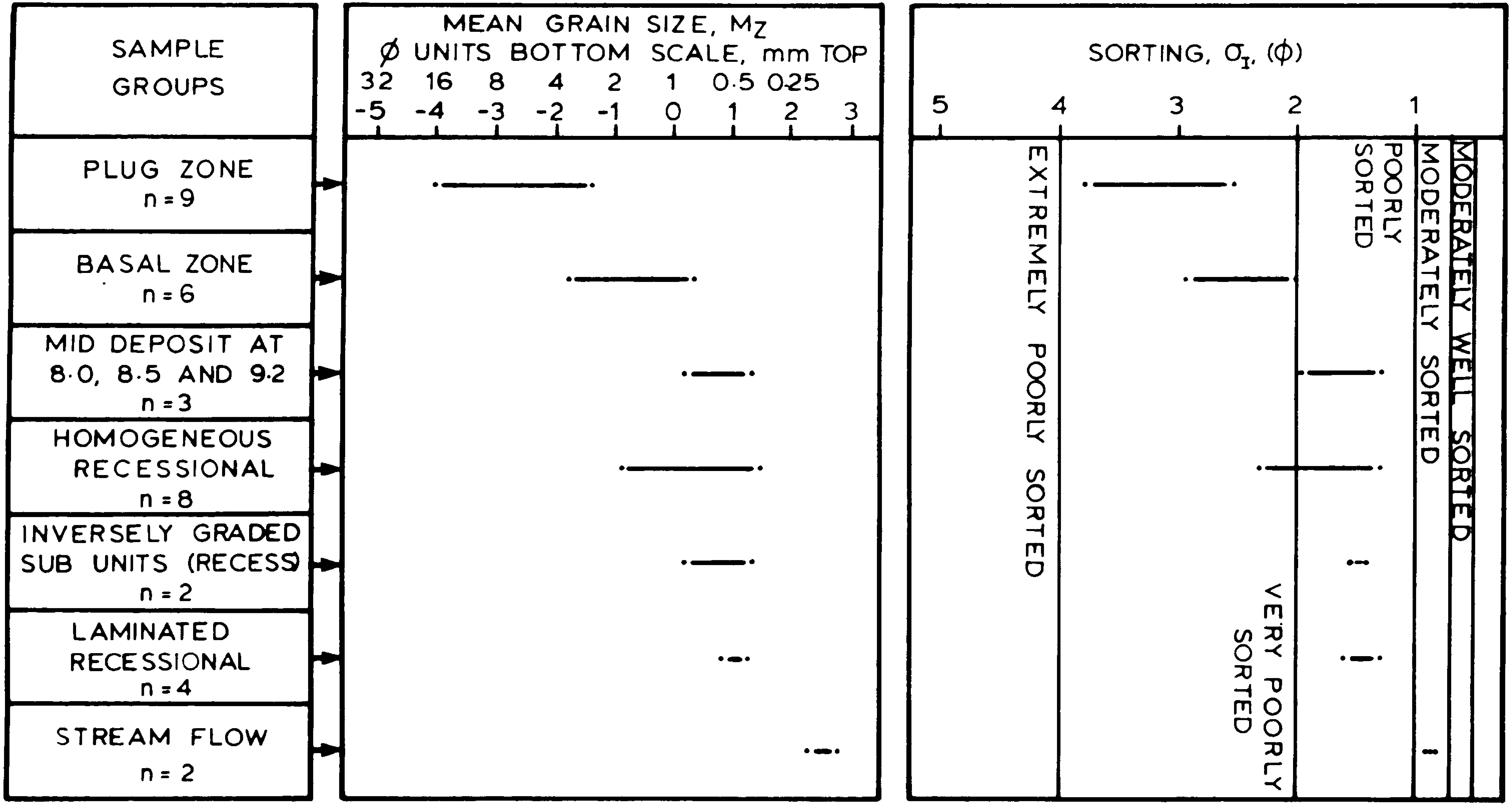


Figure 2.14. Tables showing the range of mean grain size and sorting values for the different sample groupings. Note the overlap in the ranges of values between the groups.

size values and are the best sorted.

In order to examine lateral changes in grain size parameters, plots of M_Z and σ_I versus distance along the reach were constructed in conjunction with statistical analysis (using the method outlined by Till [1974]) to determine whether there was a significant linear relationship existing between distance and M_Z and σ_I respectively. The plug zone and mid-deposit samples together show a significant downstream decrease in mean grain size with a significant increase in sorting (figures 2.15 and 2.16). The basal zone samples exhibit a general trend of decreasing mean grain size downstream (figure 2.15) but this is not significant. In contrast there is a significant downstream increase in sorting (figure 2.16). The recessional flow deposits show a slight trend of decreasing mean grain size downstream but this is not significant (figure 2.15). However a significant downstream change in sorting is evident (figure 2.16).

The 1980 South Fork Toutle lahar deposits show a similar downstream decrease in mean grain size and an increase in sorting (Gilkey, 1983; Scott, 1988a). However, the North Fork (Gilkey, 1983), Pine Creek and Muddy River lahars (Pierson, 1985b), show no such significant downstream change in mean grain size or sorting. This lack of downstream variation in mean grain size and sorting in the latter two lahars may be due to the large magnitude of these flows which exhibited very little or no change in flow character.

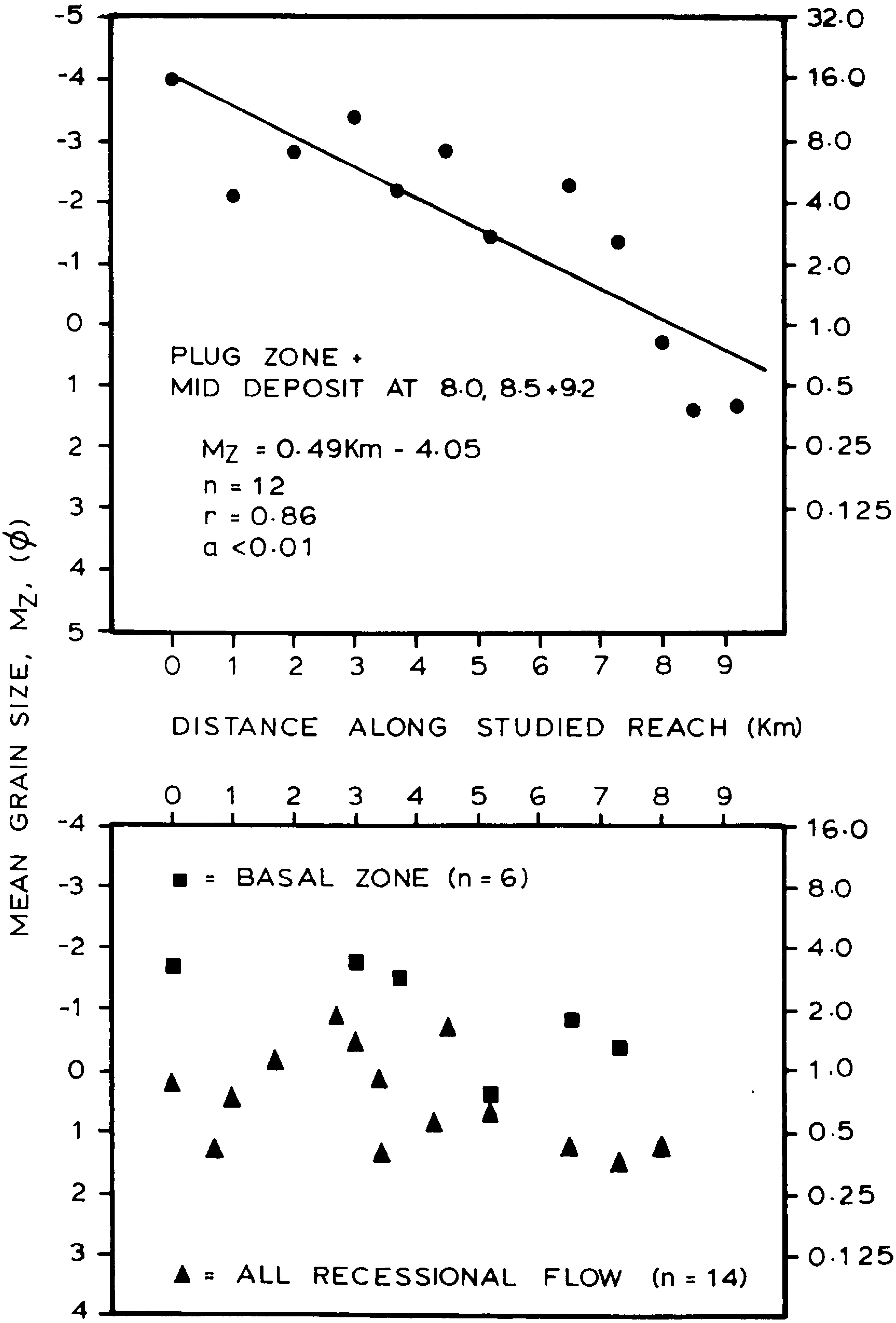


Figure 2.15. Mean grain size in phi units, versus distance along the studied reach. Only plug zone and mid deposit samples at 8.0, 8.5 and 9.2 show a significant downstream decrease in M_z.

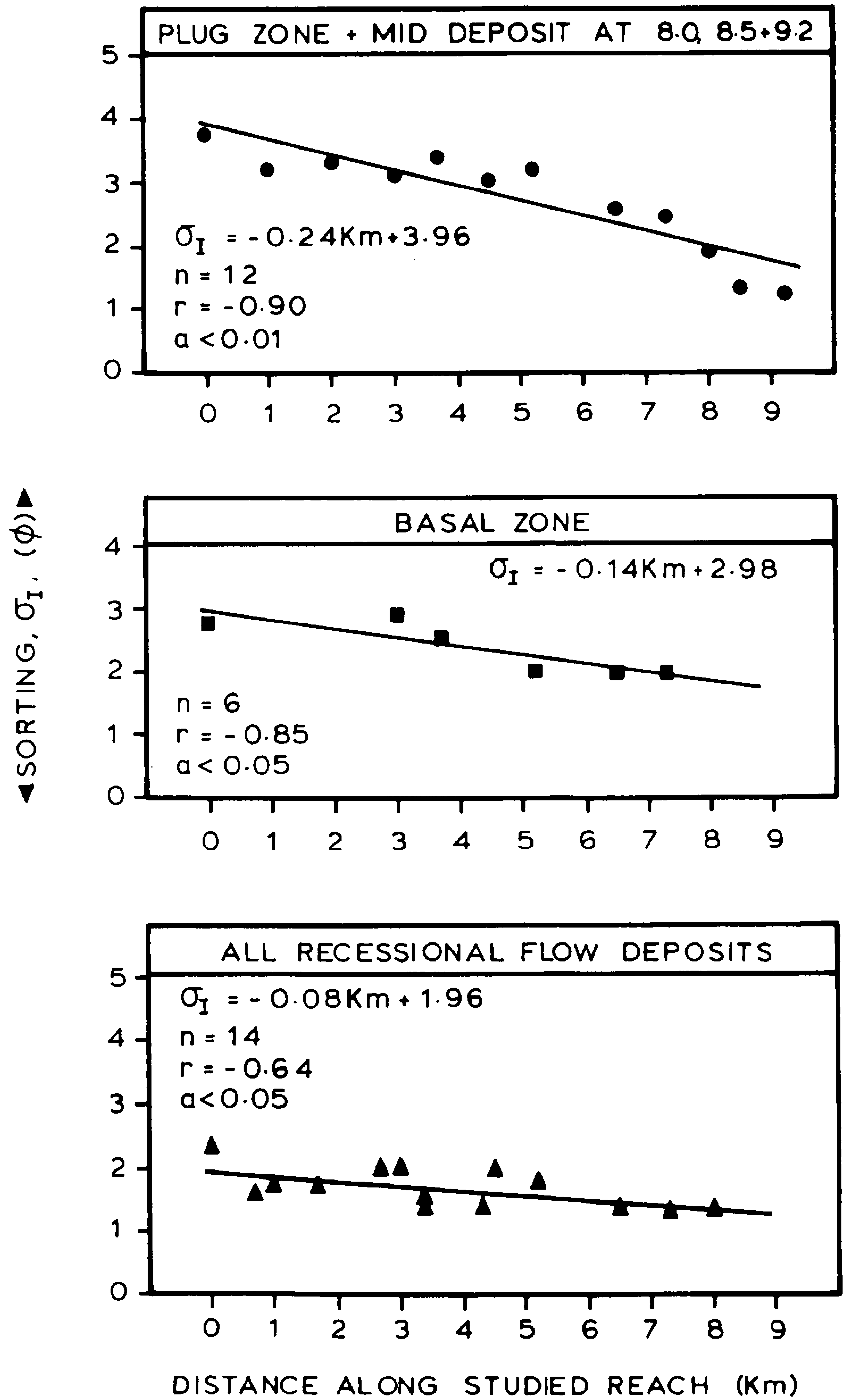


Figure 2.16. Sorting in phi units versus distance along the studied reach, all groups of samples show a significant downstream increase in sorting. The oblique lines with corresponding equations, are least squares regression lines fitted to the data.

Major and Voight (1986) indicate that downstream changes in mean grain size and sorting occur only in the basal portions of the south west flank lahar deposits, with both the mean grain size and sorting coefficient increasing with distance downstream. The fact that the south west flank lahars did not transform to "lahar-runout" (Major, personal communication, 1987) and thus remained as "lahars" throughout the deposition of sediment, would account for the dissimilarity with the results of this study.

2.4.1.3. The Textural discrimination of deposits

Passega (1957, 1964) found that logarithmic plots of the coarsest 1-percentile particle size (C) and the median particle size (M) delineate fields which are distinctive of depositional environments. Passega found that a sinuous field was distinctive of the grain-by-grain mode of deposition associated with river deposition and that a rectilinear field, roughly parallel to the C=M line was characteristic of turbidity current deposits. Passega noted that the distribution of the fields was closely related to the depositional processes with the coarse fraction of the sediment being invariably more representative of the depositional agent than that of the fine fraction. Bull (1962, 1972) used the fields established by Passega to discriminate successfully between water-lain and mud flow alluvial fan deposits.

When the thirty two samples from the 1984 flow deposits and the two stream flow deposit samples are plotted on to a CM diagram (figure 2.17), a scatter of points is produced which form a field to the left of, and sub parallel to, the C=M line. Superimposed upon figure 2.17, are written the deposit type groupings determined by Bull (1962, 1972), these mark the general positions of the points on Bull's plot.

The samples in this study show a continuum from the top right of the graph where the plug zone samples are plotted, through to the stream flow deposits at the bottom left. Basal zone and recessional flow deposits plot in between these two end members with the recessional flow deposits forming a distinct grouping away from the plug zone samples. The mid-deposit samples plot among the recessional flow deposits. Although this spread of points is largely evident through the examination of the M_Z and σ_I values (figure 2.14), the CM diagram is an excellent pictorial representation of the data and clearly demonstrates a textural continuum. Direct comparison can be made between Bull's (1962, 1972) findings and those of this study, as Bull's braided stream deposits plot in a similar position on the diagram to that of the stream flow deposits in this study and the plug zone samples of this study plot on an extension of the mudflow field defined by Bull (1962, 1972). However, it is important to note that deposits described by Bull as having been formed by flows with intermediate characteristics between mudflow and stream flow, termed "intermediate"

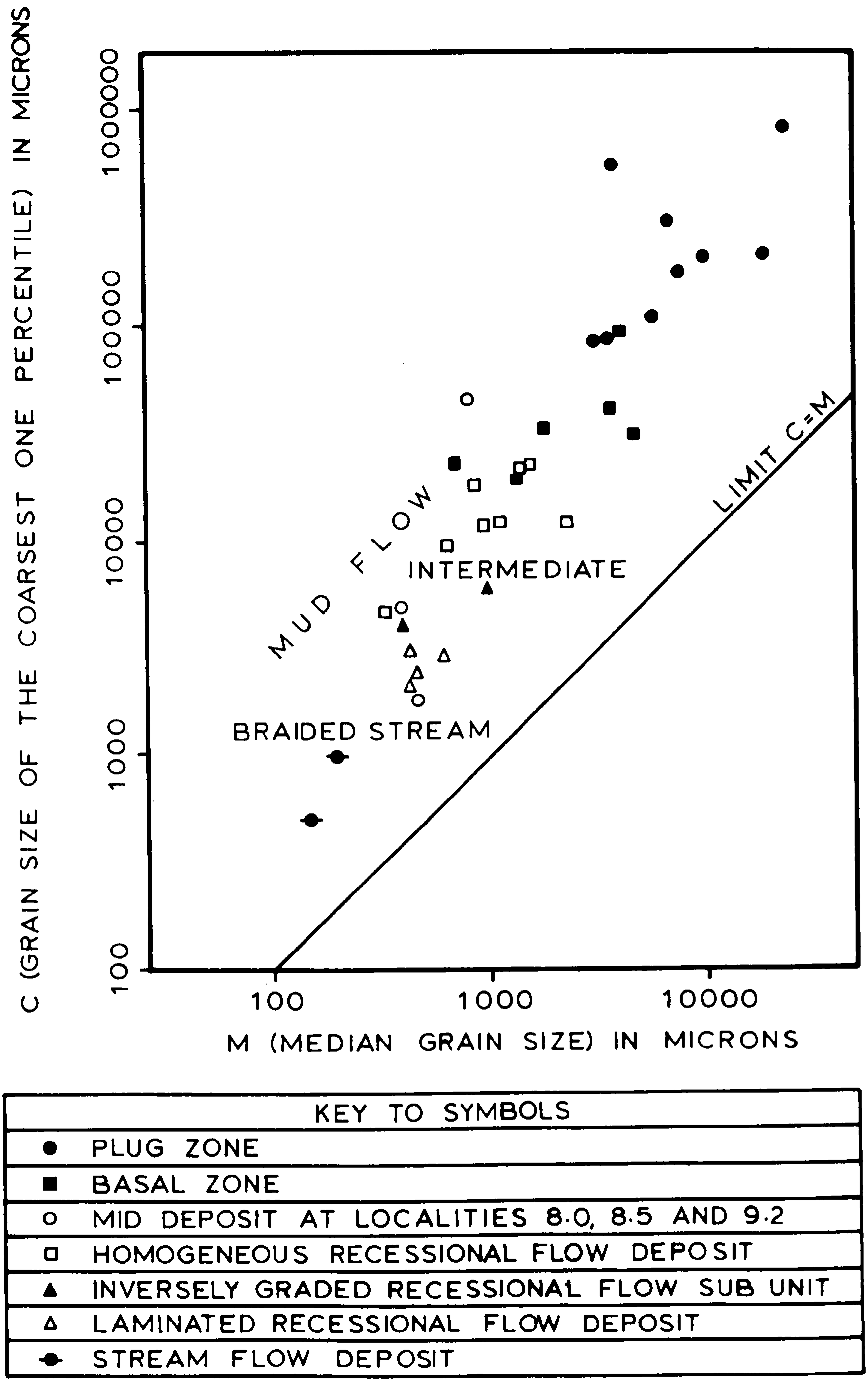


Figure 2.17. A CM diagram with all samples plotted, MUDFLOW, INTERMEDIATE and BRAIDED STREAM, refer to the approximate positions of deposits plotted on the CM diagram of Bull (1962, 1972).

deposits, occupy the same position on the CM diagram as the 1984 recessional flow and mid-deposit samples.

Passega (1957, 1964) claims that the distribution of points on a CM diagram is closely related to the depositional process, this hypothesis being established by Passega through plotting a range of deposits taken from the Mississippi river channel and other sedimentary environments. However, Passega's use of the word "process" is not specific to the actual hydraulic mechanism involved in the deposition of the sediment. Rather, it denotes in a general sense, the depositional regime in which sediment is transported, for example by running water, or as a viscous mass. Hence in this respect, Passega's CM diagram is good for the textural discrimination of a set of sediment samples as shown by this study and that of Bull (1962, 1972).

2.4.1.4. Clast composition

The clast population can be divided into four main rock types. These were: 1) a distinctive light grey porphyritic dacite, produced during the eruption of Mount Saint Helens in 1980 (blast dacite), 2) pre-1980 porphyritic red and dark grey andesites and dacites, 3) pre-1980 black basalt, some of which was vesicular, 4) altered Tertiary bedrock. Pumice was not found within the deposits, although it was present in the channel system along the reach. Clasts were homogeneously mixed by composition throughout each depositional unit despite the size grading.

One hundred pebble size clasts were examined within the main flow deposits, at eleven localities along the reach, to determine the relative proportions of the different clast types. These counts were then plotted with distance along the reach to investigate downstream changes (figure 2.18). The plot shows that the blast dacite and the Tertiary bedrock clasts are subordinate in quantity to the andesite, dacite and basalt clasts. This most likely reflects source and requires no further investigation. No significant increase or decrease in a particular clast type indicates that there was no selective winnowing within the main flow. Gilkey (1983) similarly found no change in clast composition downstream, within the deposits of the 1980 South Fork lahar.

2.4.2. Fabric analysis

2.4.2.1. Introduction and techniques

In the descriptions of some depositional units in section 2.3, it was noted that there was a visually apparent clast fabric, for example: within an inversely graded recessional flow deposit at locality 3.4 (plate 2.4B and 2.4C) and within the plug zone deposits at locality 5.2. However, in most of the depositional units a fabric was not visually apparent in the field due to the spherical nature of the clasts. In order to obtain an indication of the general shape character-

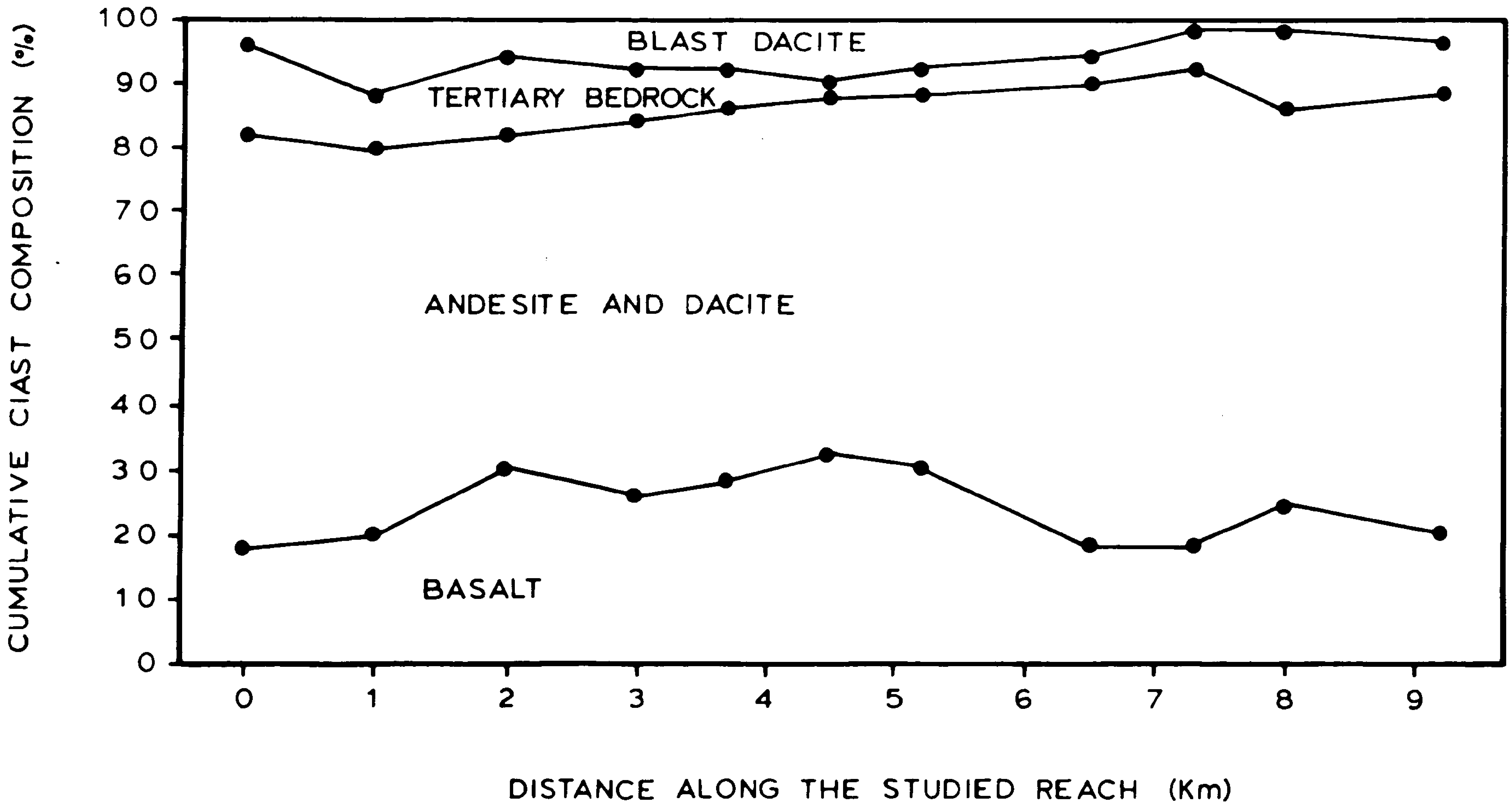


Figure 2.18. The compositional variation of pebble and cobble sized clasts from the main flow deposits along the studied reach. One hundred clasts were counted at each locality.

istics of the clast population, the long, short and intermediate axes of one hundred pebble and cobble sized clasts, randomly picked out from the plug zone deposits at locality 5.2 were measured. The resulting shape data are presented in the form of a Zingg chart (figure 2.19) after Pettijohn (1949). Study of the chart shows that the pebble and cobble sized clasts in the plug zone deposits at locality 5.2 are generally spherical in nature. Field investigations revealed that similar detailed studies of shape would produce similar results along the entire reach within deposits produced by both the main and recessional flow deposits. An extensive study was ruled out as the amount of useful information that can be extracted from such a study is limited.

In order to evaluate the clast fabric within the 1984 flow deposits as a whole, a systematic study was conducted at ten localities along the 9.2 km reach. All the flow event elements were studied except the precessional flow deposits (at locality 7.3) which did not contain clasts over granule in size. The orientation of clast a-axes with respect to flow direction and imbrication were used to indicate the presence or absence and strength of fabric development. Orientation analysis centred on clast a-axes as the measurement of a/b planes was precluded due to the spherical nature of the clasts, as shown above. Not all the flow event elements at each locality were analysed for fabric, due to the difficulty in the excavation of certain units.

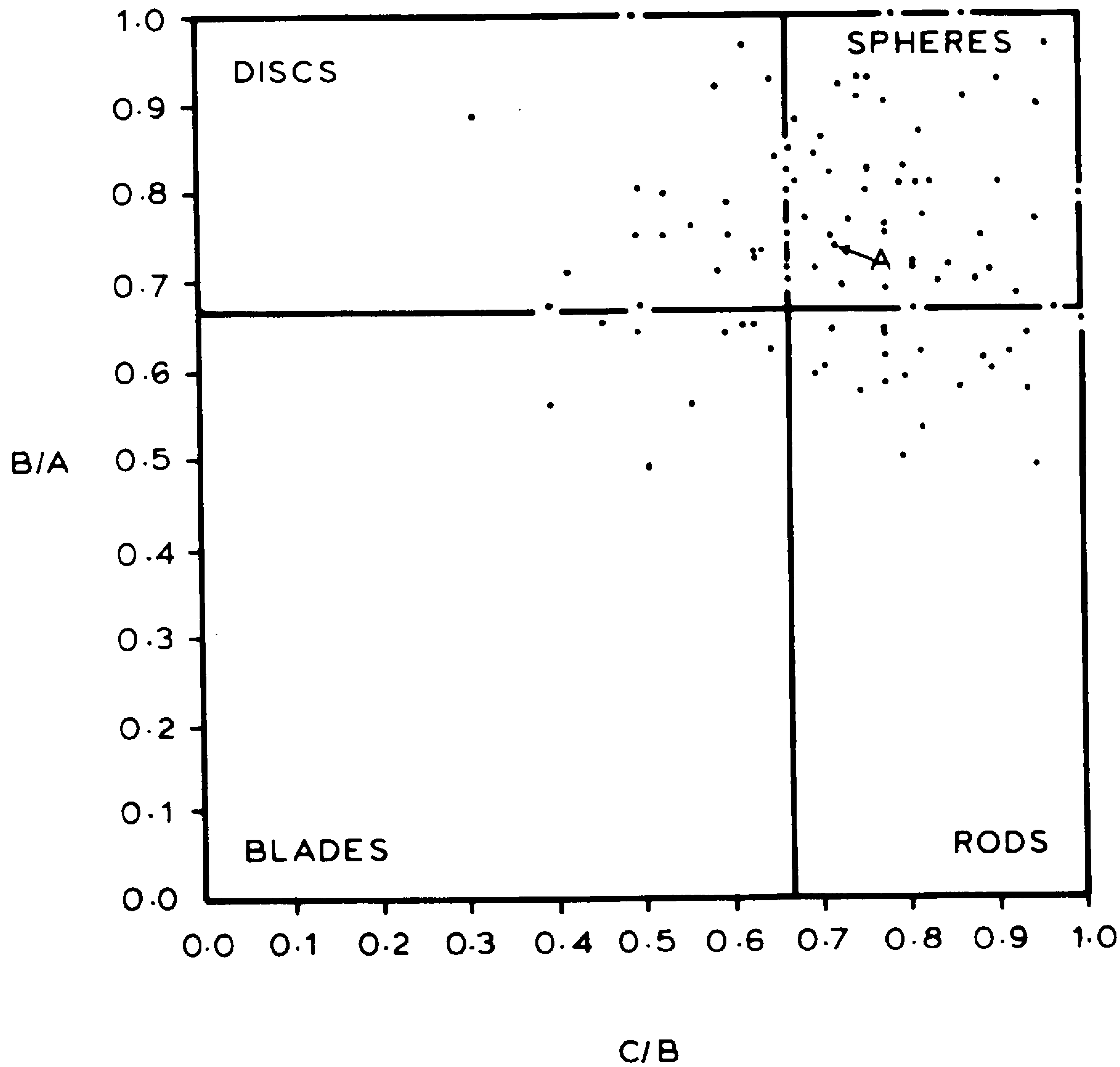


Figure 2.19. Zingg chart showing the form of 100 pebble and cobble sized clasts which were randomly selected from within the main flow deposit at locality 5.2, point A refers to the average value.

Once a unit had been selected for fabric analysis, a horizontal area 2 m by 2 m was prepared at a level halfway into the depth of the deposit. This involved the careful removal of loose material by brush and trowel and spraying of the area by water to remove fine sand and silt that tended to obscure larger clasts. This was a relatively simple procedure for recessional flow deposits which occurred on top of the depositional sequence (plate 2.11A), but at deeper levels in a sequence, within the plug zone or basal zone, deep pits had to be dug. Such excavation was unnecessary when an eroded sequence allowed direct access to the middle horizon of these lower units.

From areas where fabric was visually apparent, it was determined that clasts up to and including 2 cm in size were preferentially orientated, for example at locality 3.4, as were cobble sized clasts (6.4 cm and above), for example at locality 5.2. Hence from this approximation of fabric character, three fields were established into which clasts were grouped according to size. These were: 1) up to and including 2 cm, 2) between 2 cm and cobble size, 3) cobble and above. Two sets of callipers set at 2 cm and 6.4 cm were used to determine the size grouping of clasts and only non spherical clasts having a distinct a-axis (with an a:b ratio of 1.5:1 or above) were used, this resulted in huge quantities of clasts being rejected from the analyses. This ratio was also selected and found to be suitable by Schultz (1984) for fabric analysis involving rather equant clasts in

PLATE 2.11 [OVER]

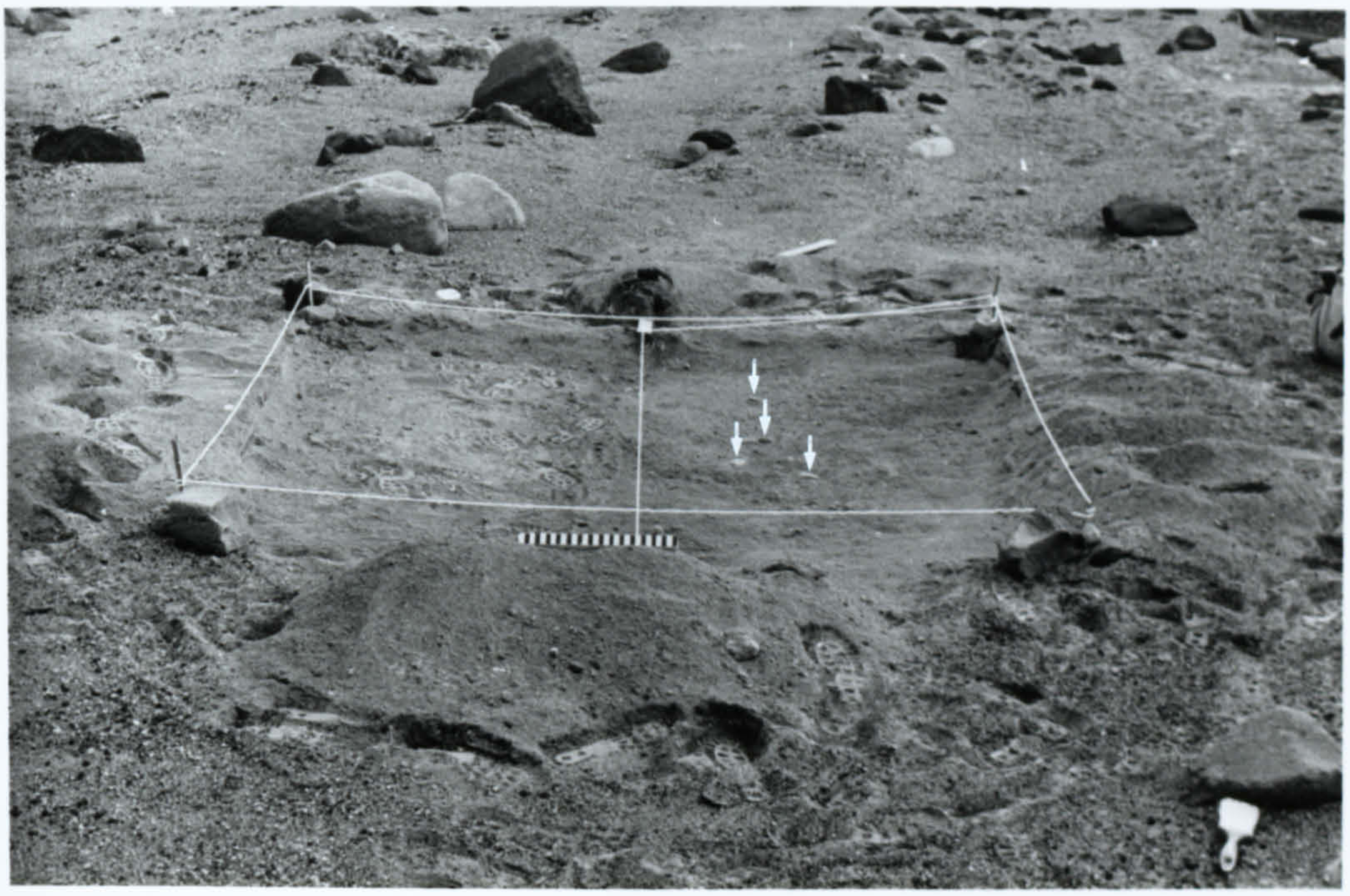
PLATE 2.11

A

An excavation pit for fabric analysis in the recessional flow deposit at locality 5.2. The area marked out is 2 m by 2 m. The arrows indicate cobble sized clasts on the prepared surface within the unit, which are orientated with their a-axes transverse to flow direction (toward the viewer).

B

A typical fragile clast projecting through the recessional flow deposit from the main flow deposit at locality 0.0. Note the weathered and crumbling appearance of the clast, which is composed of fine unconsolidated material.



Palaeozoic alluvial fan deposits in Colorado.

Imbrication analysis was conducted separately using flow parallel sections. These two studies were separated as the precise measurement of imbrication in the excavated pit, often many decimetres in depth within a sequence was impossible. This method of fabric analysis has been used by Davies and Walker (1974) and is recommended by Harms et al. (1982) where circumstances prevent 3D measurement. Imbrication was measured as the angle between each clast's a-axis and the bedding surface. The separate a-axis orientation was measured as the compass bearing of the a-axis.

The a-axis orientation and imbrication data for each analysis is expressed in this study upon rose diagrams and histograms respectively. The rose diagrams were drawn following the method outlined by Nemec (1988) and each data set was tested for randomness using the method of Davis (1986), which is described in appendix 2. The results from the fabric analysis outlined in the following sub sections are discussed in relation to other work conducted on other Mount Saint Helens mass flow deposits produced in 1980 and 1982, in addition to mass flows in general. However, detailed inferences on the processes of sediment transport and deposition within the main flow and recessional flow(s) of the 1984 event that can be derived from the fabric are deferred to section 2.6, where they are discussed in context with the results of the sedimentological investigation as a whole.

2.4.2.2. Fabric analysis within the main flow deposits

LOCALITIES 0.0 TO 6.5 INCLUSIVE

In the plug zone only the cobble sized clast group show a preferred a-axis orientation at a significance level of 5% as demonstrated at localities 2.7, 3.4 and 5.2 (figure 2.20). All other clasts measured, which were less than cobble in size, show no significant preferred a-axis orientation (figure 2.21). Due to time restraints, no orientational measurements of clasts less than cobble in size were made in the plug zones at localities 0.0, 2.7, 4.5 and 5.2. As with the plug zone, both basal zones analysed for fabric (at localities 4.5 and 5.2) show a significant preferred a-axis orientation developed within the cobble sized clast group, with all other clasts smaller than cobble size showing no preferred orientation except at locality 4.5, where clasts between 2 cm and cobble size showed a preferred orientation at a significance level of 10% (figure 2.22). All the preferred a-axis orientations within the main flow deposits without exception demonstrate parallelism with the flow direction. No significant a-axis transverse to flow direction can be demonstrated. Imbrication analysis within the plug zone deposits at localities 3.4, 6.5 and in the basal zone at locality 5.2 indicate that cobble a-axes occur

Figure 2.20. Rose diagrams of clast groupings that show preferred a-axes orientations with respect to flow direction from the plug zone or mid deposit (localities 8.0 and 9.2), of the main flow deposits. The figures in brackets represent the direction of flow at each locality.

Figure 2.21. Rose diagrams of clast groupings that show no preferred a-axes orientations with respect to flow direction from the plug zone or mid deposit (locality 8.0), of the main flow deposit. The figures in brackets represent the direction of flow at each locality.

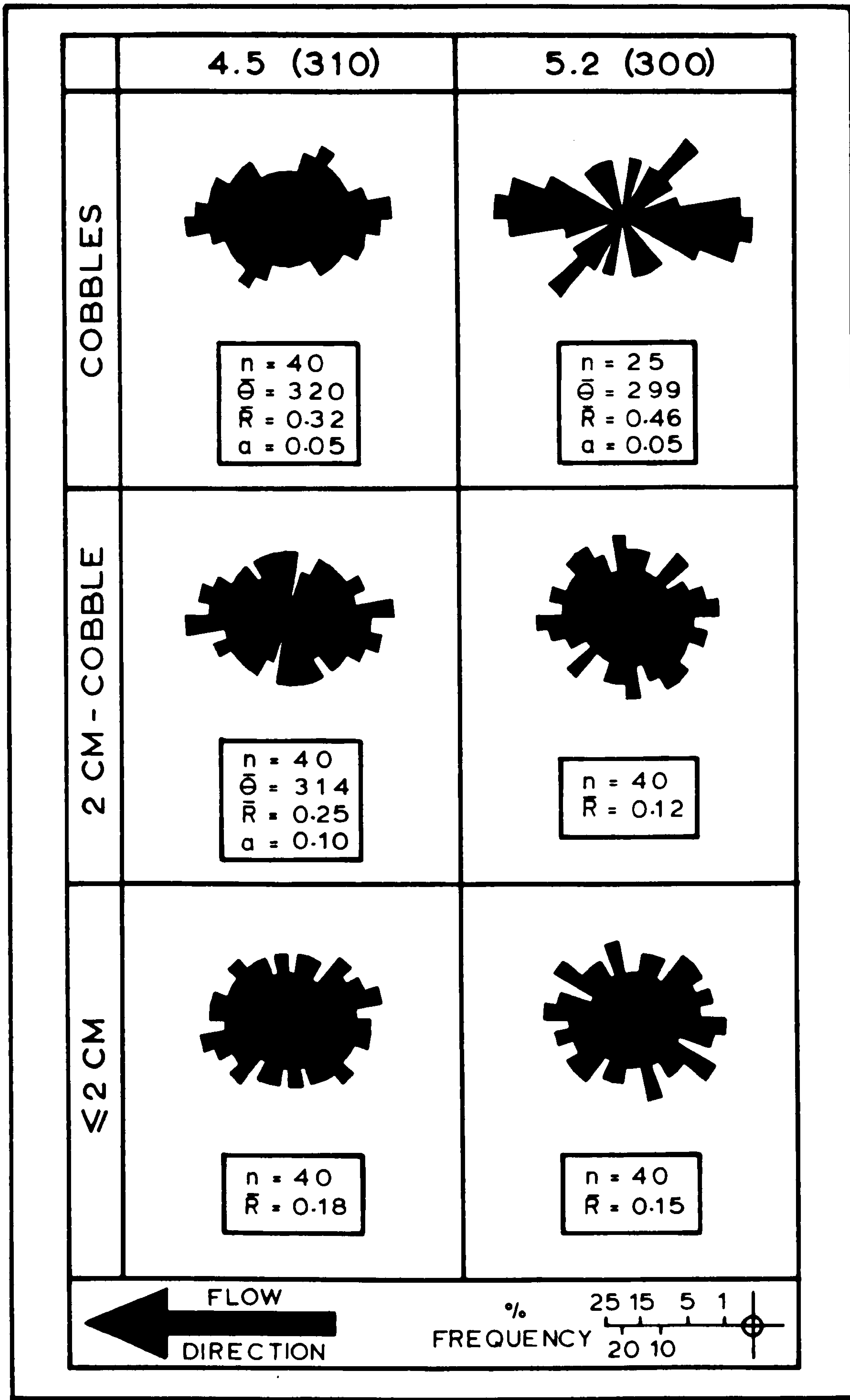


Figure 2.22. Rose diagrams of clast a-axes orientation with respect to flow direction within the basal zones of the main flow depositional sequences at localities 4.5 and 5.2. The flow directions are in brackets.

parallel to the base of the depositional units and are not dipping preferentially upstream or downstream (figure 2.23).

Thus, despite the generally round nature of the clast population, fabric analysis has indicated that within the main flow deposits the a-axes of the cobble sized clasts are preferentially orientated parallel to flow direction, within both the plug and basal zones.

Fabric analyses have also been conducted by several authors on the 1980 and 1982 Mount Saint Helens mass flow deposits. Mills (1984) found clast a-axes, both transverse and parallel to flow within deposits produced by the 1980 North Fork Toutle River lahar, the fabric being best illustrated in clast-supported deposits. Additional work on the 1980 North Fork Toutle River lahar deposits by Fritz and Ogren (1984) yielded flow-parallel clast a-axes orientations with upstream dips, in addition to clast a-axes orientations transverse to flow. Major (1984) found a preferred planar fabric developed where clast a/b planes were orientated parallel to the bedding surfaces within the south west flank lahars, but no consistently linear fabric was evident. Major and Voight (1986) further analysed the south west flank lahar fabrics and determined that both flow-parallel clast a-axes orientations with upstream dips and flow transverse orientations occurred. However, the fabric analyses of clast long axes did confirm the findings of Major (1984), indicating a strong planar orientation parallel to flow surfaces. Major and Voight (1986) after presenting their

Figure 2.23. The imbrication of clasts within selected depositional units, expressed as histograms.

data and reviewing the work of Mills (1984) and Fritz and Ogren (1984), conclude that clast fabric may be more variable and complex than previously thought. This statement is made by Major and Voight (1986) in an attempt to explain the variety of results yielded from studies of fabric in Mount Saint Helens mass flow deposits.

Major (1984) and Major and Voight (1986) are the only works that place fabric analysis into a background of other sedimentological information, concerning the particular deposits under examination. This is unlike Mills (1984) and Fritz and Ogren (1984), where only a brief undetailed account is given of the sedimentological characteristics of the deposits being studied. Thus, although the studies of Mills and Fritz and Ogren most likely represent accurate and valid findings for a particular deposit, albeit given the loosely defined term "lahar", inferences from them on the processes of sediment transport and deposition are dubious, without reference to background sedimentological information on the nature of clast support and grading. Hence, Major (1984) and Major and Voight (1986) contain the only fabric investigations comparable to this present study in terms of having supportive sedimentological information. The results of these works and this present study are also comparable in that in both situations a planar fabric is present with a-axes orientated parallel to flow direction in deposits produced from highly concentrated flows. However, within the south west flank lahar deposits, a transverse to flow fabric was also found at certain localities, which is in contrast with the findings of this study and will be discussed in section 2.6 once the rheological characteristics of the 1984 flow have been discussed.

LOCALITIES 8.0 AND 9.2

A-axis orientation analyses conducted at localities 8.0 and 9.2 yielded different results from those obtained in the previous section of the reach. The cobble sized clasts at locality 8.0 show a preferred orientation at a 5% significance level which is transverse rather than parallel to flow (figure 2.20). In addition, clasts of 2 cm and less in size at both localities show a preferred orientation parallel to flow at a 5% significance level, with clasts in the 2 cm to cobble size group at locality 9.2 also having a preferred parallel to flow orientation, but only at a significance level of 10%. Clasts between 2 cm and cobble in size at locality 8.0, show no preferred orientation (figure 2.21).

Analyses of imbrication using a sample of pebble sized clasts (figure 2.23), show a preferred orientation of a-axes parallel to the deposit base at locality 9.2, which is the same result as found in the rest of the reach. However, at locality 8.0 there is a preferred upstream dip of 9° which was not found elsewhere in the reach.

Statistical analysis of the two clast groups: cobble size and 2 cm and less at locality 8.0, show a significant bimodal orientation where the former group is transverse and the latter is parallel to flow direction. Although transverse to flow a-axis orientations and flow parallel a-axis orientations have been described from Mount Saint Helens mass flows deposits (Mills, 1984; Major and Voight, 1986), there is no description within these works concerning clast orientation bimodality within the same depositional unit, as a function of clast size. Smith (1986) describes a bimodal distribution that is a function of grain size within what Smith terms as "hyperconcentrated" flow deposits in the volcaniclastic Neogene Deschutes Formation in Oregon. However, the two groups of clasts which illustrate the bimodality (up to 15 cm and from 15 to 50 cm), are much coarser than the corresponding group in this study.

In non volcaniclastic deposits, transverse to flow a-axis orientations are an indicative feature of traction transport in river systems, where clasts are rolled on the bed (Rust, 1972; Walker, 1975a; Harms et al., 1982). This introduces a conundrum regarding interpretation of depositional processes, since in the same unit one group of clasts of a particular size is orientated in a manner indicative of deposition from suspension (Davies and Walker, 1974; Walker, 1975a, 1975b), whereas another group of different size is orientated in a manner indicative of formation by rolling on a river bed (Rust, 1972; Walker, 1975a; Harms et al., 1982). This has very important implications regarding the processes of sediment transport and deposition which will be discussed in section 2.6.

2.4.2.3. Fabric analysis within the recessional flow deposits

Fabric analysis was conducted within the recessional flow deposits at five localities along the reach. All of the units studied were described as homogeneous in the field, except for one unit analysed at locality 3.4, which is the upper inversely graded sub unit represented in log A figure 2.6. Only two localities 0.0 and 5.2 had cobbles showing a significant preferred orientation, the a-axes of the clasts being transverse to flow (figure 2.24). The other localities demonstrated no significant preferred orientation (figure 2.25). Clasts less than or equal to 2 cm in size at localities 2.0, 3.4 and 7.3 showed a significant preferred a-axis orientation which was parallel to flow direction (figure 2.24). Unfortunately the two groups of clasts (cobble and less than or equal to 2 cm in size) were not found to be significantly orientated at any locality in intimate association with each other and hence clast bimodality as illustrated at locality 8.0 within the main flow deposits was not seen. However, it can be stated that the recessional flow deposits generally feature bimodality, if the results along the reach are taken as a whole.

Clasts between 2 cm and cobble size show a preferred a-axis orientation parallel to flow at a significance level of 5% only at locality 2.0. The same clast size group within the inversely graded sub unit examined at locality 3.4 shows a-axes preferentially orientated parallel to flow only at a

Figure 2.24. Rose diagrams of clast groupings that show preferred a-axes orientations with respect to flow direction from recessional flow deposits. All are homogeneous deposits except at locality 3.4 which is an inversely graded sub unit. The figures in brackets represent the flow direction.

Figure 2.25. Rose diagrams of clast groupings that show no preferred a-axes orientation with respect to flow from recessional flow deposits. All deposits are homogeneous except at locality 3.4 which is an inversely graded sub unit. The figures in brackets represent the flow direction.

10% significance level (figure 2.24).

In the field, the imbrication of clasts with a-axes dipping either upstream or downstream was not observed. Instead, clasts were orientated parallel to the bedding surface, as epitomised within an inversely graded sub unit at locality 3.4 (plate 2.4B). Detailed analysis within this sub unit at locality 3.4, confirmed that the a-axes of pebble sized clasts showed a preferred significant parallel orientation with respect to the bedding surface (figure 2.23).

The results of fabric analysis on the recessional flow deposits and the main flow deposits at localities 8.0 and 9.2 are very similar, the only difference being that within the recessional flow deposits, bimodality can not be illustrated between clast size groupings within single depositional units.

2.4.3. Bed thickness and maximum particle size relationships

The previous sections have shown a clear downstream decrease in grain size and bed thickness of the main flow deposits along the reach. A detailed investigation of the relationship between bed thickness and maximum particle size of the deposits was conducted following the work of Bluck (1967). Bluck indicated that the thickness of a conglomerate bed (BTh) and the maximum particle size (MPS) within the bed, could be used as an approximation of the thickness and competence of a depositing flow at the point of measurement. Competence can be described as the size of the largest particle that can be completely supported above the bed (that is, suspended in the debris matrix) over the life of the flow (Hampton, 1975, 1979). Following Bluck's (1967) work, several authors have shown from various successions that mass flow deposits demonstrate a significant positive linear correlation between bed thickness and maximum particle size (Steel, 1974; Larsen and Steel, 1978; Nemec et al., 1980; Gloppen and Steel, 1981; Porębski, 1984; Nemec and Muszyński, 1982; Nemec et al., 1984; Walton and Palmer, 1988). Conglomerate of a fluvial origin formed from stream bed load does not show such a correlation, due to the grain-by-grain mode of deposition, according to Bluck (1967), Steel (1974) and Nemec and Muszyński (1982). Hence, a significant BTh/MPS correlation has been used to support the inference of a mass flow mode of deposition.

One hundred and eighty one measurements of BTh and MPS were taken from the 1984 main flow deposits along the reach from both channel and terrace. One hundred and sixty three measurements represent the deposits downstream to and including locality 7.3. The other eighteen sets are representative of the deposits at locality 8.0 and beyond, excluding the deposits at locality 9.2. The more proximal group (locality 0.0 to 7.3) encompasses deposits with a discernible plug zone (albeit only preserved as remnants at locality 7.3) which the more distal group (locality 8.0 and beyond) lacks. The BTh measurements of the deposits downstream to and including locality 7.3, incorporates both plug zone and basal zone, whereas the bed thickness of the deposits downstream from locality 7.3 was simply the thickness of the entire, essentially homogenous unit. The thickness of the recessional flow deposits that cap many of the main flow depositional units was not included in the BTh measurement, as it represented a different flow albeit produced in the same 1984 event. Following Bluck (1967), the MPS is the arithmetic mean of the ten largest clasts within the section of the deposit to be studied.

The two groups of measurements were statistically analysed using the least-squares regression line analysis method, outlined by Till (1974) and yielded strong significant positive linear correlations (figure 2.26). Following Bluck (1967), it can be inferred from figure 2.26, that both the proximal and distal 1984 main flow deposits are the result of deposition from a mass flow rather than from deposition from tractive processes in a normal fluvial regime. In addition, a very high correlation between BTh and MPS suggests a well established equilibrium between the competence and thickness of the depositing flows: this being typical for debris flows with a high component of dispersive pressure (Gloppen and Steel, 1981). Gloppen and Steel state that deposits from such flows are inversely graded, which is the situation found in this study.

If it is established that there is a strong positive

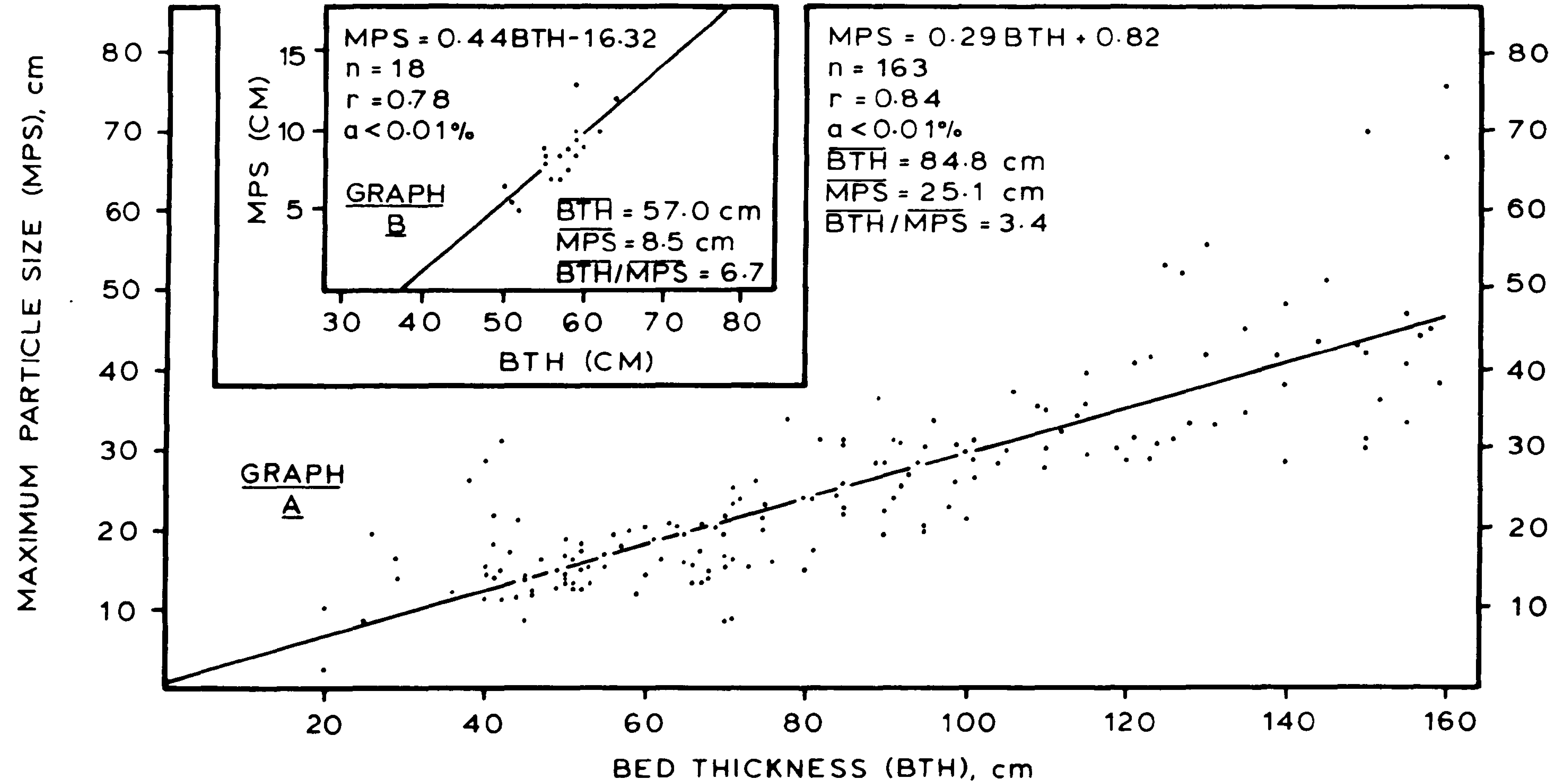


Figure 2.26. Graphs of bed thickness (BTh), against maximum particle size (MPS) for main flow deposits. Graph A represents deposits downstream to and including locality 7.3; graph B (inset), represents deposits at locality 8.0 and beyond; the oblique lines with corresponding equations are least-squares regression lines fitted to the data. $\overline{BTh}$ and $\overline{MPS}$ represent the average values of BTh and MPS respectively.

linear correlation, the BTh/MPS diagram can be used further to infer whether the mass flow deposits have been deposited from dominantly cohesive or cohesionless flows. Nemec and Steel (1984) state that provided the data reveals a high positive correlation the BTh/MPS diagram and its "best-fit-line" can be considered in terms of a model BTh/MPS diagram (Nemec and Steel, p. 22), where the presence or absence of a positive intercept on the Y axis (MPS axis), termed the "cohesive strength factor", represents cohesive or non cohesive debris flow respectively. The proximal group of 1984 deposits (graph A), when compared to Nemec and Steel's (1984) highly idealised conceptual model, cannot be inferred to have been deposited from either cohesive or cohesionless flow, due to the very low positive intercept on the Y axis. The distal group (graph B) does not have a positive intercept on the Y axis and thus can be inferred to have been produced from a cohesionless flow. These plots are discussed further in section 2.6 where all the sedimentological information and considerations of flow rheology are assimilated.

According to Gloppen and Steel (1981) and Porębski (1984), the distinction between high and low competence flows can be made by considering the BTh:MPS ratio and the gradient of a regression line. The regression line gradient of the two groups in this study are markedly different, in that the more proximal group, which contains deposits with a well defined plug zone (albeit only preserved as remnants at locality 7.3), has a much shallower gradient (figure 2.26) than the more distal group of deposits which lack a plug zone. The BTh:MPS ratios are also considerably different, being 3.4:1 for the former group and 6.7:1 for the latter. Porębski (1984) found a similar variation in regression line gradient and BTh:MPS ratio between proximal and distal conglomerate beds on a Devonian subaqueous fan delta succession, as did Gloppen and Steel (1981) for subaqueous and subaerial fan conglomerates. The proximal and distal deposits were inferred by Porębski (1984) and Gloppen and Steel (1981) to have been produced by competent and less competent flows respectively.

In summary, use of the BTh/MPS diagram has shown a strong linear positive correlation between BTh and MPS for two sedimentologically distinct groups of deposits from the 1984 main flow, which indicates that both groups are the results of deposition from a mass flow rather than a stream flow. The more proximal group of deposits which has a well defined plug zone (except at locality 7.3), has a regression line with a small positive intercept on the Y axis that indicates deposition from neither a dominantly cohesive nor cohesionless flow. In contrast, the distal group which lacks a plug zone has a negative intercept on the Y axis indicating deposition from a cohesionless flow. The regression line slopes infer a difference in flow competency, the more proximal group with the plug zone being produced from the more competent flow.

2.4.4. The distribution of fragile clasts

Rare fragile cobble and boulder sized rounded masses of soft, loosely consolidated material, consisting mainly of silt, were found within the main flow deposits (plate 2.11B). These clasts were derived from bank collapse or from the 1980 debris avalanche during the erosional stage of the 1984 flow, before it reached locality 0.0 (Pringle and Cameron, in press). In the more proximal localities 0.0 to 3.0, the fragile clasts were found within the plug zone and projected through the recessional flow deposits like other large but non fragile rafted clasts. Beyond locality 5.2, boulder and large cobble sized fragile clasts do not occur, but very rare pebble sized fragile clasts were found as far downstream as locality 7.3. Due to the round nature of the fragile clasts no fabric analysis was conducted.

In order to quantify the change in fragile clast numbers with distance along the reach, a ratio of the number of fragile clasts in a deposit, both in the channel and on the terrace, to the longitudinal sectional area (deposit extent, or length, multiplied by the deposit thickness) of the depositional sequence, was plotted with distance along the reach for each locality (figure 2.27). The counting was conducted along eroded channel parallel sections of the deposits, where fragile clasts were well exposed and not on the surfaces of deposits. (the data collected is presented in appendix 3). Only clasts 10 cm and larger were counted,

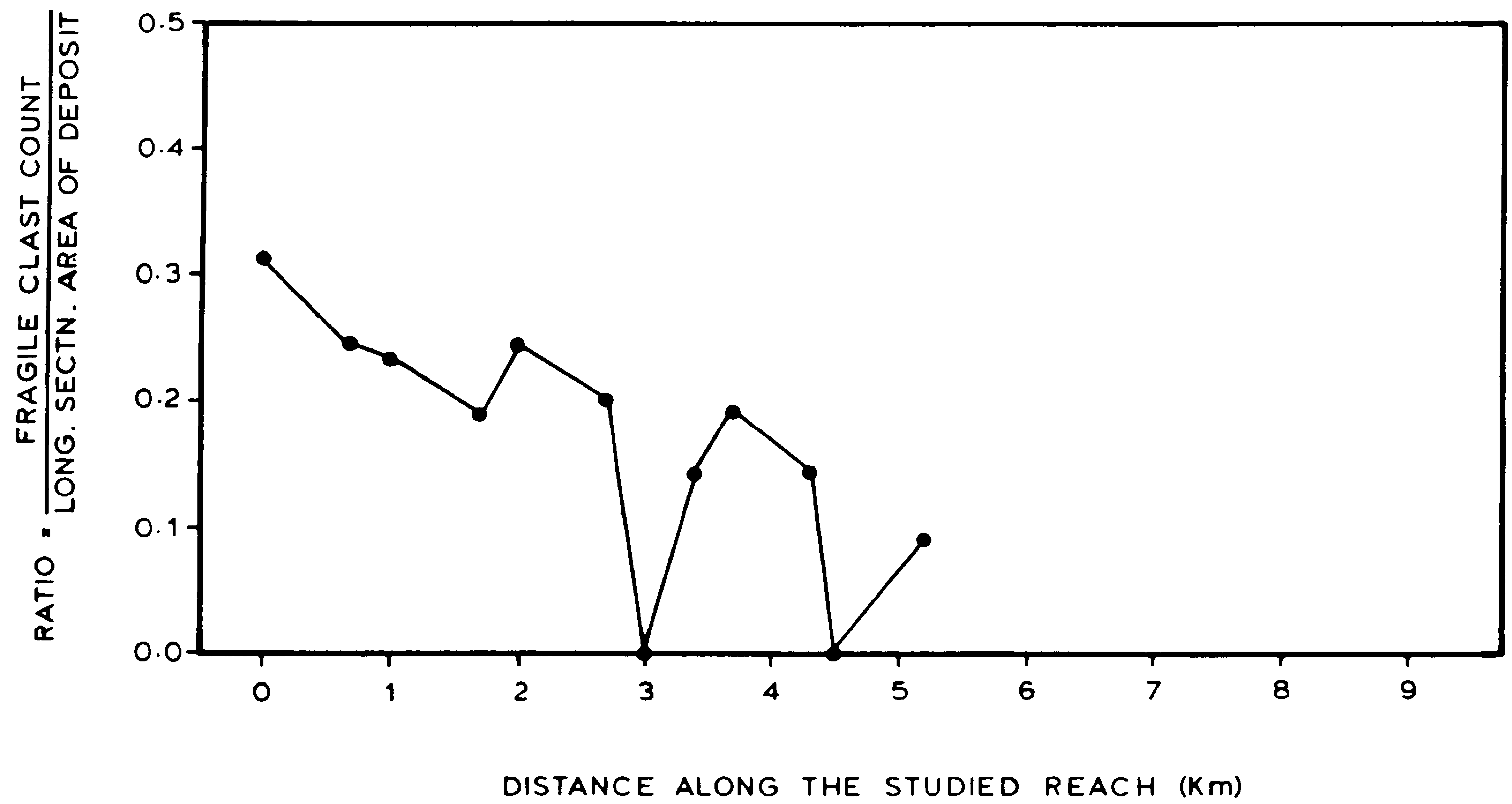


Figure 2.27. The variation of fragile clasts greater than 10 cm in size (expressed as the ratio of fragile clast count to the longitudinal sectional area of the deposit) with distance along reach.

as smaller clasts were very rare and difficult to locate. The plot shows a general downstream decrease in the ratio, with no fragile clasts greater than 10 cm in size present in the deposits beyond locality 5.2.

Pringle and Cameron (in press) produced a similar result and concluded that the fragile clasts were transported more or less intact in a rigid plug. This phenomenon of fragile clast transport within the plug zones of debris flows has been described elsewhere in non volcaniclastic debris flows by Johnson (1970), Hampton (1972), Carter (1975a) and Enos (1977).

The nature of the fragile clasts precludes their survival through transport in a turbulent stream flow regime and their survival in the 1984 mass flow is entirely due to their passive and relatively undisturbed transport within the plug. Their decrease in number and the disappearance of the larger clasts beyond locality 5.2, strongly indicates fundamental change within the flow, resulting in the loss of the plug. This is fully discussed in context with the other findings in section 2.6.

2.5. THE RHEOLOGICAL PROPERTIES OF THE 1984 MASS FLOW

2.5.1. Introduction

The previous sections have shown that there is a considerable change in the deposits produced from the 1984 flow in a downstream direction. This is related to the dilution and transformation of the flow as described by Pringle and Cameron (in press), who provide a valuable insight into the general characteristics of the flow. However, the observations of the 1984 mass flow event documented by Pringle and Cameron (in press), are mostly of the recessional flow that followed after the main flow (lahar). Only at a point twenty four kilometres from the crater was the passage of the main flow witnessed and sampled directly. Despite this, a considerable amount of information concerning the mass flow was compiled (figure 2.28). Further information concerning the rheological properties of the flow has been determined in this study, through laboratory investigations and the combination of these results with information extrapolated from Pringle and Cameron's original observations.

The aim of this section is to produce a background of the flow's rheological characteristics for section, 2.6., which endeavours to relate the 1984 flow deposit continuum to the processes of sediment transport and deposition.

Figure 2.28. The characteristics of the main 1984 flow and its recessional flow from the observations of Pringle and Cameron (in press).

2.5.2. The rheological properties of the mass flow

As mentioned in section 2.3.3 in the preliminary interpretation of the various depositional units, Johnson (1970) developed a rheological model for debris flows based upon both field observations and laboratory investigations. This is termed Johnson's Coulomb-viscous model which predicts a central plug or raft of rigid debris moving at a uniform velocity on a basal zone of shear. The parameters of cohesion and the angle of internal friction are important in the analysis of debris flow according to the Coulomb-viscous model. However, the effects of cohesion and the angle of internal friction cannot be investigated directly in the field and hence the yield strength (K) which incorporates the effects of these two parameters, must be derived instead. This involves the adoption of a slight simplification of Johnson's model for the analysis of debris flow, which is termed the Bingham model. In this model the flow can be characterised by the parameters of yield strength and Bingham viscosity (μB). Thus in this study the simplifying assumption is made that the 1984 flow behaved as a Bingham material and the yield strength and viscosity have been calculated from the methods of Johnson (1970, 1984). Application of these methods to deposits at five localities along the reach was conducted in order to assess any systematic change in flow properties corresponding to the observed flow transformation and mass flow deposits.

2.5.2.1. Yield strength

Johnson (1970) produced three methods to estimate yield strength of debris flows from their deposits. One method involves measuring the thickness of unconfined deposits, however, this is not applicable in this study, as the 1984 flow deposits are largely confined to the channel and the deposits that occur on the terracing exhibit no unconfined edge. Another method for estimating yield strength requires the dimensions of the channel plugged by debris, but in the case of the 1984 flow the width of the plug was not observed and hence any estimate would be conjectural. Although an estimate of plug width is made in 2.5.2.2, better constrained parameters can be used in the third method of estimating yield strength which involves the measurement of the largest clasts in a particular deposit. This method makes the assumptions that the transport of the largest clasts originates from a relatively small density difference between the clasts and the fluid debris, and that post depositional consolidation has been minimal. The yield strength is given by:

$$K = 0.219\, h\, (\gamma b - n\, \gamma d) \qquad \text{----- equation 1.}$$

where K is the yield strength (dyne/cm^2), h is the height of the largest clast (cm), γb and γd are the specific weights (density x gravitational acceleration [dyne/cm^3]) of the clast and debris matrix respectively, and n is the ratio of submerged to total clast height. The value 0.219 is the constant for zero internal friction (Johnson and Hampton, 1969). It should be noted that where large clasts projected upward through overlying recessional flow deposits, the thickness of the upper unit was not included in the calculation of n, since it not deposited from the main flow.

Before the estimates of yield strength could be made, it was necessary to calculate the densities of the clasts and the debris flow matrix. Calculation of the former involved the removal of a piece of the large clast which was then weighed under laboratory conditions in water and then in air, using a balance. The weight in air value was then divided by the difference between the weight in air and the weight in water values (a standard method outlined by the American Society For Testing and Materials). The calculation of flow matrix density was more involved and was conducted in the following way. A sample of matrix from the plug zone at locality 0.0 was reconstituted by the method of Fink et al. (1981), whereby small increments of water were added to the sample until it had the appearance of "flowing mud". This approximated the saturated bulk density of the flow at locality at 0.0 and corresponded to a sediment concentration of 86% by weight. This method is valid for the flow at locality 0.0, as the sedimentological information indicates that the plug in this vicinity was rigid and hence very highly concentrated. However, simply adding water to the matrix samples from other localities along the reach to obtain a "flowing mud" must give erroneous flow density values as the sediment concentration of the flow is not known and would therefore produce minimum estimates of water content. Only at twenty four kilometres from the crater was the sediment concentration of the flow determined by Pringle and Cameron (in press). This problem of determining flow density at intervals along the reach was overcome in two stages. Firstly, the saturated bulk density of a sample from a homogenous sub unit at locality 9.2, which most likely represents the texture of the 1984 flow deposits at the point twenty four kilometres from the crater (that is nearly 5 km further downstream), was assumed to represent the most likely saturated bulk density of the flow at that point. By making this assumption and using the value of 34% (by weight), which was Pringle and Cameron's (in press) measured sediment concentration in the flow, it enabled the determination of the approximate flow density at the twenty four kilometre point. The second stage in determining the flow density at intervals along the reach, involved plotting the values of the flow density at locality 0.0 and at the twenty four kilometre point, with distance along the reach (figure 2.29). From this graph, approximate values of flow density at a particular locality being studied could be determined. In addition to figure 2.29, this combination of laboratory estimation of flow concentration and actual field measurement has allowed the construction of a simple plot of sediment concentration versus distance along the reach, using the sediment concentration value derived at locality 0.0 and Pringle and

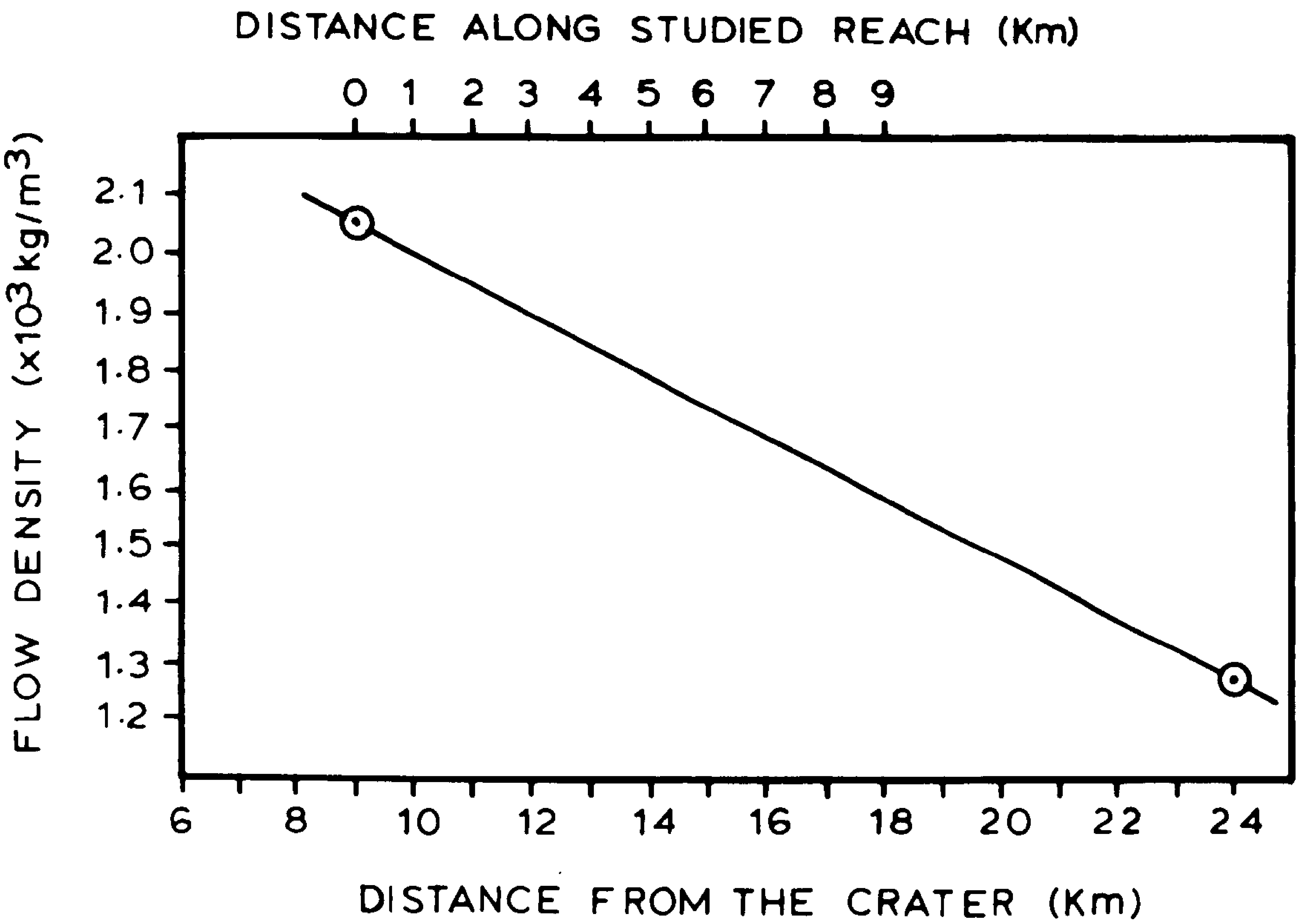


Figure 2.29. The variation in the density of the main 1984 flow with distance along the reach from the crater.

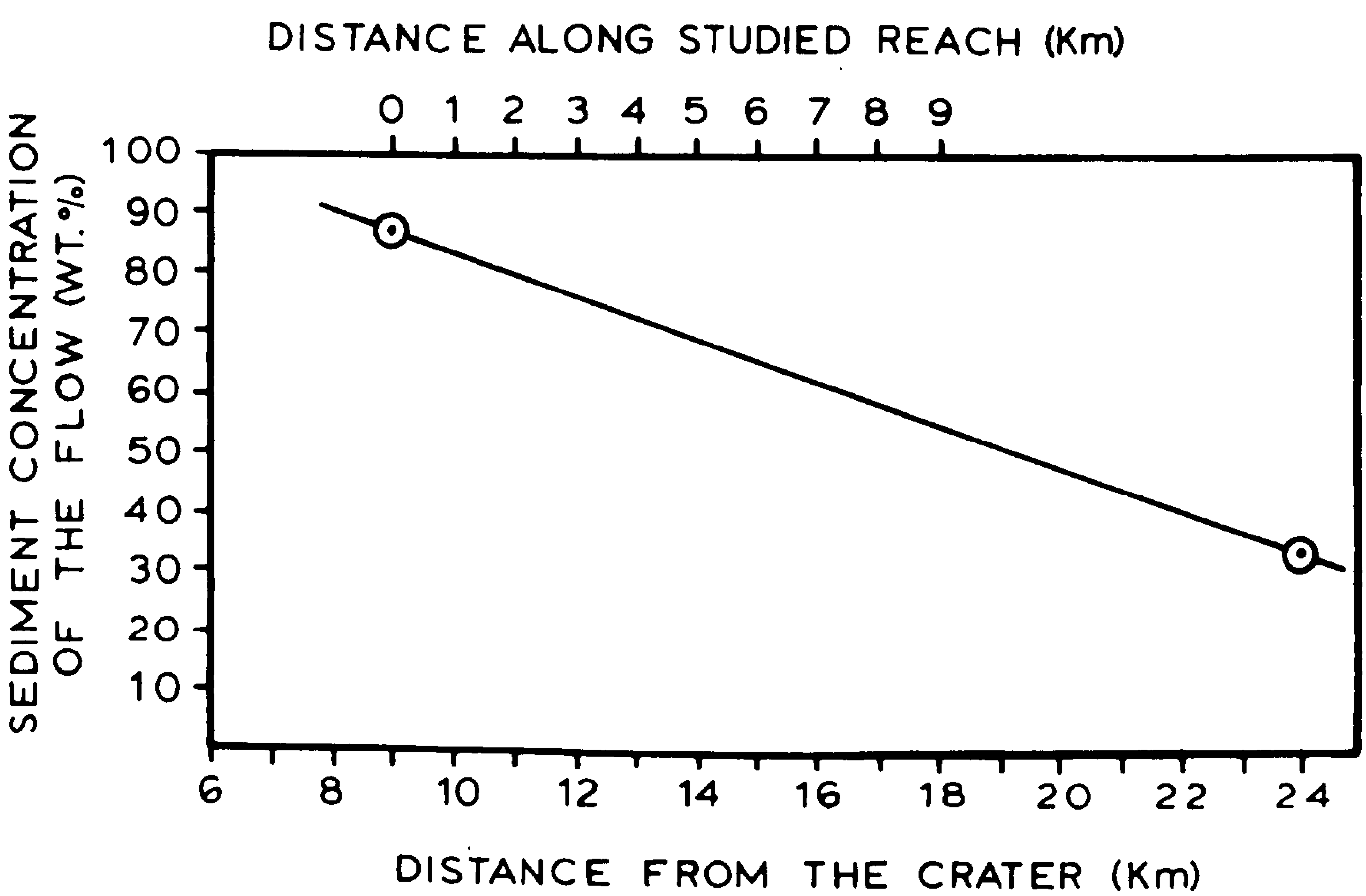


Figure 2.30. The variation of sediment concentration of the main 1984 flow with distance along the reach from the crater.

Cameron's (in press) measured value of 34% (figure 2.30).

The values of flow density from figure 2.29, together with the clast density values were converted to unit weights (dyne/cm^3) through multiplication by 980 cm/s^2 (the acceleration due to gravity). The unit weights together with the other parameters used in equation 1 are presented in appendix 4. The average values of yield strength obtained using two or more large clasts at each locality are plotted with distance along the reach (figure 2.31). The plot illustrates a general downstream decrease in yield strength with an anomalous decrease at locality 3.7, or alternatively an anomalous increase at locality 4.3. From an examination of the data set (appendix 4) there is no indication as to the cause of such variation, for example, in terms of anomalous values of n or unit weights. However, the general decrease in yield strength downstream endorses Pringle and Cameron's observations of the flow and the findings from the deposits, which indicate that the flow transformed as it progressed downstream.

The values of yield strength which range from 5.67×10^3 to 2.46×10^4 dyne/cm^2 are directly comparable to the other values obtained from volcaniclastic mass flows at Mount Saint Helens (Fink et al., 1981; Major, 1984; Pierson, 1985a). However, there is no indication from these earlier works of a downstream decrease in yield strength as demonstrated by the 1984 flow.

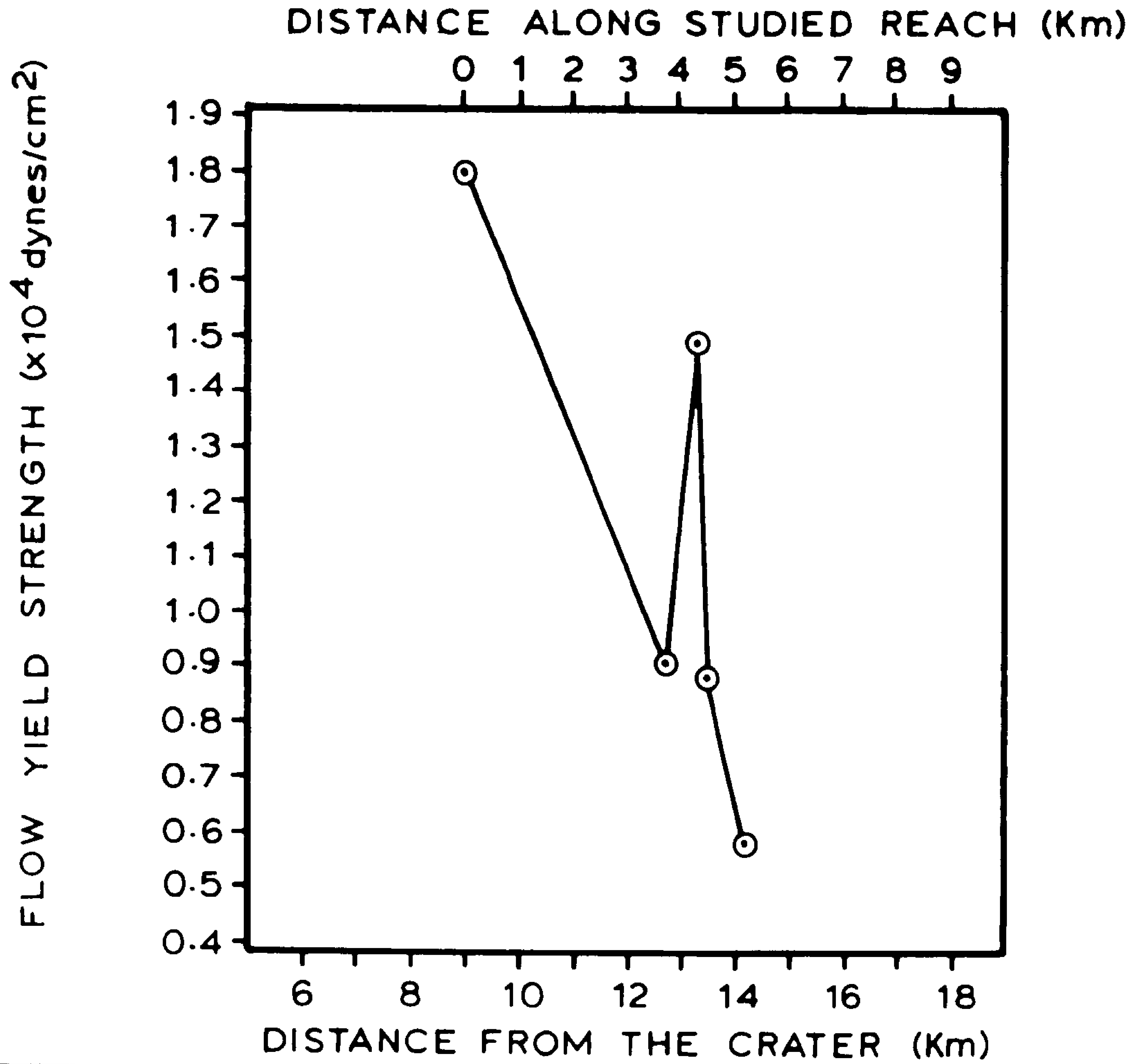


Figure 2.31. The variation of yield strength of the main 1984 flow with distance along the reach from the crater.

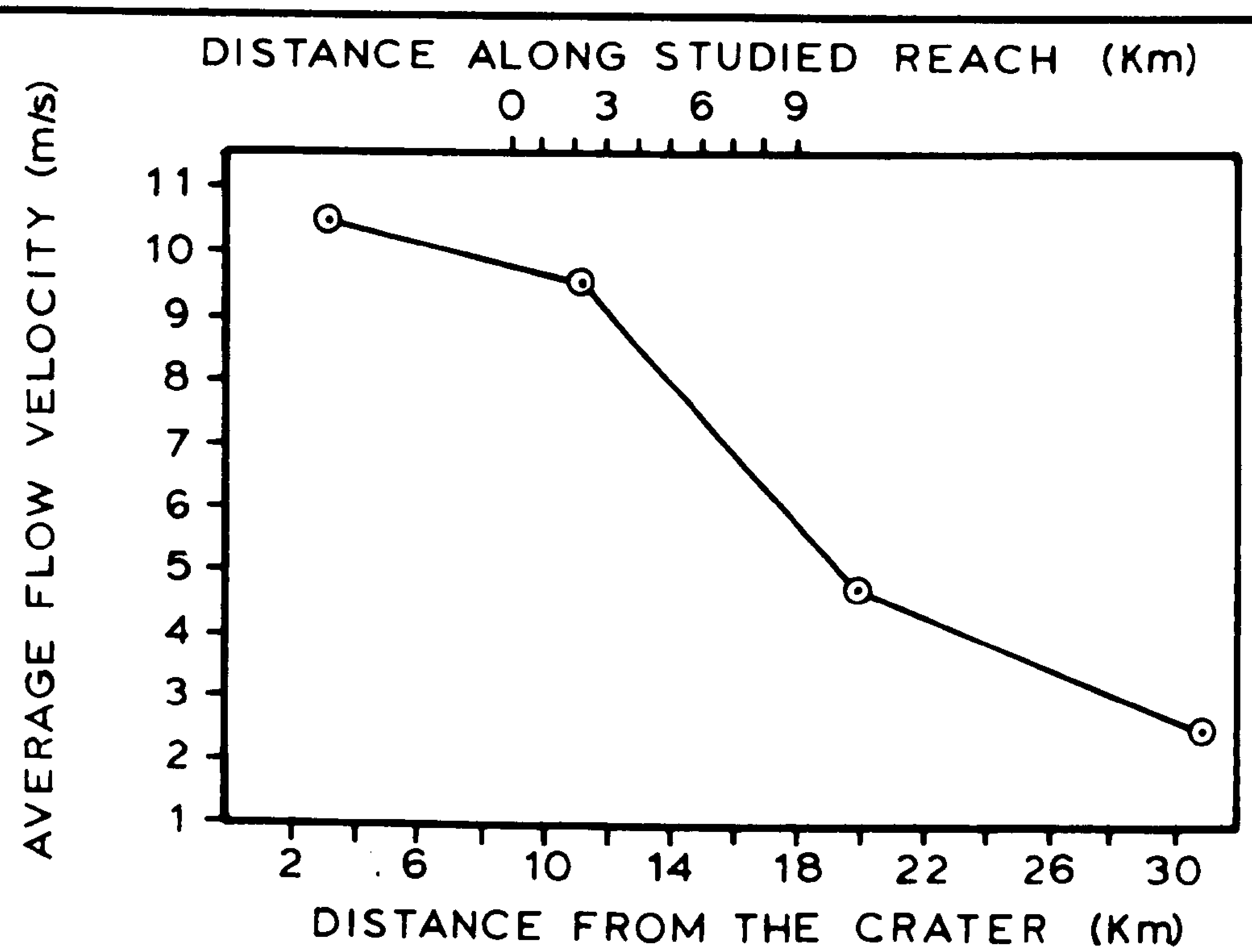


Figure 2.32. The variation of the velocity of the main 1984 flow with distance along the reach from the crater.

2.5.2.2. Bingham viscosity

As previously outlined, yield strength is one of the two parameters that characterise Johnson's (1970) Bingham model, the other is Bingham viscosity. An approximation of the Bingham viscosity of a flow can be determined using Johnson's equation:

$$\mu B = (K\ Wp\ /\ 4\ Vm)\ [(W\ /\ Wp) - 1\ ]^2 \quad \text{----- equation 2.}$$

where μB is Bingham viscosity (poise), K is the yield strength (dyne/cm^2), Wp is the width of the plug (cm), Vm is the maximum velocity of the plug (m/s) and W is the width of the flow (cm).

There could be considerable error in such a calculation as the errors produced from the calculation of yield strength may be compounded. In addition, error is introduced through the assumptions concerning plug width, flow width and velocity. However, an estimation of this value does allow comparisons to be made with similar investigations elsewhere.

The velocity at each locality used in equation 2. was derived from a graph (figure 2.32) constructed from the average values given by Pringle and Cameron (in press). The assumption in this case is that the plug was moving at the same velocity as the flow and that the use of average values is valid in an equation that requires maximum values. The width of the channel, which is equal to the width of the flow (Pringle and Cameron, in press), was measured at each locality by pacing and includes an estimate of the deposit extent on the terrace, where present. Although this is accurate, the estimation of plug width may introduce a major source of error, as it was not observed. Hence it was assumed to be one half of the flow width, as in an example illustrated by Johnson (1984, p304) for a non volcaniclastic debris flow.

The values of Bingham viscosity calculated using equation 2. and the parameters used in their derivation are given in appendix 4. When plotted with distance along the reach, the Bingham viscosity shows a general downstream decrease, with values varying from 8.52×10^3 to 2.5×10^4 poises (figure 2.33). In view of the clear downstream decrease in yield strength, a similar decrease in Bingham viscosity was expected. However, the errors inherent in the calculation introduce concern over the validity of this trend. The values are comparable to those of Major (1984) for the south west flank lahars, but are much lower than other Mount Saint Helens mass flows (Pierson, 1985a; Fink *et al.*, 1981), and other non volcaniclastic mass flows (Johnson, 1970; Morton and Campbell, 1974; Pierson, 1980). This is due to the large channel width, the like of which is not recorded in these other rheological studies.

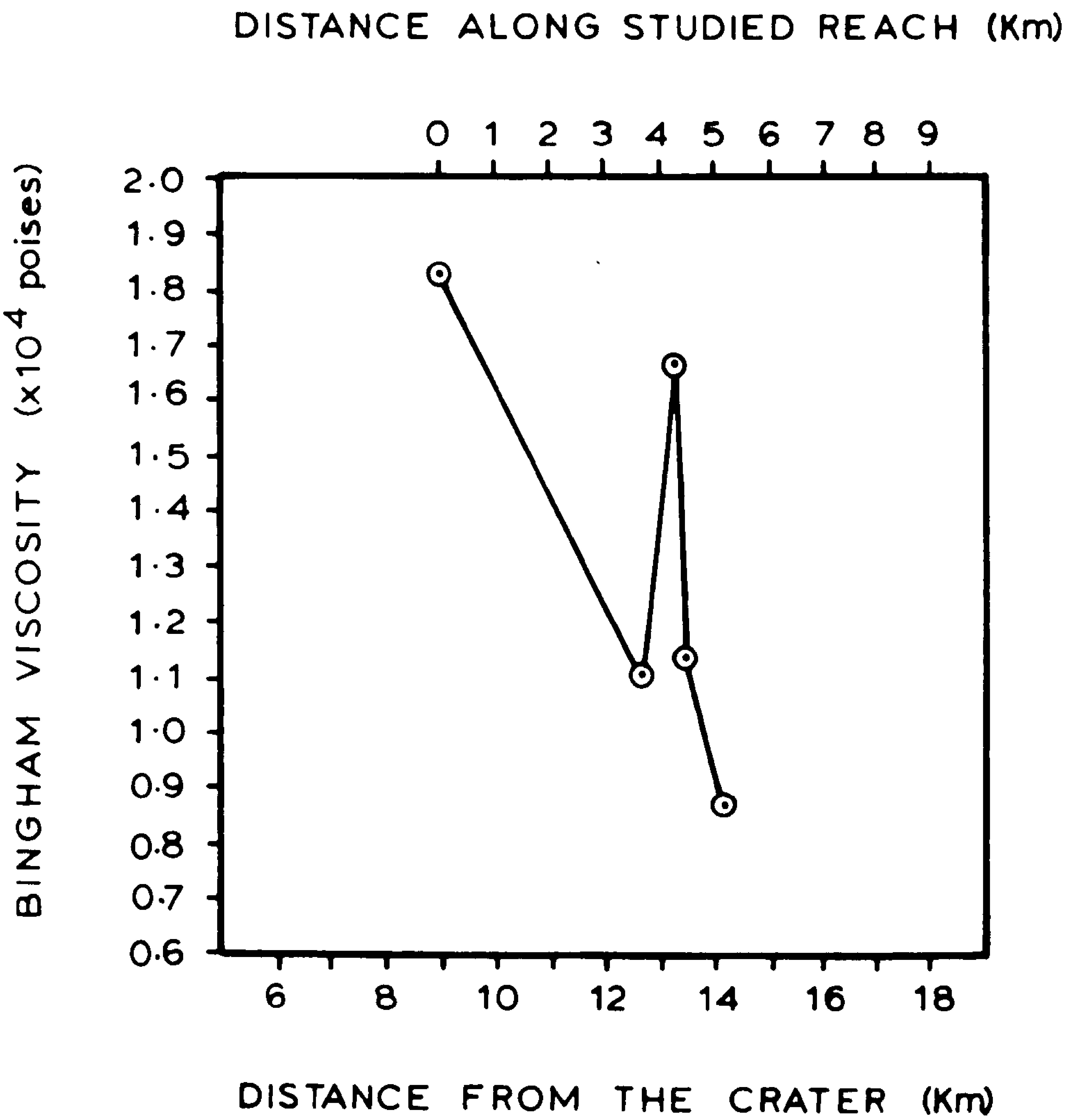


Figure 2.33. The variation of estimated Bingham viscosity values with distance along the reach.

2.6. THE RELATIONSHIP OF THE DEPOSITIONAL SEQUENCE TO THE PROCESSES OF SEDIMENT TRANSPORT AND DEPOSITION WITHIN THE TRANSFORMING FLOW

2.6.1. Introduction

So far this chapter has presented the detailed and systematic characterisation of a spectrum of deposits from the 1984 mass flow at Mount Saint Helens. Details of the processes of sediment transport and deposition within the diluting, decelerating and transforming flow can now be discussed, using all the information obtained from the deposits and by considering flow rheology.

This section deals firstly with the main mass flow and secondly with the recessional flow. Discussion of the former is divided into four sections which correspond to downstream changes within the deposit continuum and the discussion of the latter is divided into three sections that correspond to the three sedimentologically distinct groups of recessional flow deposits.

2.6.2. The main flow deposits from localities 0.0 to 2.0 inclusive

The deposits produced by the flow in this section of the reach were thick, very poorly sorted, matrix to clast-supported, unstratified polymodal conglomerates that had no

Grain size analysis of the proximal 1984 main flow deposits, indicate that clay and silt sized particles compose less than 2% of the sediment (appendix 1A). The clay fraction which comprises only less than 1% of the sediment, like the clay fraction in other Mount Saint Helens mass flow deposits, is composed of lithic fragments, rather than clay minerals (Pierson personal communication, 1987). Such a low level of silt and clay is not unusual in debris flows according to Fisher and Schminke (1984) and Rodolfo (1989). Most volcaniclastic debris flows are notably depleted in silt and clay whereas non volcaniclastic debris flows contain significant fractions of these particles.

The low clay content of these deposits indicates that the flow was dominated by frictional and inertial effects rather than by cohesive forces as would be expected in a flow with abundant fine grained particles (Fisher, 1971). This relative importance of cohesive or frictional effects has been utilised by Lowe (1979) to erect two types of debris flow, cohesive debris flow/mudflow and grainflows. However, according to Lowe (1979, 1982), the abundance or scarcity of silt and clay in the matrix does not seem to be a reliable discriminant criterion. Hence, using Lowe's (1979) classification, Nemec and Steel (1984) have concentrated on making the distinction between what they term cohesive debris flows or mudflows and cohesionless debris flows or grain flows, based on the use of the BTh/MPS diagram. Nemec and Steel (1984) claim that on such a diagram the distinction between dominantly cohesive and dominantly cohesionless flows can be made (section 2.4.3). According to this diagram (figure 2.26), the 1984 flow at this proximal section of the reach (and downstream to and including locality 7.3), was neither dominantly cohesive or cohesionless as the regression line had only a very minor positive intercept on the Y (MPS) axis. Therefore, despite the use of the BTh/MPS diagram, there is no clear indication in this study that the flow in the proximal reach had cohesive strength. However, unlike Scott (1988a) who on the basis of low clay contents argued that Mount Saint Helens mass flows in general were cohesionless, the view is taken here that the 1984 flow in this proximal reach had some degree of cohesion. Albeit in small amounts, the silt and clay fraction of the flow combined with water and aided in the support and lubrication of clasts. This must have been the case as the buoyancy of the larger clasts in debris flow is dependent in part upon the fine grained matrix (Costa, 1984). Buoyancy as indicated in section 2.3.3, is an important support mechanism of larger clasts (Johnson, 1970; Hampton, 1975, 1979; Middleton and Hampton, 1976). Large clasts literally float within the debris because of the small density differences between the clasts and the rest of the debris. This is augmented by the silt and clay mixture in the matrix as outlined in 2.3.3..

Among the boulder sized clasts buoyed up and rafted along within the plug were fragile clasts, which were indicated to have been supported and transported undisturbed (section 2.4.4). Fragile clasts in debris flows have been described elsewhere (Johnson, 1979; Hampton, 1972; Carter, 1975b; Enos, 1977; Lawson, 1982) and in all these examples preservation of these clasts was due to transport in rigid non-deforming plugs where intergranular motion was near absent. Immobility of clasts within the plug of the 1984 flow in this proximal reach is also indicated by the random clast fabric, as a strong clast fabric indicates laminar flow (Enos, 1977).

Despite apparent immobility of the clasts within the plug, the upward movement of cobble and larger sized clasts out of the finer grained basal zone must have occurred. This zone as indicated earlier in this section, represents the basal zone of shear upon which the rigid non-deforming plug moved and which is predicted by Johnson's (1970) Coulomb-viscous model. This movement of larger clasts up into the plug zone did not produce inverse grading within the plug itself and thus the process was restricted to the base. Inverse grading in debris flow deposits is widely believed to be the result of dispersive pressure (Schminke, 1967; Johnson, 1970; Fisher, 1971; Sallenger, 1979; Lowe 1982), which as indicated in section 2.3.3, is a mechanism of clast support resulting from clasts being sheared together (Bagnold, 1954). According to Bagnold, when particles are sheared together the larger clasts will drift toward the zone with the least rate of shear. In this case large clasts in the basal zone beneath the rigid plug moved up into the plug zone. However, these clasts did not move further up into the plug, which as indicated above was unsheared. There have been other mechanisms proposed to explain inverse grading. Middleton (1970) found Bagnold's dispersive pressure arguments erroneous and suggested that inverse grading develops when "smaller particles... fall into the spaces between the larger particles and... displace the larger particles toward the surface". Naylor (1980) proposes an alternative mechanism for the formation of inverse grading, based on the strength loss (or sensitivity) that clay suffers on deformation. Naylor argues that in debris flows consisting of a plug zone and basal zone, the matrix shear strain decreases and its strength and competence increase upward toward the plug. This occurs as a result of the loss of strength clay experiences in the basal zone. The result is that "oversized clasts in the sheared layer would drop out of the flow and be left upslope", thus producing inverse grading. However, Naylor's sensitivity mechanism implies that relatively matrix free coarse lag deposits develop upslope of inversely graded beds.

Fisher and Mattinson (1968) and Mattinson and Fisher (1970), attempt to explain inverse grading at the base of conglomerate beds (within turbidite sequences) in terms of what they call the "Bernoulli boundary layer effect". This effect can be considered in terms of lift forces supplied to individual large particles resulting from lower pressure at the top than at the bottom of large particles, due to velocity gradients within the flow. However, Southard (1970) argues that the "Bernoulli boundary layer effect", is not possible.

The high values of flow yield strength, viscosity and sediment concentration estimated in section 2.5, strongly suggest that all the clast fractions within the flow were in close intimate contact with each other. Therefore, it is unlikely that small clasts were able to "fall into the spaces between the larger particles", as envisaged by Middleton (1970). The relevance of Naylor's (1980) mechanism for producing inverse grading in this study is largely negated, since clay sized material in the flow was not composed of clay minerals. In addition, nowhere in the entire 1984 flow depositional sequence are there any matrix free lags in lateral continuity with the inversely graded mass flow deposits. Therefore the mechanism proposed by Naylor for producing inverse grading, was not operational in the 1984 flow. Thus the dispersive pressure mechanism proposed by Bagnold (1954) for producing inverse grading, is the most feasible in this study.

The involvement of the three generally accepted clast support mechanisms of debris flow have been reviewed and applied to the 1984 flow in this proximal part of the reach. However, turbulence, which is the main sediment support and transport mechanism in water flows (Costa, 1988), can be ruled out as a major sediment support and transport mechanism in the flow at this reach, as the evidence presented overwhelmingly suggests laminar flow with en masse transport and deposition. From consideration of the extent of inverse grading and the lack of an ordered clast fabric, the laminar flow was restricted to the basal zone as Lawson (1982) describes for his type II flows. The absence of any scour on the pre 1984 flow fluvial deposits also suggests the lack of turbulence at the base of the flow (following the work of Enos, 1977)

The 1984 flow was not directly observed in this proximal section of the reach by Pringle and Cameron (in press) and so the general large scale mechanism by which deposition occurred, that is, whether or not the flow clogged the channel, is thus conjectural. A lack of deposits in mid channel areas indicates that the flow did not stop or clog the channel but continued and transformed downstream with a velocity estimated to be between 9 and 10 m/s (figure 2.32). The velocity estimates rule out a stop and start mode of deposition, (a mechanism observed by Johnson [1984]) in which a debris flow comes to a halt and clogs a channel and is remobilised by subsequent debris waves.

Johnson (1984) states that although plug zones are clearly visible in channelised flows, it is difficult to detect them in a wide flow. The Toutle River channel is up to 80 metres wide in this proximal section of the reach and it is probable that the plug zone was not continuous across the channel but was composed of several smaller plugs acting almost independently of each other. This concept can be used to explain how some deposition occurred while the bulk of the flow passed downstream and transformed through dilution. The possibility of multiple plugs in the same debris flow event has been postulated by Cas and Landis (1987), who describe a single debris flow deposit with several plugs contained within it. Cas and Landis (1987) suggest that during movement these plugs may have been flowing together but were separated by stationary or slower moving parts of the flow and were capable of sideways migration or movement, whereupon they were abandoned (deposited) at the flow margins. The abandonment of plugs that had migrated into channel margin areas would explain the production of the channel margin deposits in this proximal section of the reach of the 1984 main flow. Upon deceleration the shear stresses exerted upon the migrated flow segment would decrease and the lower part of the flow would progressively freeze as the yield strength of the debris was reached. The basal zone would progressively become part of the rigid non deforming plug (Fisher, 1971). Lawson (1982) and Schultz (1984) suggest that the factors which may cause such freezing are: 1) a decrease in flow thickness, 2) a decrease in bed slope, 3) the loss of water or interstitial fluids, or 4) a combination of all these factors. However, in this study the channel floor (bed surface) was found to be a flat braid plain and so there was no thinning of the flow or a decrease in bed slope, this excludes factors 1 and 2. The loss of water or interstitial fluids out of the debris into the fluvial sand and gravels of the channel margin as described by Hooke (1967) and Lawson (1982), that is factor 3, was in this case a distinct possibility.

Pringle and Cameron (in press) described a precessional flood phase in the channel preceding the 1984 main flow, but as its magnitude was not recorded it is difficult to determine whether the underlying fluvial sands and gravels at the channel margins of the proximal reach were inundated by the flood. If so they may have become water saturated immediately prior to the superimposition of the debris and hence brought about the reduced drainage of interstitial fluids from the flow. However, it is known that the proximal deposits were "not dry" several days after they were deposited (Pringle and Cameron, personal communication, 1987) and so the rapid draining or loss of the interstitial fluids from the flow during deposition is most unlikely. The flow, or rather the individual plugs that had migrated into the channel margin area, were thus deposited en masse as a result of freezing, through decreased shear stresses produced by a reduction of velocity. Once deposition occurred, the settling of clasts through the depositional sequence appears to have been insignificant, as large rafted clasts still protruded from the top of the deposit. Johnson (1984) described a similar situation in alluvial fan debris flow deposits. In the static deposits, grain to grain contacts or structural support were provided by a framework of clasts in contact with the bed and each other (Pierson, 1981; Costa, 1984).

2.6.3. The main flow deposits from localities 2.7 to 6.5 inclusive

In this section of the reach the 1984 flow had slowed down to between approximately 7 and 9.5 m/s (figure 2.32), with sediment concentration having declined to between 60 and 80% by weight (figure 2.30). Indications from section 2.5 are that the flow viscosity remained high compared to the previous reach but that yield strength showed a general decrease. The dynamics of the flow clearly changed and this must in part have been a consequence of sediment loss through deposition in the channel margin further upstream, as has been suggested of debris flows in general by Cannon and Savage (1988).

The deposits in this 3.8 km section of the reach are very poorly sorted matrix to clast-supported conglomerates, which show well developed coarse-tail inverse grading. Along the section the deposits become finer grained and better sorted, with the local development of clast fabric among cobble sized clasts. In addition large fragile clasts decrease in number, eventually disappearing from the plug zone beyond locality 5.2. Locality 5.2 and localities 4.3 and 4.5 represent the only sites along the entire reach where main flow deposition on the terrace is preserved.

Despite the decrease in the estimated values of both yield strength and sediment concentration, Johnson's (1970) Coulomb-viscous model is still applicable to the flow in this section of the reach, as a plug zone/basal zone arrangement is very much in evidence within the deposits. However, unlike the last section of the reach, there is no clear distinction between the two zones in the flow as they grade imperceptibly with each other. For discriminatory purposes in this study, the basal zone is generally defined as occurring below the level in which cobble sized clasts occur in the deposit. However, at localities 4.5 and 5.2, cobble sized clasts do occur scattered within the basal zone. The formation of the inverse grading is related to the support mechanism of dispersive pressure as discussed in the last section (2.6.2). Its role within the flow in this section of the reach is discussed in turn, after the two other particle support mechanisms, cohesive matrix strength and buoyancy.

Grain size analysis of the main flow deposits in this section did not involve the pipette analysis of the silt and clay fraction. However based on the analyses conducted, the amounts of silt and clay within the deposits was low and did not exceed 5.5% (appendix 1A). As indicated in the last section from the work of Hampton (1975), the silt and clay fraction together with water perform an important function in the support and lubrication of clasts in debris flow. Its role in the support of clasts in the last section of the reach was acknowledged. However, from the consideration of the work of Hampton (1979), it can be stated that in this more distal section of the reach the silt and clay fraction's effectiveness in supporting and lubricating clasts may have been diminished slightly, due to the estimated increase in water content of the flow. The BTh/MPS measurements of this section of the reach are plotted on figure 2.26, together with the rest of the deposits exhibiting a plug zone/basal zone arrangement and as discussed in the last section (2.6.2), the dominance of either cohesive or cohesionless behaviour within the flow, cannot be inferred from the BTh/MPS diagram because of the low positive intercept of the regression line on the Y (MPS) axis.

Buoyancy in this section of the reach was an important sediment support mechanism, as it was in the more proximal section. Although the flow had become slightly less concentrated, it still exhibited considerable yield strength and viscosity and so large clasts continued to float as a result of the small density difference between them and the rest of the debris. From the work of Pierson (1981), it can be suggested that this support was augmented by the loading by the large clasts of the finer grained matrix which produced excess pore pressures.

The thick zone of inverse grading in these deposits suggests that dispersive pressure within the flow described in the last section of the reach, became an important sediment support mechanism as the flow progressed downstream. The basal zone/plug zone arrangement, which was well defined further upstream, became diffuse indicating that dispersive pressure was producing vertical size gradation of clasts within a greater thickness of the flow and that the rigid plug boundary moved upward in the flow, in a manner similar to that described by Hampton (1975).

The shearing of clasts that produces inverse grading Bagnold (1954), also has the effect of producing preferred clast orientations (Lindsay, 1968; Fisher, 1971; Walker, 1975a; Enos, 1977; Lewis et al., 1980; Nemec and Steel, 1984). In this section of the reach, a clast fabric was well developed in both the basal and plug zones, where cobble a-axes were orientated parallel to the direction of flow, with no imbrication. This fabric is identical to that described elsewhere (Fisher, 1971; Heward, 1978) and is in marked contrast to the non-sheared plug zone upstream which possessed a completely disorganised clast fabric. Hein (1982) found several types of clast a-axis orientation in a variety of deep marine conglomerates, one of which was a unimodal, parallel to flow fabric as found in this study. Hein (1982) attributed this fabric to clasts moving under applied shear in a flow with strong grain interactions and high dispersive pressures in which the rolling of clasts was ruled out.

Turbulence as a major sediment transport mechanism is ruled out in this section of the reach, as in the last, because laminar flow indicators are prevalent. These include the plug zone/basal zone arrangement with associated fabric which indicated shear, the lack of scour marks and the presence of large rafted clasts, some fragile.

The large fragile clast count shows a decline along the reach and beyond locality 5.2 they disappear altogether, in section 2.4.4 this was thought to reflect profound change in the flow. Further upstream in the more proximal section, fragile clasts like the other large clasts were buoyed up within the rigid non-deforming plug above the basal shear zone, where shear was concentrated. This decline in numbers suggests that the fragile clasts were broken up and assimilated into the matrix of the flow. There are three mechanisms by which this could have happened: firstly, intense shear producing dispersive pressure, may have brought about the break up of the clasts through grain-to-grain collision. Secondly, laminar flow may have given way to brief transient periods of turbulence, as described in other debris flows by Lawson (1982) and hence through grain-to-grain interaction within the highly concentrated flow the clasts would have been broken up. Thirdly, the fragile clasts may have broken up as a result of a combination of the first two mechanisms. There is no sedimentological evidence of turbulent flow behaviour as described above and hence the first mechanism of fragile clast destruction is the more likely. Whatever the precise mechanism, it is clear that the rigid plug present in the flow upstream had become progressively weakened in a downstream direction with clasts becoming mobile. This loss of plug rigidity is reflected in the general decrease in yield strength estimates for the flow in this section of the reach (section 2.5). Additional good sedimentological evidence for the downstream loss of plug strength is exhibited at locality 5.2, where a boulder jam occurs within the deposits on the sloping channel margin (section 2.2.3, plate 2.7A). Field observations show that the leading boulder in the jam came to rest in a trough which it scoured on the underlying pre-flow fluvial deposits. The flow at this point was unable to suspend this large clast, which moved downward through the plug and basal zones, despite the shear stresses that were supporting the other clasts in the vicinity of the boulder (for example, the two cobbles immediately in front of the leading boulder as seen in plate 2.7A) and was hence transported as bed load. A series of other boulders subsequently piled up behind the large leading boulder as the flow continued downstream. A loss of plug strength during flow has been recorded elsewhere by Lowe (1982).

Localities 4.3, 4.5 and 5.2 represent the only points in the reach where main flow deposition occurred on the terrace. This could have arisen through a slowing of the flow in general in this part of the reach, with the result that a faster flowing more fluid component or surge, as described in flows elsewhere by Johnson (1984) and Rodolfo (1989), perhaps spatially detached from the main flow, overtopped the slowing main flow in the channel and hence flowed onto the terrace. Surging of the flow in this reach undoubtedly occurred as the repetition of the plug zone is clearly demonstrated at locality 5.2 in the vicinity of the boulder jam (plate 2.7A). As the flow at locality 5.2 moved over the terrace it thinned markedly. According to Lawson (1982) and Schultz (1984), such thinning is a mechanism of deposition. In addition, the loss of interstitial fluids from the debris with the resulting increase in matrix cohesive strength, may have aided the on-terrace deposition. This consideration is supported by the fact that the terrace was relatively unsaturated in water, unlike the channel floor which had been inundated by the precessional flood phase. Although thinning of the debris across the terrace may have been a function in deposition at locality 5.2, such a deduction at localities 4.3 and 4.5 is precluded due to the lack of extensive terrace exposure.

Deposition within the channel in this reach most likely resulted from the abandonment of a plug of material from the main flow that had migrated into the channel margin area as described for the deposits upstream. Upon slowing down, there would have been progressive freezing of the flow from the base upward as the yield strength of the debris was reached (Fisher, 1971). Settling of the clasts within the newly produced deposits seems most unlikely, due to the strength and viscosity of the debris. This view is endorsed when it is considered that the outsized clasts transported by the recessional flow did not sink into the recently deposited main flow deposits.

2.6.4. The main flow deposits from localities 7.3 to 8.5 inclusive

The flow in this section of the reach had slowed down to between approximately 6 and 7.5 m/s (figure 2.32), with sediment concentration having declined to between 55 and 65% by weight (figure 2.30). Unlike the deposits upstream, estimates of yield strength and viscosity based on Johnson's (1970) work have not been possible in this section of the reach, because the deposits do not posses a well developed plug zone/basal zone arrangement, or any rafted outsized clasts. However, it can be inferred, by an examination of the plots in figures 2.31 and 2.33 in section 2.5, that the yield strength and viscosity of the flow probably declined in this section of the reach. Although this comment on flow rheology is speculative, sedimentological considerations indicate that the dynamics of the flow continued to change profoundly along the reach. This must in part have been a result of sediment loss further upstream which was postulated in the last section.

The deposits along this section of the reach, which are generally poorly sorted and matrix-supported conglomerates, are markedly different from those upstream. The only similarity occurs at locality 7.3 where there is the remnant of a plug zone in the depositional sequence. Downstream from locality 7.3, the deposits are generally homogeneous with no plug zone, or plug zone remnant. However, at locality 8.5

there is local weakly developed inverse grading. In view of these characteristics that suggest the flow became unable to maintain a rigid non deforming plug, the applicability of Johnson's (1970) Coulomb-viscous model for the description of debris flow must be questioned in this section of the reach. The plug zone remnant at locality 7.3 can therefore be regarded as a very disjointed mass of sediment transported within the flow, rather than constituting a major coherent and rigid component of the flow, as did the plug zone further upstream. Beyond locality 7.3 the remnant of the plug zone was broken up within the flow, as no trace of it can be found further downstream at localities 8.0 and 8.5. In the vicinity of locality 7.3, the concentration and yield strength of the flow may therefore have been heterogeneous, with the remnant of the plug zone having greater sediment concentration and yield strength than the bulk of the encompassing flow. However, this suggestion cannot be verified based on the data available.

The silt and clay fraction of the sediments in this section of the reach amounts to less than 4%, but following the discussion of the last two sections, the silt and clay fraction would have had a role in the support and lubrication of clasts in the flow (after Hampton [1975]). However, this role would have been relatively minor compared to the flow upstream, because of the reduced sediment concentration and hence increased water content of the flow. Hampton (1979) suggests that the clay (silt and clay) fraction to water ratio is important when considering the effect of clay on flow mobility. Thus the greater the water content, the less the effect of the silt and clay fraction. From the BTh/MPS diagram (figure 2.26, graph B), the flow at locality 8.0 and beyond can be inferred to be cohesionless from the negative intercept of the regression line with the Y (MPS) axis. Thus the effect of silt and clay as a sediment support mechanism appears to have been minimal in the flow, in this section of the reach.

Buoyancy which arises through the density difference between submerged clasts and the fluid debris (Rodine and Johnson, 1976; Hampton, 1979), would be affected by the dilution of the clay and silt containing interstitial fluids. Since the effect of buoyancy is augmented by an increase in pore pressure, caused by the partial transfer of the weight of particles to the interstitial fluids (Costa, 1984), a reduction in the fines content of the interstitial fluids could lead to a more rapid dissipation of this increase in pressure. Therefore, there was a reduction in the role of buoyancy in this section of the reach.

The role of dispersive pressure is indicated by the inverse grading developed in association with the plug zone remnant at locality 7.3 and at the bases of the generally homogeneous units further downstream. Although the units in this section of the reach are described as matrix-supported, the only fundamental change texturally between these and the more proximal units, is the lack of large clasts. In addition there is no increase in the proportion of silt and clay. This suggests that the cohesivity of the flow does not increase (as borne out from the findings of the BTh/MPS graphs). Therefore, dispersive pressure, which is ineffective in cohesive sediment according to Smith (1986), would still be a major clast support mechanism.

In the previous section of the reach, it was demonstrated that as a result of the inverse grading (after Bagnold [1954]), clasts became preferentially orientated with a-axes parallel to flow direction and no imbrication. In this section of the reach, a clast fabric is developed at locality 8.0, which demonstrates bimodality in clast a-axis orientation as a function of grain size (section 2.4.2), where cobbles are orientated transverse to flow and pebbles are parallel to flow direction. In addition there was a slight upstream dip of 9° among the pebble sized clasts aligned parallel to flow, that is an a(p), a(i) fabric (notation after Walker [1975a]). Such bimodality of a-axis orientation as a function of grain size in mass flows is a rare phenomenon. It was revealed in section 2.4.2 that by applying generally accepted mechanisms of fabric formation a conundrum is introduced in the interpretation of this fabric. Since in the same depositional unit an a-axis transverse to flow orientation, characteristic of rolling on the bed as produced in experiments by Johansson (1965) and observed in river gravels by Rust (1972), occurs in the same depositional unit as an a-axis parallel to flow and imbricate upstream fabric, that does not indicate rolling on the bed (Davies and Walker, 1974; Walker, 1975a, 1975b; Harms et al., 1982), but which instead indicates deposition from suspension. Smith (1986) inferred that such a bimodal distribution represents rapid traction and suspension deposition, with turbulence being a primary sediment support mechanism aided by grain interactions in a highly concentrated dispersion. Within the dispersion smaller clasts were held within the flow above the bed, but the larger clasts were transported by traction. Smith's (1986) mechanism has to be rejected in the case of the deposits at locality 8.0, as it requires turbulence as a support mechanism and in this section of the reach the flow was laminar, as implied by the unstratified inversely graded nature of the deposits together with the high sediment concentration, yield strength and viscosity of the flow.

Bimodal clast a-axis orientation in deep marine conglomerates has been inferred by Hein (1982) to originate from a flow that had "high applied shear stress with strong grain interaction". Clasts within the flow were orientated with a-axes parallel to flow, but on deposition some clasts became reorientated through rolling and produced the a-axis transverse to flow orientation. Hein (1982) does not indicate whether the bimodality is a function of grain size, as found in this study and by Smith (1986). However, the inferences by Hein seem the most plausible in this section of the reach, where it is considered that the flow was still highly concentrated, had considerable yield strength and viscosity and was being sheared to produce inverse grading, albeit rather weak. As shown in section 2.4.2.2, the only other clast fabric analysis conducted on other mass flow deposits at Mount Saint Helens, that was comparable to this study in terms of having supportive sedimentological information, was that of Major (1984) and Major and Voight (1986) on the south west flank lahars. Major and Voight (1986) present similar results to those of this study, in which clasts showed planar and upstream dipping orientations, with a-axes parallel to flow, in addition to flow transverse a-axes orientations. Despite flow parallel and flow transverse clast a-axes orientations occurring in the same deposit, Major and Voight do not indicate whether these orientations represent bimodality and attribute the fabric in general to a "shear gradient" under "high-velocity conditions", with no further detail or explanation. Thus, although the results presented by Major and Voight (1986) are broadly similar to those of this study, a detailed comparison of flow characteristics is negated because of the lack of detail given by Major and Voight. If Major and Voight had chosen more than one clast size grouping to measure, they may have duplicated the findings of this work.

Deposition by the flow in the last two sections has been through en masse freezing of a segment of the flow as it migrated and slowed into the channel margin areas. However, in this section, although a segment of the flow may have migrated into the channel margin and been deposited, the actual deposition of the sediment may not have been simultaneous throughout the flow because of the lack of a rigid plug zone with an underlying basal zone. Deposition may have taken place in which a surface, separating stationary from moving particles, moves rapidly up through the flow as transport ceases, with the result that successively higher parts of the flow "shear out" from "over" earlier parts of the flow. This is a mechanism described by Carter (1975a) for the deposition of debris flows. Carter states that if the depositional surface migrates upwards gradually, a comparatively homogeneous bed might be expected. Alternatively, if the depositional surface migrates up more spasmodically, then the resulting bed might consist of several superimposed sub units. The generally homogeneous nature of the deposits in this section of the reach, would therefore suggest that the former gradual upward migration mechanism was operational. A rising plane of stationary particles as envisaged by Carter, would allow the development of reorientated clasts, through rolling, as inferred in this study (after Hein [1982]) to explain bimodality.

Following deposition, the recessional flood phase deposited generally fine grained sediment and boulders over the main flow deposits. This is well displayed at locality 7.3 (plate 9A). As in the previous two sections the presence of boulders on the newly deposited static mass flow deposits with no evidence of sinking, indicates that the debris possessed structural support from grain-to-grain contacts

(Pierson, 1981).

In summary of this section it can be stated that the flow continued to change downstream, becoming more dilute with the resulting increase in water content causing a decrease in matrix strength and buoyancy. At locality 7.3 and beyond the flow cannot be described in terms of Johnson's (1970) Coulomb-viscous model in which a rigid non deforming plug moves over a basal shear zone. Rather, the flow can be described as a highly concentrated dispersion, exhibiting a degree of strength and viscosity, in which clasts were able to move with respect to one another under shear.

2.6.5. The main flow deposits at locality 9.2

In this most distal section of the reach the flow had slowed to between approximately 5.5 and 6 m/s (figure 2.32), with the sediment concentration having declined to between 50 and 60% by weight (figure 2.30). At this locality estimates of yield strength and viscosity based on Johnson's (1970) work have not been possible because the deposits (as found upstream between localities 7.3 and 8.5), do not possess the features of debris flow, for example, outsized rafted clasts. However, in contrast to the deposits further upstream, the deposits are poorly sorted granule sands which are horizontally stratified to form sub units on a centimetre scale (section 2.3). These deposits indicate that the flow had undergone further fundamental changes in character as it progressed downstream.

These deposits represent the finest grained main flow deposits in the entire reach and represent a complete departure from the sequences upstream, which either demonstrated a plug zone/basal zone arrangement (localities 0.0 to 6.5, with only remnants of a plug zone at locality 7.3), or were generally homogeneous (localities 8.0 and 8.5). However, the presence of a coarse grained homogeneous unit which forms the most distal of the exposures that constitute locality 9.2 (plate 2.10C), represents a localised return to the depositional style present upstream at localities 8.0 and 8.5.

Clast support mechanisms in the flow at locality 9.2 are difficult to infer from the deposits, as there is no rigid plug which would implicate cohesive matrix strength and buoyancy. Neither is there any obvious evidence of turbulent behaviour which would manifest itself as scour on the underlying deposits (Enos 1977). Thus, in order to envisage the characteristics of the flow, the findings of other authors from experimental and field investigations have to be considered.

As mentioned above, the flow had a sediment concentration of between 50 and 60% by weight and a flow density (estimated in section 2.5) in the order of 1.5 to 1.6 g/cm. This indicates that the flow could still have possessed yield strength (Chu, 1980; Qian _et al_., 1980; Yang 1983; and Engelund and Wan, 1984) and therefore may be regarded as a non-Newtonian fluid. In comparison to clear water, the high sediment concentration would have resulted in much reduced clast fall velocities (Nordin, 1963; Simons *et al.*, 1963; Howard, 1966; Graham and Bradley, 1982; Wan, 1985). In addition, clast interactions would have dominated flow behaviour (Bagnold, 1956), with turbulence being severely suppressed (Hino, 1963; Howard, 1966; Dai *et al.*, 1980; Itakura and Kishi, 1980; Qian *et al.*, 1980; Wang *et al.*, 1983; and Wan, 1985).

The flow at this locality can thus be regarded as a highly concentrated, viscous sediment/water mixture which may have exhibited a degree of yield strength. Clast interactions dominated the flow behaviour, with turbulence having a minor role in sediment support. Although clast fall velocity was considerably less than in clear water, sediment must have settled through the suspension to produce the depositional sequence, as an en masse mode of deposition, in terms of a plug zone/basal zone arrangement, is not evident at this locality.

The deposits as mentioned above, consist of a stack of thin granule sand sub units. They have coarse-tail inverse grading that in some sub units does not persist laterally for the length of the exposure (section 2.3). In a vertical sense, the sub units grade into each other with no layers of fines or other well defined breaks separating them. This suggests that the deposition of these sub units, although not en masse in terms of a flow with a plug zone, did occur without a break in sedimentation.

These sub units are very similar to deposits in the geological record produced by turbidity currents described by Lowe (1982). Both are granule sands with a depositional thickness of between a few centimetres and 15 cm. The depositional units Lowe (1982) described were formed by what he termed "a coarse grained high-density turbidity current". Clasts in the flow were supported by turbulence and hindered settling and at some point during flow Lowe envisaged that the sediment concentration at the bed increased progressively. As the concentration increased, sediment transport at the base of the flow became increasingly dominated by grain collisions, leading to the formation of a "traction carpet". This was a basal layer of particles that was maintained by dispersive pressure and which was "fed" by a "rain" of coarse grained sediment from the turbulent flow above, however, turbulence in the basal layer (traction carpet layer) was suppressed by dispersive pressure. Continued sediment fallout from the overlying flow caused the carpet to collapse and freeze, with the process repeating itself to produce new carpets in succession, on top of what became a rising bed surface (figure 2.34 illustrates this process).

Lowe's (1982) mechanism outlined above would explain the vertical gradation of the sub units at locality 9.2 without the presence of depositional breaks between them. In addition, the intense shear at the flow base producing dispersive pressure, would explain the production of the a-axis parallel to flow, non imbricate fabric, exhibited by the

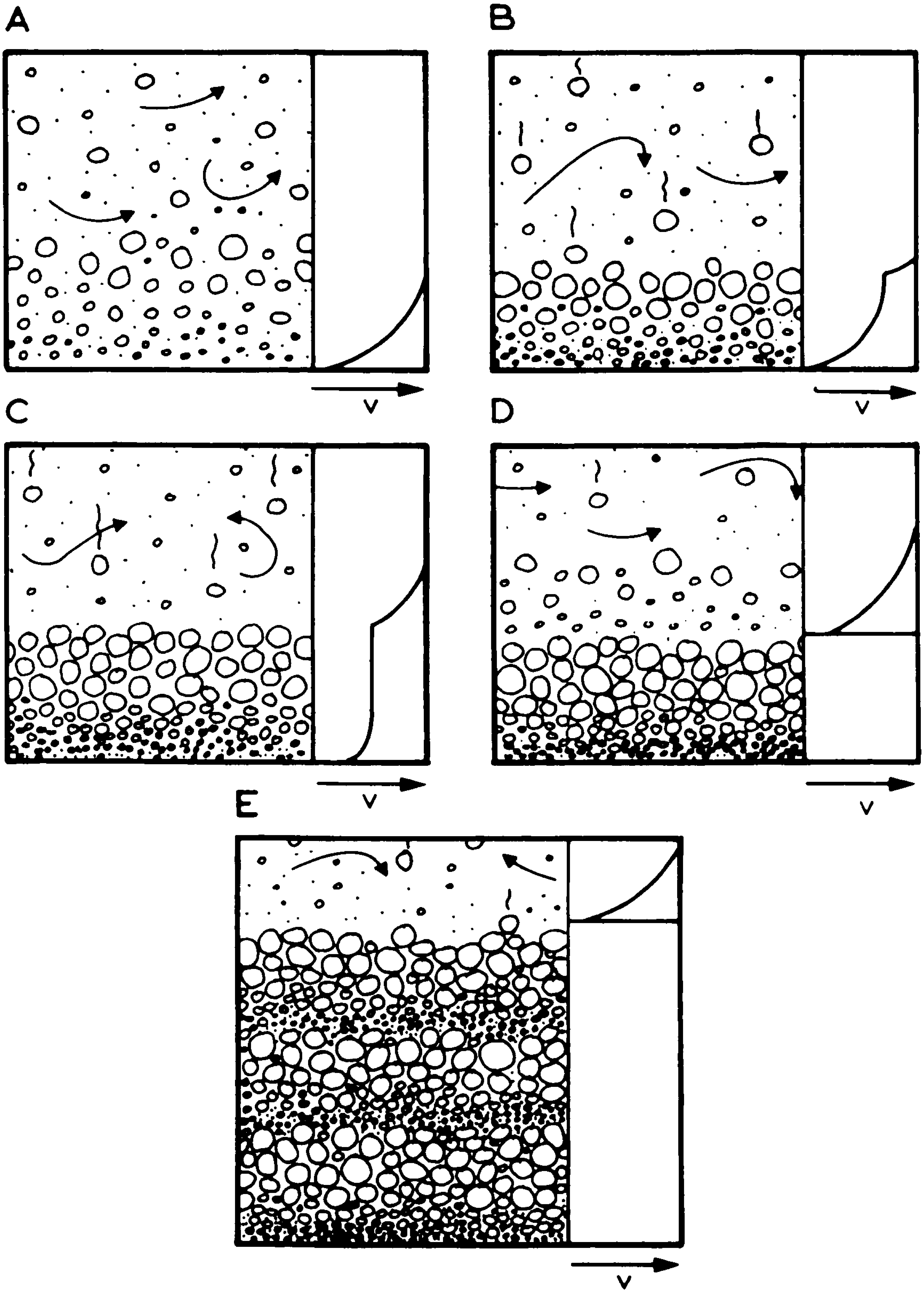


Figure 2.34. The origin of traction carpet layers, modified after Lowe (1982). A) The sheared base of a highly concentrated flow showing the development of inverse grading due to intergranular dispersive pressure. Note the velocity profile to the right. B) Fallout from suspension causes increased basal concentration and the formation of a traction carpet fully supported by dispersive pressure. C) Fallout continues from suspension loading the carpet causing freezing. D) Final freezing of the carpet results in the formation of a new traction carpet above. E) The process repeats itself producing a stack.

largest sized clasts within the sub units (the same mechanism as discussed in relation to the cobble fabric in section 2.6.3). The degree or scale to which the flow above the carpet possessed turbulent behaviour, is not noted by Lowe, but as indicated above, turbulence in the flow at locality 9.2 would have been suppressed. Lowe's mechanism can be described as non simultaneous deposition of sediment, as the depositional surface migrated upward. Therefore, the mechanism is broadly similar to that suggested in the last section (2.6.4) for the deposition of sediment further upstream, after the mechanism proposed by Carter (1975a). However, unlike the more proximal reach, the upward migration of the depositional surface, at locality 9.2, was spasmodic rather than gradual and was associated with the formation, collapse and freezing of successive traction carpet layers.

Hiscott and Middleton (1979) also attribute inversely graded sub units to traction carpet layers formed through intense shearing at the base of turbidity currents, as described by Lowe (1982). Hiscott and Middleton note that the thickness of the traction carpets layers diminishes as mean grain size decreases from the base to the top of a sequence. They interpret this as decreasing current velocity during deposition of the sequence, with the traction carpet thickness being a function of flow strength. Although the grain size distribution analysis of the sub units through the vertical sequence at locality 9.2 was not conducted, there is a marked decrease in the number of small pebbles and large granules upward in the sequence, together with a general decrease in the thickness of the sub units (section 2.3, figure 2.10B). Following Hiscott and Middleton (1979), this vertical variation in this sequence could indicate that the 1984 flow was slowing and losing yield strength as deposition was occurring. The only dissimilarity between these deposits and those described by Hiscott and Middleton (1979) and Lowe (1982), is that some of the sub units at locality 9.2 do not maintain inverse grading in a lateral sense. This could indicate localised decreases in dispersive pressure in a lateral sense through reduced shear. Such localised heterogeneity in sediment transport and depositional processes is evident in a larger scale at locality 9.2, when the origin of the most distal depositional unit preserved at locality 9.2 is considered. This rather coarse grained and homogeneous unit reflects the depositional style of the deposits at localities 8.0 and 8.5 and therefore represents a localised return within the main flow to the processes of sediment transport and deposition operable at those more proximal localities, or it may represent deposition from a more highly concentrated spatially or temporally detached segment of the main flow, at this locality.

In summary, the main flow at locality 9.2, when it produced the stacked inversely graded sub units, was a highly concentrated sediment/water mixture, which had a complex integration of clast support mechanisms, that included turbulence (albeit suppressed). Sediment was not transported en masse and as a result was able to fall from suspension to the base of the flow to form traction carpets under shear. The sediment falling from suspension became progressively finer grained and the traction carpets themselves became thinner as the sequence was rapidly deposited.

2.6.6. The recessional flow deposits

2.6.6.1. Introduction

In the wake of the main mass flow there was a recessional flood flow event (Pringle and Cameron, in press). Although the velocity, sediment concentration and depth(s) of the flow(s) are not known, observations (figure 2.28) indicate that the flow was locally turbulent, caused localised erosion of the main flow deposits and transported boulder sized clasts (Pringle and Cameron, in press). Deposition from the recessional flow(s) occurred almost immediately after the main flow, to form the top depositional units of the bipartite or tripartite sequences. The contacts between the units at some localities were obscured through minor erosion or reworking of the top surface of the main flow deposits. There are three distinct groups of deposits: 1) homogeneous, 2) the coarse-tail inverse graded sub units at locality 3.4, 3) laminated. All three groups are poorly sorted except for the homogeneous deposits at locality 0.0 which are very poorly sorted. The homogeneous and laminated groups vary from a few centimetres up to 30 cm in thickness. The inversely graded sub units individually do not exceed a thickness of 20 cm.

Localities 3.4 and 3.7 are the only sites that demonstrate multiple emplacement of recessional flow deposit groups. At locality 3.4, all three groups occur superimposed with cross cutting relations existing between them and at locality 3.7 laminated deposits occur without an erosional contact upon homogeneous deposits. There is no evidence to suggest that these three groups of deposits were produced from a flow undergoing downstream dilution and transformation. Hence these three groups likely represent deposition from different flows within the recessional flow event. The processes of sediment transport and deposition within each flow are discussed below.

2.6.6.2. Homogeneous recessional flow deposits

These very poorly sorted to poorly sorted cobble containing granule sand deposits, are the most voluminous recessional flow deposits. They totally lack stratification and show no grading, but do exhibit a clast fabric. The fabric data is sparse (in terms of significant preferred orientations), however, it does indicate that bimodality occurs as a function of grain size, in which clasts less than cobble in size are orientated with a-axes orientated parallel to flow, whereas cobble sized clasts are orientated with a-axes transverse to flow (section 2.4.2.3). This fabric is identical in character to that displayed by the main flow deposits at locality 8.0.

The processes of sediment transport and deposition are difficult to ascertain due to undetailed flow observations, but the lack of scoured surfaces on the underlying main flow deposits indicates laminar rather than turbulent behaviour (Enos, 1977). The bimodal fabric as described in section 2.6.4 presents a conundrum regarding the mode of deposition, because some clasts indicate rolling on the bed to produce the transverse to flow fabric while others indicate high applied shear stress with deposition from suspension to produce a parallel to flow fabric. The explanation for the fabric bimodality at locality 8.0 was based upon Hein's (1982) hypothesis of the reorientation of originally a-axis parallel to flow orientated clasts upon deposition. Consideration of the fabric, sedimentology and flow characteristics, suggested that the flow at locality 8.0 was a highly concentrated dispersion, exhibiting a degree of strength and viscosity in which clasts were able to move with respect to each other under shear. Apart from lacking weak inverse grading and being considerably thinner, the homogeneous recessional flow deposits are very similar to the main flow deposits at localities 8.0 and 8.5 and hence it is concluded that similar sediment transport and depositional mechanisms were involved in the production of these deposits, albeit on a smaller scale.

2.6.6.3. Coarse-tail inversely graded sub units

These are thin, poorly sorted pebbly granule sands that do not exceed 20 cm in thickness. As mentioned above they occur only at locality 3.4 on the terrace, at the bottom of a sequence of other recessional flow deposits. They are very similar to the main flow deposits at locality 9.2 in terms of their coarse-tail inverse grading and thickness, but these sub units are coarser grained and the inverse grading is maintained laterally for 8 m in a downstream direction. Unlike locality 9.2, the depositional surface upon which these sub units were emplaced was uneven and represents a minor pre-flow channel cut into the terrace (plate 2.4A). The inversely graded sub units within this minor channel are thick but visibly thin over the corresponding minor terrace, in effect blanketing the minor channel/terrace system. The topmost sub unit is visible only on the minor terrace (log B, figure 2.6), as it has been eroded off the minor channel sequence by a later recessional flow. The upper sub unit in log A figure 2.6 (the middle inversely graded sub unit stratigraphically), demonstrated an a-axis parallel to flow, non imbricate clast fabric among pebbles. This is identical in character to the fabric developed within the main flow inversely graded sub units at locality 9.2.

The sedimentology of these sub units is so similar to the main flow deposits at locality 9.2, that near identical clast support and depositional mechanisms must have operated within the recessional flow that produced them. Hence, the recessional flow at locality 3.4, during the deposition of the inversely graded sub units, was a highly concentrated sediment/water mixture, in which sediment was not transported and deposited en masse, but rather fell from suspension, to form traction carpets under shear, as described by Lowe (1982), (figure 2.34). The presence of the minor channel cut into the terrace did not destroy the basal traction carpet of the flow or cause a break in sedimentation, because the traction carpets conformed to the irregular topography and merely thinned over the surface of the minor terrace adjacent to the minor channel.

At locality 9.2, the flow was inferred to have lost yield strength during deposition, as there was a loss of coarse clasts upward in the inversely graded unit sequence and the sub units (or traction carpets) became thinner (this inference is after the work of Hiscott and Middleton [1979]). These recessional flow inversely graded sub units show a similar pattern: the top sub unit is thinner than the lower two units and has a mean grain size of only 0.39 mm, compared to 0.88 mm for the lowermost (or bottom) unit (appendix 1A). Hence the two depositional sequences infer near identical mechanisms of deposition from what must have been near identical highly concentrated sediment/water flows that possessed a degree of turbulence.

2.6.6.4. Laminated deposits

These poorly sorted granule sands, which generally lack pebbles or other larger clasts are among the finest grained deposits in the entire reach. Their formation from a recessional flow, or flows, represents a complete departure in terms of depositional processes from all other previously described deposits in this study.

Locality 3.7 exhibited the best example of this type of recessional flow deposit (plate 2.5C). The horizontal laminae were defined by the presence or absence of coarse and fine grain sizes rather than by sharply bounded layers with distinct grain size differences. The laminae varied from several grain size diameters up to a few millimetres in thickness, with no discernible inverse or normal grading between them. Individual laminae could be traced for 1.8 m downstream, which was the length of the eroded recessional flow deposit. Some laminae which were subhorizontal, intersected or merged in a downstream sense.

Following the work of Walker, 1975a; Harms *et al.*, 1982; Paola *et al.*, 1989, these predominantly horizontal laminae indicate deposition on a surface with little or no relief, in which the bed appears to have been free of bedforms. In addition the association of parallel lamination in sands with flat-bed conditions indicates abundant sediment in suspension and as bedload in the flow (Paola *et al.*, 1989). A variety of detailed mechanisms have been postulated for the formation of horizontal parallel laminae. Allen (1984) proposes a model in which thin horizontal laminae are produced by turbulent fluctuations on a flat upper-regime plane bed and Bridge (1978) invokes the burst sweep cycle to explain the vertical sorting that defines laminar boundaries. Other models for the formation of laminae involve the migration of low-relief bedforms (Smith, 1971; and McBride et al., 1975). More recently, Paola et al. (1989) suggested that continuous parallel laminae are produced by the alignment of small scale turbulent scour and fill structures along the paths traced by migrating bedform troughs on an upper-regime plane bed.

Despite the wealth of experimental investigations and discussion concerning the formation of horizontal laminae, the precise mechanism by which the 1984 recessional flow laminated deposits were produced, in terms of the detailed models proposed by Allen (1984), or Paola et al., (1989), is difficult to determine, due to the bad exposure and the complete absence of detailed turbulence characteristics or measures of flow concentration. However, their formation as low amplitude bedforms on a near planar surface seems likely, when considering the rare low-angle merging, or intersection, of subhorizontal laminae in a downstream sense, these are reminiscent of foresets produced on the lee face of a bedform. This is the same explanation used by Smith (1986) to explain similar horizontally laminated sands within older depositional sequences at Mount Saint Helens and the volcaniclastic Deschutes Formation in Oregon. Whatever the precise mechanism that produced the horizontal laminae, it is evident that turbulence was important as a sediment transport and depositional processes. This is given credence by the the observation of turbulent behaviour of the recessional flow (Pringle and Cameron, in press) and the erosion of the traction carpet layers at locality 3.4, before the deposition of the laminated sands above. The recessional flow(s) that produced the parallel laminated sands represent the least concentrated flow(s) that have produced deposits (that still remained at the time of study) in the entire 1984 mass flow event

2.6.7. Summary

The 1984 main mass flow produced a spectrum of deposits that show profound changes along the North Fork Toutle River. Through the integration of sedimentological characteristics, inferences on flow rheology from laboratory analysis and flow observations, it has been possible to postulate the clast support mechanisms within the diluting and transforming flow. It has also been possible, through the extrapolation of the findings to postulate the processes within the recessional flow(s). Figure 2.35 is a summary of the inferred sediment support mechanisms and their variation in importance for the production of the various depositional units along the reach.

Figure 2.35. Variation of sediment support mechanisms and sediment concentration within the main flow and recessional flow(s), together with schematic logs of the deposits produced.

2.7. THE DELINEATION OF HYPERCONCENTRATED FLOW DEPOSITS WITHIN THE 1984 MASS FLOW DEPOSIT CONTINUUM

When the estimated sediment concentration values of the 1984 mass flow (figure 2.30) are compared with Beverage and Culbertson's (1964) suggested terminological scheme (figure 1.1), they indicate that the flow passed from debris flow to hyperconcentrated flow in the vicinity of locality 2.0, when the sediment concentration was 80% by weight. However, this limit is arbitrary and if Beverage and Culbertson's scheme is used in this case, it would imply that the deposits in the vicinity of locality 2.0 were produced from hyperconcentrated flow rather than from debris flow. The flow 24 km from the crater had a sediment concentration of 34% by weight (Pringle and Cameron, in press). Hence the application of Beverage and Culbertson's suggested terminology would indicate that the flow had passed from hyperconcentrated flow to stream flow within 6 km downstream of locality 9.2, when the sediment concentration passed below 40% by weight. Unfortunately no deposits remain beyond locality 9.2, which may have documented such a flow transformation.

Before inferences are made on the delineation of hyperconcentrated flow deposits within this sequence, it is necessary at this stage to review the work of Pierson and Scott (1985). They conducted an investigation into the transformation of the 1982 mass flow at Mount Saint Helens and noted the resulting debris flow and hyperconcentrated flow deposits. The 1982 mass flow event was produced in a similar manner to the 1984 flow and transformed from a debris flow, which was estimated to be in the order of 79 to 90% sediment by weight, to hyperconcentrated streamflow when the total sediment concentration had decreased to about 78% by weight (Pierson and Scott, 1985). The flow transformation was unobserved and occurred over a 16 km reach with the hyperconcentrated streamflow having a peak sediment concentration of 61% by weight. This information from Pierson and Scott (1985) is summarised in figure 2.36, together with the corresponding depositional sequence from Scott (1988a), which shows a downstream change in the textural characteristics of the deposits. Examination of the logs from the more proximal part of the reach (figure 2.36), reveals two basic units: a "lower coarse sand" unit and an upper unit which constitutes deposition from a "debris flow slurry". The upper unit has an ill defined "normally graded" portion at its top (marked X on figure 2.36).

Pierson and Scott (1985) state that this lower unit/upper unit arrangement documents the transformation mechanism of the 1982 flow. Although the transformation was not observed, they hypothesised that the flow would have overtaken the existing stream flow in the channel and incorporated it by turbulent mixing. In response to the resulting flow dilution, mean grain size would decrease and sorting would improve in the body of the flow through deposition. They add further detail by suggesting that as

Figure 2.36. Schematic logs, terminology, sediment concentration and postulated flow transformation model for the 1982 mass flow at Mt. St. Helens, after Pierson and Scott (1985) and Scott (1988).

long as the flow moved fast enough, the turbulent mixing zone at the flow front would be eventually overridden by the debris flow as a whole. If the debris flow slowed, as Pierson and Scott (1985) indicate, the flow would become partitioned with a "hyperconcentrated flow" at the front and a "debris-flow-slurry" at the tail. With distance downstream the mixing zone would move back through the body of the flow until the entire flow was transformed. Thus the downstream thickening lower unit represents deposition from the hyperconcentrated head of the flow and the upper unit represents deposition from the debris flow slurry at the tail of the flow. Pierson and Scott's (1985) hypothesised model is also illustrated in figure 2.36, after Scott (1988a).

The findings from the 1984 flow deposits are profoundly different from those of the 1982 flow deposits. The crucial difference is the absence from the 1984 sequences of the thick coarse sand unit which forms the base of the 1982 proximal sequences. This disparity is related to a fundamental difference in the hydrology of the two flow events. Twenty nine kilometres from the crater, the 1982 flow was trapped behind a sediment retention dam (indicated on figure 2.36 and 3.1 [N1 dam]), which ponded the coarse front of the flow, whilst the watery tail of the flow passed downstream (Pierson and Scott, 1985). Pierson and Scott infer that the transformation of the 1982 flow from debris flow to hyperconcentrated stream flow commenced in the vicinity of the sediment retention dam. However, it seems more likely that the watery tail of the debris surge that escaped from the sediment retention dam, produced the lower deposits in the depositional sequence described by Pierson and Scott (1985) and Scott (1988a) and that a subsequent surge of debris that overtopped the dam (Pierson and Scott, 1985), produced the upper deposit.

If the upper unit of the 1982 flow deposits is considered separately from the lower unit (figure 2.36) it is very reminiscent of the 1984 main flow sequence. Along the reach, the upper units of the 1982 flow deposits, progressively thin, show an increase in sorting, a decrease in mean grain size, and exhibit inverse grading. These are all features of the 1984 main flow depositional sequence. With regard to grain size distributions, the 1982 upper units compare directly with the 1984 main flow deposits in the vicinity of locality 7.3 and 8.0. The presence of strong inverse grading within the debris flow units, as presented in the form of schematic logs by Pierson and Scott (1985) and Scott (1988a), is reminiscent of a plug zone/basal zone arrangement in the 1984 flow deposits. However, the apparent plug zone/basal zone arrangement within the 1982 deposits is not recognised by Pierson and Scott (1985) or Scott (1988a). Scott (1988a) does not discuss the significance of the normally graded portion of the upper unit in the 1982 deposits marked X on figure 2.36. X appears to be comparable to the finer grained recessional flow deposits capping the 1984 main flow deposits. However, a detailed comparison is precluded as no detailed information is given by Scott to account for their existence.

The deposits recognised by Pierson and Scott (1985) as having been produced by hyperconcentrated streamflow are stratified gravelly sand deposits with no coarse debris on top (figure 2.36). Some of the sub units defined by the stratification are noted as being inversely graded (Scott, 1988a) but receive no detailed attention either in terms of their description, or with regard to their processes of formation. These units are similar as regards their texture to the 1984 recessional flow deposits and the mid main flow deposits at localities 8.0, 8.5 and 9.2 (the grain size distribution data for these 1984 deposits is given in appendix 1A).

It can be inferred that the upper units in the proximal 1982 deposits, and the gravelly sand deposits, produced from "hyperconcentrated streamflow", form a proximal to distal sequence very similar to the 1984 flow deposits: the normally graded top to the upper unit in the 1982 deposits (X on figure 2.36) having a direct analogue in the 1984 recessional flow deposits.

Both flow events have undoubtedly produced a deposit continuum that can be generally classified as hyperconcentrated or debris flow using Beverage and Culbertson's suggested terminology. However Pierson and Scott (1985) and Scott (1988a), have not thoroughly examined or characterised the 1982 flow depositional sequences. As mentioned above, there is no detailed attention given by Scott (1988a) to the inversely graded sub units produced by the 1982 flow. In addition, the clast fabric of the upstream debris layer has been ignored by Pierson and Scott (1985) and Scott (1988a). This lack of background sedimentological information calls into doubt the value of the sediment concentration estimates of the 1982 flow from the reconstitution of the 1982 debris flow deposits, which Pierson and Scott (1985) use as a base in the delineation of hyperconcentrated flow deposits. In this study, concentration estimates for the 1984 flow were determined using samples from locality 0.0, which were inferred from sedimentological investigations to represent deposition from a highly concentrated debris flow that contained a minimum amount of water. However, based on the limited sedimentological information in Pierson and Scott (1985) and Scott (1988a), the 1982 debris flow deposits (upper units in figure 2.36) are directly comparable to the 1984 main flow deposits in the vicinity of localities 7.3 and 8.0, which were shown to be produced from the 1984 flow when it was considerably more dilute than at locality 0.0. Thus, the sediment concentration of the more proximal parts of the 1982 debris flow as estimated by Pierson and Scott (1985), may be erroneous and may in fact be too high. Given the concerns regarding the lack of sedimentological analysis of the 1982 deposits, the validity of Pierson and Scott's transformation mechanism, which is inextricably linked to the presence of the sediment retention dam and the debris reconstitution techniques which were conducted without regard to the sedimentological characteristics of the deposits: the delineation of hyperconcentrated flow and thus hyperconcentrated flow deposits by Pierson and Scott (1985) and Scott (1988a), appear like the divisions in Beverage and Culbertson's (1964) scheme, to be quite arbitrary.

The delineation of debris flow deposits and hyperconcentrated flow deposits within the 1984 sequence, as indicated at the beginning of this section, based solely on the sediment concentration of the flow as in Beverage and Culbertson's suggested terminological scheme, is most unrealistic. Pierson and Costa's (1987) classification (figure 1.3) with flow velocity and concentration as variable parameters, represents a departure from classification schemes containing concentration as the only variable parameter. The divisions between the different flow types represent major rheological boundaries being crossed as sediment concentration increases. Pierson and Costa (1987), point out that the sediment concentration a fluid acquires to have yield strength and hence become a non-Newtonian fluid is highly dependent on the grain size distribution. This is demonstrated by the comparison of different clay and other suspensions (figure 1.2). Pierson and Costa (1987) further define "hyperconcentrated streamflow" as a flowing mixture of water and sediment that possess a measurable yield strength (probably less than 400 dyne/cm^2), but still appears to flow like a liquid, despite marked damping of turbulence. Pierson and Costa (1987) define debris flow as occurring in a sediment-water dispersion when the yield strength rapidly increases. This transition being identifiable as the bends in the plots of yield strength versus sediment concentration (figure 1.2).

Pierson and Costa's (1987) classification offers the most realistic approach in the delineation of flow types in the sediment-water flow continuum and their associated deposits. In its application to the 1984 flow, an abrupt change in yield strength, which could indicate the transition between debris flow and hyperconcentrated flow is not apparent on figure 2.31, although there is a general decrease. This decrease could represent the transition between debris flow and hyperconcentrated flow. The decrease in yield strength is expressed in the deposits as the downstream loss of the rigid non-deforming plug zone. Thus, based on the sedimentological evidence together with the consideration of yield strength the boundary of debris flow and hyperconcentrated flow is placed between localities 6.5 and 7.3. Consequently, this suggests that the deposits downstream to and including those at locality 6.5, represent the deposits from debris flow and that the deposits downstream from locality 6.5 represent deposits from hyperconcentrated flow. However, the yield strength of the flow that produced the deposits at locality 7.3 can be inferred from the investigation of the graph in figure 2.31 (section 2.5.2.1), to be much greater (perhaps over 10 times greater) than Pierson and Costa's postulated maximum yield strength value for hyperconcentrated flow of 400 dyne/cm^2. This is not a major problem, because as Pierson and Costa (1987) strive to point out, there are no rigid boundaries or absolute numbers used in their classification, due to grain size distribution and physical-chemical compositional variation that exists between different flows. It must be stressed that at locality 7.3, the remnant of the plug zone does not represent a rigid non deforming mass of sediment above a basal zone (as found further upstream) and hence the delineation divides flows that have/have not got a well defined plug zone/basal zone arrangement. The remnant plug may have greater yield strength and concentration than the hyperconcentrated flow that transports it, but this cannot be proved in the field.

In considering the recessional flow deposits, the homogeneous units and inversely graded sub units which have very strong affinities with the main flow deposits at localities 8.0 and 9.2 respectively, can be regarded like the main flow deposits at these localities, as the result of hyperconcentrated flow deposition. The laminated recessional flow deposits on the other hand, are the result of deposition as low amplitude bedforms on a near planar surface from a stream flow that was much more dilute than any other produced in the 1984 flow event. It can be postulated that this stream flow was derived from a hyperconcentrated recessional flow which had transformed with a loss of yield strength through the rheological boundary that divides hyperconcentrated flow from stream flow, as per Pierson and Costa (1987), but this cannot be verified in the field. The lower rheological boundary which can regarded as the division between non-Newtonian and Newtonian behaviour (Pierson and Costa, 1987) was not crossed by the main 1984 flow in the 9.2 km of the studied reach. However, it can be assumed that beyond locality 9.2 the flow continued to dilute and transform. Support for this argument is Pringle and Cameron's (in press) description of the flow 24 km from the crater as a "turbulent muddy flood" (figure 2.28). No depositional evidence exists that documents this transformation, but it can be suggested that at some point beyond locality 9.2, horizontally laminated sands synonymous with the laminated recessional flow deposits, would be found if the deposit continuum were complete.

Using the data available, the delineation between debris flow and hyperconcentrated flow deposits based on the information from the 1984 mass flow event can be presented (figure 2.37). However, due to the deposit continuum being incomplete, with no exposure preserved beyond locality 9.2, the delineation of the boundary between hyperconcentrated flow and stream flow is vague. This lower boundary is delineated in chapter three.

Figure 2.37. The delineation of hyperconcentrated flow deposits within the 1984 flow event (main flow and recessional flow) depositional sequences. The deposits are represented by schematic logs.

2.8. A NOTE ON THE TRANSFORMATION MECHANISM

The deposits from the 1984 flow event have formed the basis of this chapter. However the details of the mechanism by which the main mass flow transformed are outwith the scope of this study. Since the flow was not observed as a part of this study and evidence of the flow transformation mechanism is not preserved in the depositional sequence, any detailed model proposed here would be purely speculative and would be based on the presumptions of Pringle and Cameron (in press). Nevertheless, a brief consideration of the probable mechanism is necessary.

Pringle and Cameron (in press) attributed the flow transformation to dilution, which was inferred to have taken place at the base of the flow, by the deposition of sediment and the incorporation of channel water. This is after Pierson and Scott's (1985) transformation mechanism proposed for the 1982 flow; a review of which was given in the last section (2.7). It is felt here that the detailed transformation mechanism postulated by Pierson and Scott (1985), involving the relative velocities of the 1982 debris flow with its mixing zone, is highly conjectural. It was not observed and as mentioned in section 2.7, was derived by Pierson and Scott in an attempt to explain the sequence of deposits produced by the 1982 mass flow.

In a review of Pierson and Scott's (1986) work, Smith (1986) suggests that the dilution of the 1982 flow represents a "surface transformation" in the flow transformation classification of Fisher (1983), although this classification is not applied to the 1982 flow by Pierson and Scott. Fisher states that: "surface transformations occur when ambient air or water become mixed or lost at flow boundaries by drag over the top of a high-concentration flow, at a hydraulic jump, or beneath the nose of the flow, resulting in dilution, consequent turbulence and separation into laminar and turbulent moving parts". According to Fisher (1983), surface transformations are well described by Hampton (1972), who showed that the sediment stripped from the nose and surface of a subaqueous debris flow can become a turbulent current that continues beyond the debris flow. In this study there is no evidence to suggest that the 1984 flow actually separated into "laminar and turbulent moving parts", or that there was "stripping of sediment from the nose and surface of the flow". Although the latter "stripping mechanism", would really only apply in particular to subaqueous flows and has not much relevance to the 1984 flow. However, the observation by Pringle and Cameron (in press) that the main flow was preceded by a precessional flood phase, does suggest that there was "ambient water" with which the flow could mix and hence cause its dilution: but, there is no evidence to suggest that the mixing occurred as a result of hydraulic jumps (a mechanism noted in Fisher's [1983] classification). Therefore, the view taken in this work concerning the 1984 flow, is that water was mixed into the flow from the channel, either at the head or beneath the main body of the flow, or both, as the flow overtook the precessional flood flow at considerable velocity. The interaction of the water on the rigid plug or plugs (as indicated may have been the case in section 2.6), brought about the dilution of the body of the flow as a whole. The dilution of the flow was aided by the removal of sediment through deposition within the channel and on the terraces. This mechanism which involves the intake of water, could therefore be generally termed a "surface transformation", after the transformation classification of Fisher (1983).

2.8.1. The relationship of the 1984 main flow depositional sequence to traction carpets formed at the base of sediment/water flows in other sedimentary environments

2.8.1.1. Introduction

It has been suggested by Postma (personal communication) that the depositional sequence produced by the 1984 main flow, in particular between localities 2.0 and 6.5 (inclusive), is reminiscent of deposits in other sedimentary environments that have been produced from traction carpets at the bases of subaqueous and normal stream flows. Therefore, the aim of this section, is to review the origin of the 1984 main flow deposits in light of the research regarding the traction carpet mechanism.

2.8.1.2. The traction carpet mechanism

A very recent reference to the traction carpet mode of deposition, has been made by Todd (1989). Todd (1989) states that "high density flood flows in fluvial channels are capable of developing and driving decimetre- to possibly metre-thick, non-turbulent gravelly traction carpets (rheologically comparable to density-modified grain flows) along the channel floor." Todd (1989) uses this traction carpet mechanism to account for the formation of thick clast-supported conglomerates within the Trabeg Conglomerate

Formation in south west Ireland. This Devonian Formation is attributed to deposition on a stream flow dominated alluvial fan. The conglomerates to which a traction carpet mode of formation has been attached, are poorly to moderately sorted pebble/cobble/boulder clast supported beds, which have a coarse sand matrix.

In order to understand the processes involved in the formation of these particular conglomerate beds, Todd (1989) draws upon the work of several researchers, including: Dzulynski and Sanders (1962), Scott and Gravlee (1968), Lowe (1982), Postma _et al_. (1988). Dzulynski and Sanders (1962) first proposed the term "traction carpet" to describe a dense saltation zone at the base of a turbulent subaqueous flow, which "is not invaded by turbulent eddies of any size from the overlying turbulent flow". Such traction carpets are thought by Dzulynski and Sanders to protect mud bottoms beneath turbulent subaqueous flows from scour. The fact that rheological divisions occur within turbidites is utilised by Postma _et al_. (1988) in an attempt to resolve the transportation mode for large "floating" clasts. Postma _et al_. (1988) suggest that these "floating" clasts "glide" along the top of an underlying "pseudolaminar inertia-flow layer" partly submerged within it and are "driven by the downflow component of turbulent shear-stresses transmitted from the overlying, faster-moving turbulent layer" above. Bipartite subaqueous flows, consisting of a basal traction carpet with an overlying turbulent flow above, have also been discussed by

Lowe (1982). It is Lowe's model for the production of stacked traction carpets which has been utilised in this study to explain the stacked inversely graded sub units which form the main flow deposits at locality 9.2 and part of the stacked sequence of recessional flow deposits at locality 3.4. This mechanism has been discussed in section 2.6.5. and has been diagrammatically represented in figure 2.34.

Scott and Gravlee (1968) attributed coarse grained deposits in the Rubicon River in California to bed material movement which they describe as "viscous subaqueous rockflows". These subaqueous mass movements formed beneath a subaerial surge flow which had a discharge that greatly exceeded any flow in the river. The surge, caused by dam failure, had an average velocity of approximately 7 m/s and had a peak stage of approximately 15 m (Scott and Gravlee, 1968).

Todd (1989) envisages that the principal driving mechanism for the conglomerate depositing carpets, within the Trabeg Conglomerate Formation, is attributable to the shear stress exerted by an overlying turbulent stream flow, at flood-peak stage, which is decoupled from the underlying carpet. According to Todd (1989), the shear stress on the traction carpet is converted to dispersive pressure which supports much of the weight of the clasts in the flow. Additional support for larger clasts in the carpet was derived from buoyant lift which was enhanced by the dense nature of the interstitial fluid (watery sand). According to

Todd, (based on the work of Middleton, 1967; Postma et al., 1988), traction carpets have quasi-plastic rheological behaviour (intermediate between plastic and fluid, with yield strength), but they behave as viscous fluids at high shear rates. In addition, Todd (1989) states that the deposits of stream-driven gravelly traction carpets are most likely to accumulate in higher-gradient streams which carry a high concentration of sediment, probably during high-magnitude flash-floods (see Scott and Gravlee [1968]).

2.8.1.3. The 1984 main flow: the applicability of the traction carpet mechanism of deposition

In section 2.8 it was postulated that the 1984 main flow transformation could be generally termed as a surface transformation after the classification scheme of Fisher (1983). This category, in Fisher's classification, was chosen as it suggested that the flow transformation occurred as a result of water incorporation and sediment loss as the flow progressed downstream. However, it was stressed in section 2.8 that the 1984 main flow was not divided into laminar and turbulent moving parts as was inferred for turbidites undergoing surface transformation, as noted by Hampton (1972). In the case of the main 1984 flow, the observed thickness of the flow was generally close to the thickness of the depositional sequence. This statement is supported by considering figure 2.28 (section 2.5.1.), which illustrates the observation of Pringle and Cameron (in press), that the main flow decreased from 2 to 0.4 m in thickness between localities 0.0 and 7.3. This observed flow thickness is close to the actual deposit thicknesses measured in this study along the corresponding section of the reach, therefore confirming that the depth of the main flow equalled the resulting deposit thickness.

It is important to note that the recessional flow(s) that followed in the wake of the main flow was not emplaced until after the deposition of the main flow deposits; in effect, it was temporally detached from the main flow. It is therefore extremely important to stress that the recessional flow did not represent a flow that was overlying, or decoupled, from the main flow and therefore was not implicit in the formation of the main flow deposits (through the conversion of tangential shear stress into dispersive pressure). The only affect the recessional flow had on the main flow, was to produce minor reworking of the upper surface of some of the main flow deposits (when it eventually flowed on top of the newly produced sediments) causing locally gradational contacts.

The above observations, that flow thickness was equal to resulting deposit thickness and that the recessional flow followed in the wake of the main flow and did not override it until deposition, indicate that the 1984 main flow with its inverse grading, downstream weakening plug zone and strong fabric development, was not produced at the base of a stream flow in the form of a traction carpet as described elsewhere by Scott and Gravlee (1968), Postma et al. (1988), Todd (1989). Instead, as discussed within this chapter, based upon sedimentology and flow characteristics (including actual flow observations from Pringle and Cameron [in press]), the 1984 main flow can be described as a debris flow between localities 0.0 and 3.7 and that it diluted and transformed beyond locality 3.7, becoming hyperconcentrated flow at locality 7.3. Consequently, the main flow was not influenced by an overriding flow exerting a tangential shear stress. This tangential shear stress, had it existed, would have been converted to dispersive pressure (following the work of Todd [1989]). Thus, the 1984 main flow as it progressed along the North Fork Toutle River, would have had the sediment support mechanisms as outlined in section 2.6 (summarised in figure 2.35), which would have arisen within the highly concentrated sediment/water mixture as it flowed at considerable velocity. Hence, the 1984 main flow (including the section of reach from localities 2.0 to 6.5), represents general overall similarity with subaerial highly concentrated flows described elsewhere worldwide (eg. Johnson 1970, 1984; Lawson, 1982; Costa, 1984, 1988; Pierson 1985a, 1985b) which do not have an overriding turbulent flow affecting sediment support mechanisms. Only at locality 9.2, could deposition be described as occurring as traction carpets beneath an overriding flow.

A clear distinction can now be drawn between the traction carpet mode of deposition, which is inferred from Todd's (1989) work (which is based on the work of earlier researchers) and the mode of deposition of the 1984 flow, which as stated above can be considered as a debris flow/hyperconcentrated flow. This distinction is diagrammatically represented in figure A, in which Model A represents a traction carpet mode of deposition and Model B, represents the 1984 main flow.

The only deposits attributed to traction carpets in this study are those produced at localities 9.2 (main flow deposit) and 3.4 (recessional flow deposit on the terrace). These deposits, which are composed of inversely graded sub units, were produced sequentially from the base upward from an overriding flow. The thickness of each sub unit did not represent the total flow thickness.

Although the traction carpet mode of deposition for the 1984 main flow has been dismissed in this section based upon actual flow observations which negate the presence of an overriding flow, this finding does not doubt the validity of the traction carpet mechanism for the transport of sediment under certain sediment/water flows, for example as postulated by Dzulynski and Sanders (1962). Indeed, Postma _et al_. (1988) have very clearly shown the existence of thin gravelly traction carpets beneath turbulent overriding flows in laboratory experiments and also, Lowe's (1982) model for traction carpet formation has found acceptance and been adopted in this study in relation to the stacked inversely

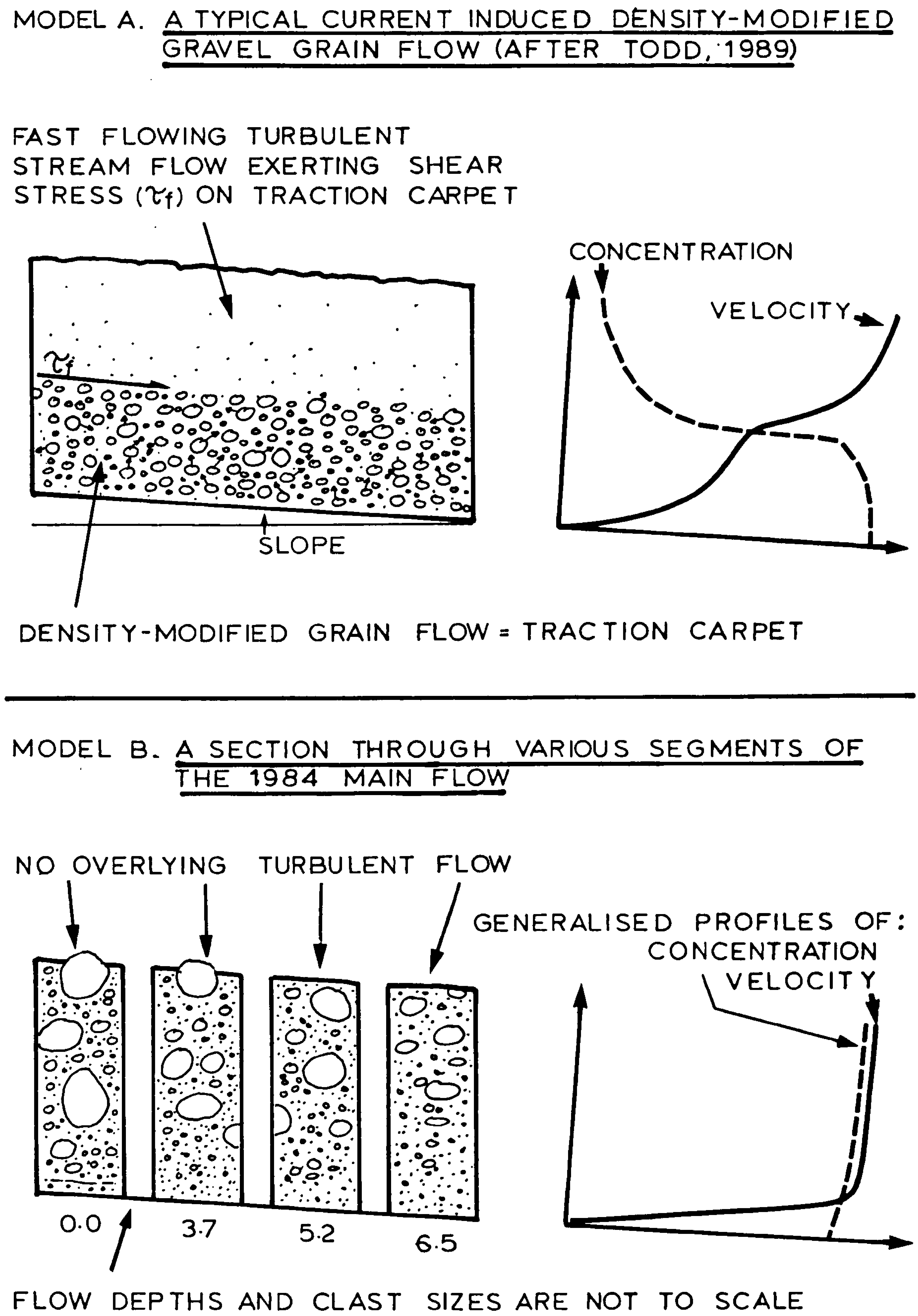


Figure A. An illustration of the distinction between the traction carpet mode of deposition at the base of a decoupled flow, Model A and the actual situation within the 1984 main flow, Model B (which had no decoupled overflow).

graded units (as mentioned above). However, it should be noted that although Scott and Gravlee (1968) have adequately demonstrated that an extremely large, fast and deep surge produced traction carpets in the Rubicon River, Todd (1989) does not have such observational evidence to support his hypothesis that the thicker conglomerate beds in the Trabeg Conglomerate Formation were produced as traction carpets beneath an overriding flow. It may well be the case that some of the thicker conglomerates, described by Todd, could have been produced from subaerial debris flows without an overriding flow providing dispersive pressure (through the conversion of tangential shear stress), however, Todd (1989) does not address this possibility.

2.8.1.4. Summary

This section has set out to answer the question (posed by Postma, personal communication) regarding the interpretation of the 1984 main flow deposits, in particular between localities 2.0 and 6.5, in the light of investigations by other researchers elsewhere, on the deposition of coarse grained deposits from traction carpets. This section has emphasised that the 1984 main flow deposit thicknesses were directly comparable to the actual flow depth observations made by Pringle and Cameron (in press). In addition it has been emphasised that the 1984 recessional flow followed in the wake of the main flow and thus at no time could it be regarded as an overlying flow. Therefore, the 1984 main flow deposits cannot be considered as having formed as a traction carpet at the base of a decoupled flow and the processes of sediment transport occurred without the additional shear stress that an overriding flow would supply.

2.9. SUMMARY

In 1984 a minor eruption of Mount Saint Helens caused the production of melt water, which formed a highly concentrated sediment-water flow in the head waters of the North Fork Toutle River. The main part of the flow produced a continuum of deposits along the river, which at the time of study, occurred in a 9.2 km reach, beginning 9 km from the crater. A 1.6 m thick matrix to clast-supported, unstratified, polymodal boulder conglomerate with a disorganised fabric occurs at the most proximal locality, 0.0, with a 50 cm thick granule sand deposit composed of inversely graded sub units at the most distal locality, 9.2. Between these two end localities, there is a systematic decrease in mean grain size, a downstream increase in sorting, the development of clast fabric, and the formation and subsequent downstream disappearance of inverse grading.

The depositional spectrum produced by the main flow is the result of the flow having undergone flow transformation, through dilution, with the incorporation of water from the channel and the deposition of sediment. In the first few kilometres of the reach, the main flow was a debris flow with a rigid non-deforming plug, moving above a basal shear zone. Over the subsequent length of the reach, the plug weakened and broke up with the sediment concentration, yield strength, and flow velocity all decreasing. As the flow transformed, the sediment support mechanisms varied from dominantly cohesive matrix strength and buoyancy in the more proximal parts of the reach, to include dispersive pressure in the middle section of the reach, with the particle support mechanisms at the most distal parts of the reach, consisting of dispersive pressure and a degree of turbulence.

The main flow deposits from locality 0.0 downstream to and including locality 6.5, which exhibit a well developed plug zone/basal zone arrangement, can be regarded as the results of debris flow deposition. Deposits downstream from locality 6.5 (that is at locality 7.3 and beyond), which lack a well developed plug zone/basal zone arrangement, or contain only remnants of a plug zone, can be regarded as the results of hyperconcentrated flow deposition. Their classification as such, is based upon sedimentology, flow characteristics and the consideration of the rheologic classification scheme of Pierson and Costa (1987).

Following in the wake of the main mass flow, there was a recessional flow event that produced three groups of deposits. The homogeneous deposits and a unit which was composed of inversely graded sub units, have strong affinities with the main flow deposits at localities 8.0 and 9.2 respectively and hence can be regarded as hyperconcentrated flow deposits. The third group of recessional flow deposits consists of laminated sands and represents deposition as low-amplitude bedforms formed under conditions synonymous with stream flow, during the recessional flow event.

CHAPTER 3

OTHER DEPOSITS FROM THE DEBRIS FLOW/STREAM FLOW CONTINUUM AT MOUNT SAINT HELENS AND THEIR INTERPRETATION BASED ON THE FINDINGS FROM THE 1984 FLOW DEPOSITS

3.1. INTRODUCTION

The 1984 flow deposit continuum was studied as it represented the most complete depositional record from a transforming mass flow, produced in modern times at Mount Saint Helens. However, due to erosion the continuum was not complete and no deposits were preserved beyond locality 9.2, which may have recorded the transition from hyperconcentrated flow to stream flow. In order to produce a more complete picture of the debris flow to stream flow deposit continuum and to fully delineate hyperconcentrated flow deposits in this volcaniclastic environment, further work was conducted on the remnants of the 1982 flow deposits.

Throughout chapter two, reference was made to the findings of other investigations concerning modern Mount Saint Helens mass flow deposits produced in this most recent phase of activity, that started in 1980. In addition to these recent works, mass flow deposits produced in the 40, 000 year history of Mount Saint Helens have been described by Mullineaux and Crandell (1962), Crandell and Mullineaux (1973), Crandell (1987), Scott (1988b) and Scott (in press).

Apart from Scott (in press), all these works are superficial in their treatment of mass flow deposits and their processes of formation. In the works of Crandell and Mullineaux (1973), Crandell (1987) and Scott (1988b), the deposits are used only as an integral part in the interpretation of the eruptive history of Mount Saint Helens, rather than forming the basis of detailed sedimentological analysis.

Swanson (1966), Schminke (1967), Crandell (1971) and Smith (1986, 1987, 1988) have described similar volcaniclastic mass flow deposits elsewhere in the north western U.S.A. However, as in the works concerning older Mount Saint Helens mass flow deposits, the works of Swanson (1966) and Crandell (1971) are very superficial and lack detailed systematic characterisation of mass flow deposits. Schminke (1967) and Smith (1986, 1987 and 1988) present detailed sedimentological characteristics of deposits, produced by mass flows, with criteria for the recognition of hyperconcentrated flow deposits being proposed by Smith (1986). Smith's criteria form the basis of major discussion in Chapter four. These works on older deposits in the geological record, with the exception of Smith (1986, 1987 and 1988), use the term "lahar" to denote mass flow deposits, as in the works concerned with modern deposits (references cited in section 2.1.2). In addition, the literature concerning older deposits, with the exception of Crandell (1971), Smith (1986, 1987 and 1988) and Scott (in press), do not indicate the presence of a deposit continuum. The lack of such information regarding these older deposits may be due to the paucity of laterally continuous exposure. For, as demonstrated by the 1984 flow, erosion reduces the deposits to mere remnants, which may be separated by many hundreds of metres. Examination of the 1984 flow deposit remnants in isolation, without the knowledge that a single mass flow had deposited the whole sequence, could possibly lead to the conclusion that the individual deposits represent deposition from a variety of flows, rather than than one flow undergoing transformation. This would account for the introduction and use of the general term "lahar" to describe a multitude of deposit types (for example, as used by Mullineaux and Crandell, 1962).

The aims of this chapter are, firstly, to complete the sedimentological characterisation and hence the delineation of hyperconcentrated flow deposits in the debris flow/stream flow deposit continuum in the volcaniclastic environment of Mount Saint Helens and secondly, to determine whether elements of the continuum illustrated by the 1984 flow deposits (with added information from the 1982 flow deposits) are represented among the eroded remnants of mass flow deposits produced earlier in the history of Mount Saint Helens.

3.2. DISTAL REMNANTS OF THE 1982 FLOW DEPOSITS

3.2.1. Location and sedimentological setting

The mass flow deposits produced in 1982 have been studied by Pierson and Scott (1985) and Scott (1988a) and their work has been reviewed in the last chapter. The analysis of deposits which Pierson and Scott (1985) attribute to hyperconcentrated flow deposition, forms the basis of this section. The 1982 deposits examined in this study, occur in a channel margin setting, 44 km from the crater of Mount Saint Helens (figure 3.1). At the time of this study, they represented the last known exposure of the hyperconcentrated stream flow deposits noted by Pierson and Scott (1985) in the Toutle River system (Janda and Major, personal communication, 1987). The locality is close to log site 43.7 in Scott's (1988a) figure 36 which is redrawn in this work in figure 2.36.

3.2.2. Sedimentological characteristics

The deposits which blanket the pre-flow channel gravels (plate 3.1A) are composed of horizontally laminated sands and vary in thickness from 30 to 50 cm. The laminae are defined by the presence or absence of coarse and finer grain sizes, rather than by sharply bounded layers with distinct grain size differences. Individual laminae vary in thickness from a few grain size diameters up to a few millimetres (plate

Figure 3.1. Map showing the locations to the west of Mount Saint Helens, in the North Fork Toutle River, of the depositional sequences investigated in chapter three.

3.1B) and no inverse or normal grading could be determined. Although single laminae can be traced for up to one and a half metres in a downstream direction, distinct intersection relationships between laminae can be demonstrated (plate 3.1C), where rare subhorizontal laminae merge in a downstream sense.

Granulometric analysis allowed a comparison to be made with the depositional units analysed in the last chapter. The results (appendix 5) show that the deposits have mean grain size and sorting values, closer in character to the stream flow deposits (taken from the same reach as the 1984 flow deposits) than any of the 1984 flow event deposits, including the laminated sands (compare appendix 5 with 1A). Derivation of the coarsest one percentile and the median diameter allows the comparison to be made on a CM textural discrimination diagram (figure 3.2). The sample plots in the same area as the stream flow deposit samples, which also corresponds to Bull's (1962, 1972) braided stream deposits and is quite distinct from the other groups produced by debris and hyperconcentrated flow. Although its fine grained nature precludes a direct comparison with the 1984 laminated recessional flow deposits, its position on the CM diagram may indicate deposition from stream flow. This indication is given credence when the origin of the laminae are considered. As in the case of the 1984 laminated recessional flow deposits, the presence of distinct low angle intersection or merging of laminae, does indicate their deposition as

PLATE 3.1 [OVER]

PLATE 3.1

A

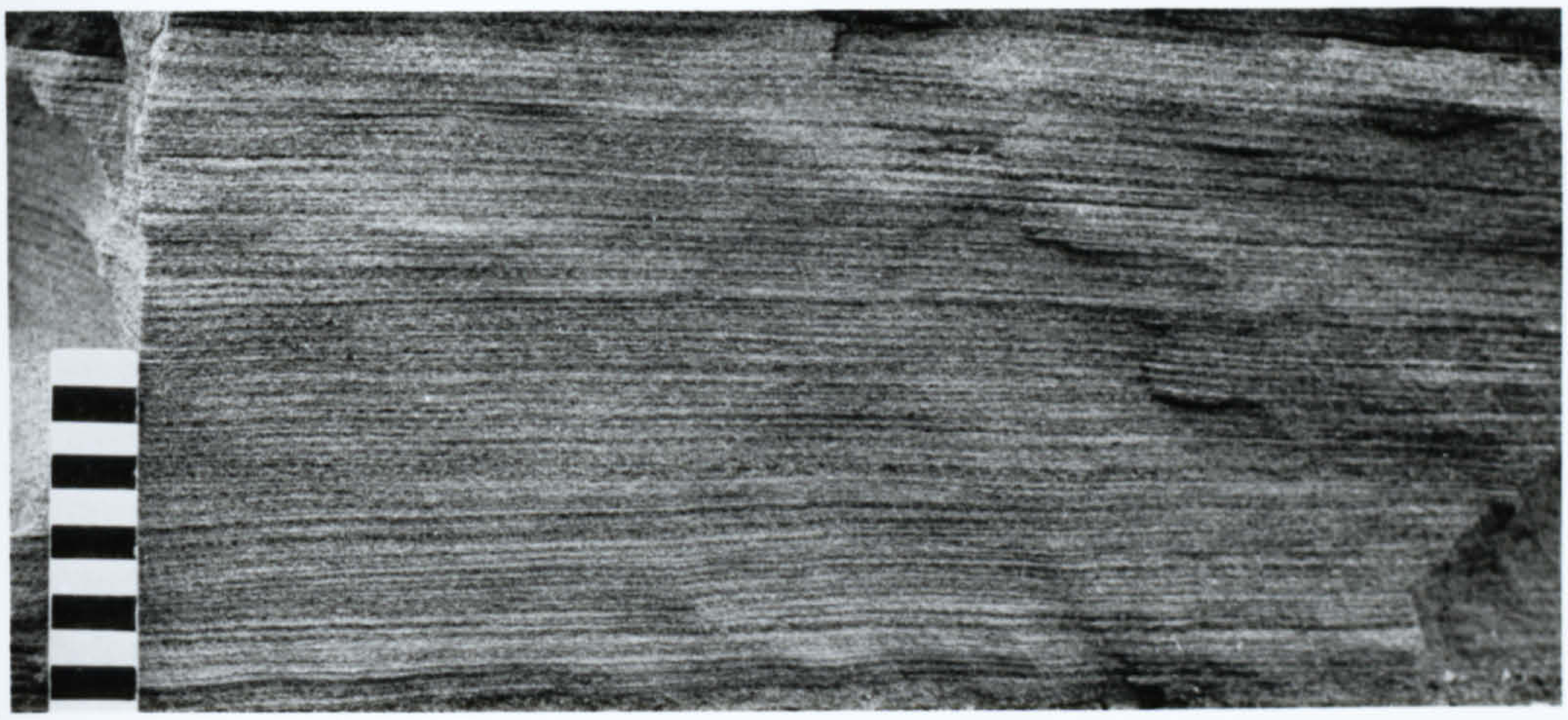
The exposure of the laminated sand deposits produced by the 1982 flow, 44 km from the crater of Mount Saint Helens, on the channel margin of the North Fork Toutle River. The pebble and cobble capping that is locally preserved over the laminated sands represents post 1982 flow, stream deposits. Flow direction is toward the viewer.

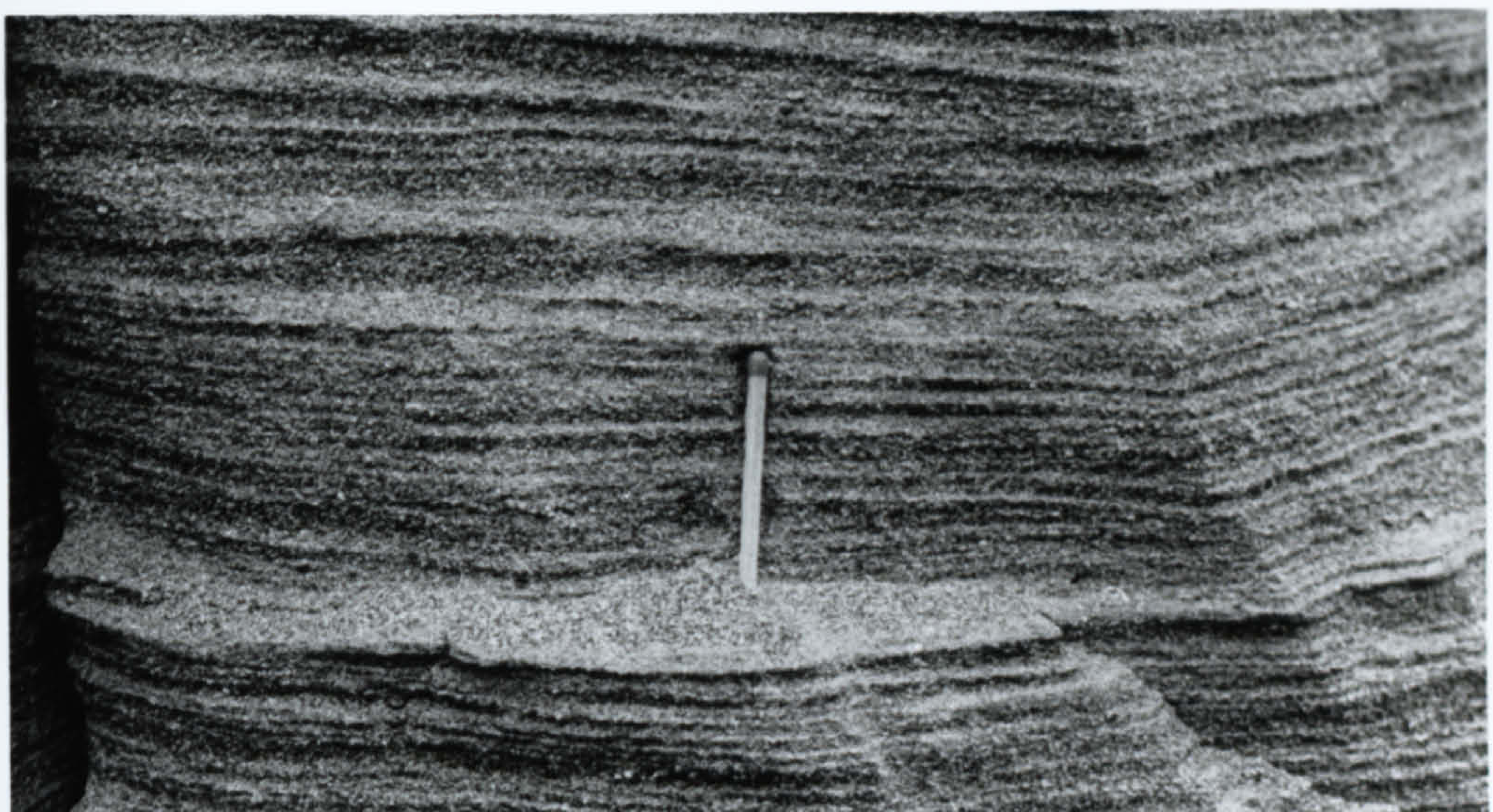
B

Close up of a flow normal section of the 1982 horizontally laminated sands. Note the vertical variation in grain size distribution that defines the laminae and the absence of sharp boundaries.

C

Close up of a flow parallel section of the 1982 horizontally laminated sands. Note the low angle intersection or merging relationship between some of the laminae in a downstream sense (the flow direction was from left to right). The match used for scale is 35 mm in length.





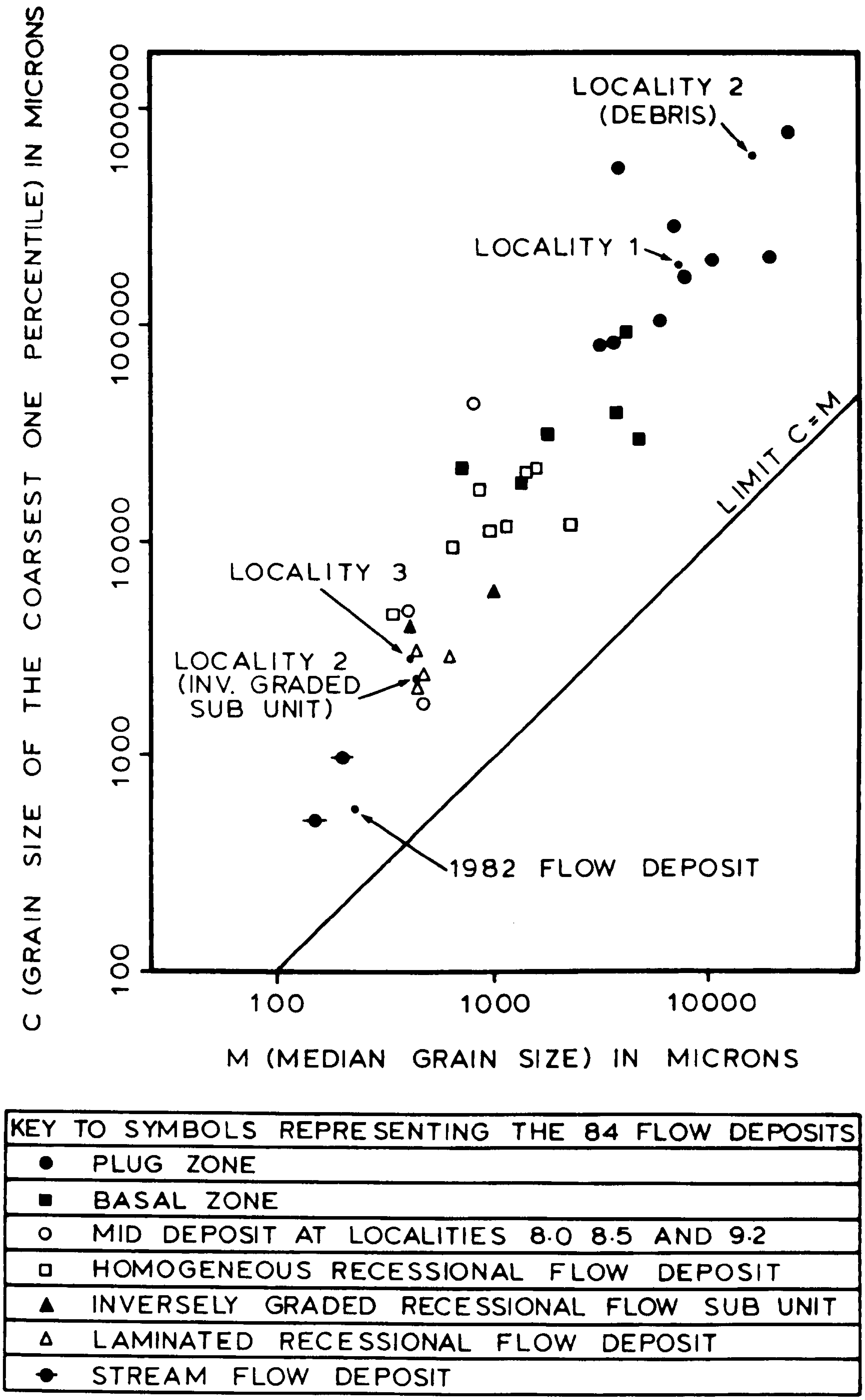


Figure 3.2. A CM diagram with the older Mount Saint Helens mass flow deposits plotted together with the 1984 flow deposits samples for comparison.

foresets on the lee surface of a low amplitude migrating bedform, in a flow where turbulence was important as a sediment transport and depositional process.

In marked contrast to these deposits, Scott (1988a) notes the occurrence of thin inversely graded units within the deposits further downstream from this locality (figure 2.36 [63.4 km from the crater]), but these had been eroded by the time of this study. Despite this, their distal position in the 1982 deposit continuum suggests that they are analogous to the most distal deposits preserved at locality 9.2, in the 1984 deposit continuum.

3.2.3. Flow characteristics

The mean velocity of the 1982 flow at an observation point 2 km further downstream from the laminated sand deposit described above, was 2.75 m/s (Pierson and Scott, 1985) and was associated with a peak sediment concentration of 64% by weight. Pierson and Scott state that "non stationary rolling waves " and "stationary waves" were observed in the flow when the sediment concentration was 32% by weight. In addition, at concentrations of less than 25% by weight, "plane bed and transverse antidune bed conditions" were observed. Despite such turbulent behaviour, the flow had an "oily, glassy smooth" appearance and Pierson and Scott (1985) suggest that the high sediment concentration suppressed secondary turbulence, which they defined as "small waves, bubbles and froth". It can be inferred from Pierson and Scott's (1985) work that turbulence, although not fully developed within the flow, was a major sediment support mechanism in which clast interactions dominated flow behaviour (after Bagnold 1956).

In section 3.2.2, the 1982 laminated sands were attributed to deposition from migrating low amplitude bedforms, based upon the intersecting or merging relationship between laminae. The precise mechanism of their formation, for example, from the alignment of small scale turbulent scour and fill structures, along the paths traced by bedform troughs as envisaged for the formation of horizontal laminae by Paola et al. (1989), is unlikely, based upon the flow observation of Pierson and Scott (1985) that secondary turbulence was suppressed. Small scale turbulence would not be expected under such high concentrations (Wang et al., 1983) and due to the high concentration, the bedforms that produced the laminae (indicated in section 3.2.2.) would have been low amplitude (by considering the experimental investigations performed by Wan [1982]).

Further downstream, to a point over 80 km from the crater, the flow exhibited a range of sediment concentrations from 14 to 67% by weight, with velocities of between 2.5 and 4.6 m/s. Despite this information, Pierson and Scott (1985) do not link flow characteristics with deposits at specific localities. Hence it is difficult to attribute the deposits to any particular flow regime.

3.2.4. The delineation of the hyperconcentrated flow/stream flow deposit boundary

By combining the sedimentological investigations of the 1982 deposits conducted in this study and those of Scott (1988a), with the flow observations of Pierson and Scott (1985), it can be stated that between 43 and 81 km from the crater, the 1982 flow produced laminated sands and inversely graded sandy units. This occurred when the flow was moving at between 2.6 and 4.6 m/s with a sediment concentration between 14 and 67% by weight Pierson and Scott (1985). Pierson and Scott (1985) have termed the 1982 flow beyond 43 km from the crater, "hyperconcentrated streamflow" (figure 2.36), after Beverage and Culbertson's (1964) suggested terminology (figure 1.1). This terminology seems reasonable when the inversely graded units are considered, because despite meagre data on them, they do appear to be directly analogous to the 1984 flow sub units, which were attributed to hyperconcentrated flow in chapter two. What seems unreasonable is that the 1982 laminated sands described in this study, which have the attributes of deposition from normal stream flow, are by implication from Pierson and Scott (1985), the results of deposition by hyperconcentrated stream flow.

According to Pierson and Costa's (1987) rheologic classification, which is dependent on the variables velocity and concentration, the boundary between stream flow and hyperconcentrated flow is marked by the acquisition of yield strength by the former, through increased sediment concentration (figure 1.3). As indicated in section 2.7, this rheological boundary was crossed by the 1984 main flow beyond locality 9.2, when sediment concentration had dropped to between approximately 50 to 60% by weight. The 1982 flow in its distal reach (43 to 81 km) had a sediment concentration which varied enormously, both spatially and temporally, with no apparent steady downstream decrease (Pierson and Scott 1985). It is conceivable that the 1982 flow termed "hyperconcentrated stream flow" by Pierson and Scott (1985), could have crossed the rheological boundary from hyperconcentrated stream flow to stream flow and back again. However, Pierson and Scott state that the concentration did not increase to a point where debris flow concentrations recurred, which was approximately 80% by weight. This variation in the sediment concentration of the 1982 flow would account for laminated sands attributable to stream flow deposition occurring in a more proximal position in the river system, rather than inversely graded units (sub units), which were regarded in chapter two as traction carpets which formed at the base of a more highly concentrated flow.

Based on this discussion, the transformation from hyperconcentrated flow to stream flow in the 1984 flow can be envisaged in the following way. At locality 9.2, as sediment concentration of the flow decreased, yield strength also decreased, with clasts falling from suspension to form traction carpets at the base of the flow (as outlined in section 2.6.5), in a manner described by Lowe (1982) and Hiscott and Middleton (1979). The upper part of the flow was perhaps turbulent, as Pierson and Scott (1985) observed in the more distal sections of the 1982 flow reach (where inversely graded units were formed). However, no bedforms were produced due to the high sediment concentration of the flow, as suggested from the experimental work of Wan (1982). Hence, the flow still possessed a degree of cohesive matrix strength and dispersive pressure dominated sediment support at the base of the bed, where traction carpet formation occurred (as outlined in section 2.6.5). A further decrease in sediment concentration reduced clast interactions and yield strength still further, with the result that the formation of traction carpets ceased and low amplitude bedforms were produced instead, as turbulence became important in sediment transport and deposition. This transition from a non-Newtonian, to a Newtonian fluid occurred in the 1984 main flow when sediment concentration fell below about 55% by weight, which was the estimated sediment concentration of the flow at locality 9.2. The amplitude of the bedforms produced in the resulting highly concentrated stream flow would have been small, due to the high sediment concentration (following the investigations of Wan [1982]).

It can now be stated that beyond locality 9.2, deposits from the 1984 main flow would have been composed of laminated sands produced from low amplitude bedforms. This confirms the opinion in section 2.7 which extrapolated the findings of the laminated recessional flow deposits to the main flow deposits.

3.3. OLDER MASS FLOW DEPOSITS

The eroded remnants of mass flow deposits produced within the last 40,000 years at Mount Saint Helens were examined at four localities along the North Fork Toutle River, downstream from the 1984 flow deposits (figure 3.1). The sections were logged and where possible, granulometric and clast fabric analyses were conducted in a similar manner to that described in chapter two. However, owing to minor consolidation, the deposits sampled for granulometric analysis were gently pounded prior to sieving, to ensure separation of grains (after the method of Folk [1980]). The sequence at locality 4 has been previously noted in the literature by Scott (in press) and hence represents the only accurately dated deposits discussed in the following sections.

3.3.1. Locality 1, Alder Creek Bridge

At this locality, a bipartite sequence composed of a lower thick matrix-supported, inversely graded, unstratified polymodal conglomerate, capped by an upper finer grained unit, blankets a poorly exposed, coarse conglomerate (figure 3.3, plate 3.2A).

The coarse-tail inverse grading in the matrix-supported conglomerate (lower unit), represents the basal shear zone/plug zone arrangement that constituted the original flow. Within the plug zone there is a well defined fabric,

Figure 3.3. Representative descriptive log and clast fabric analysis of the depositional sequence at locality 1 (Alder Creek Bridge).

PLATE 3.2 [OVER]

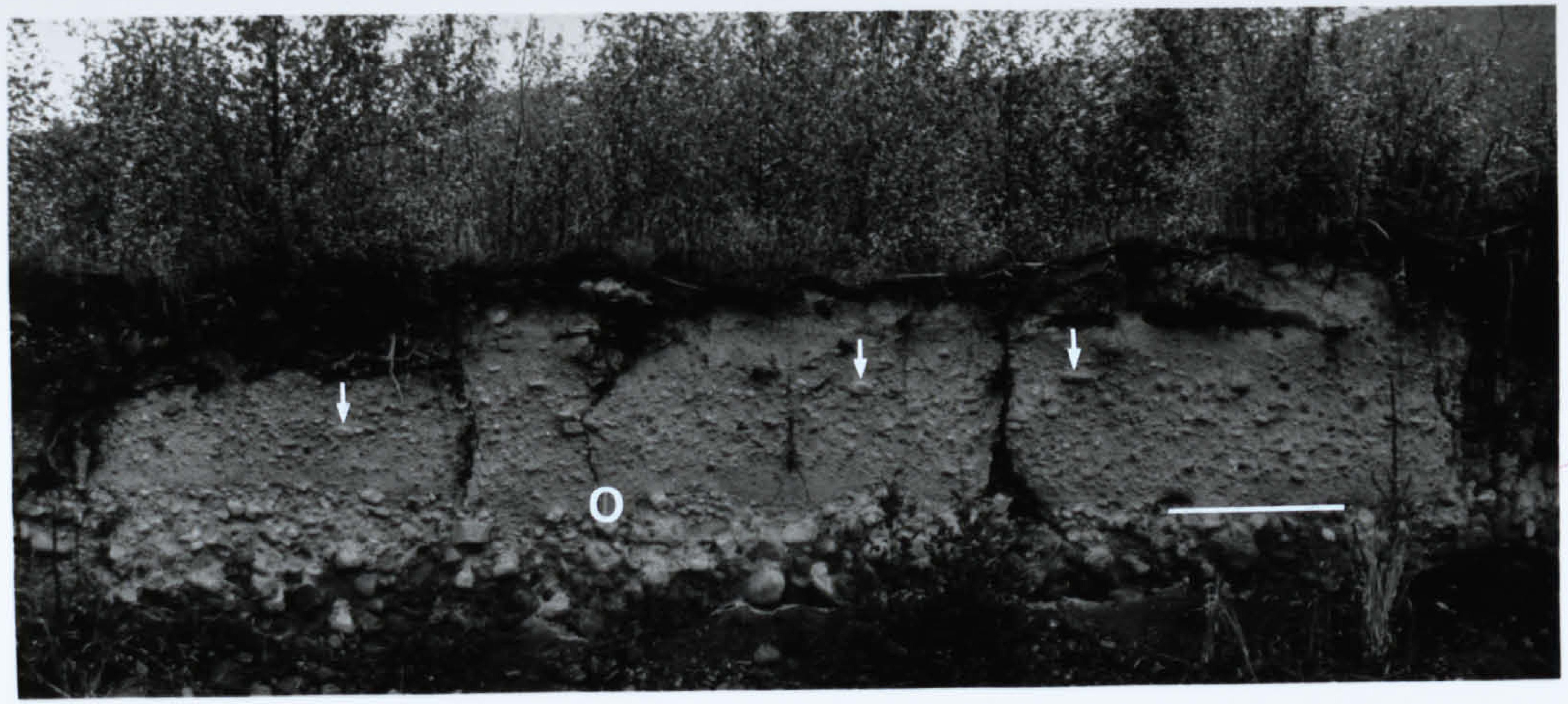
PLATE 3.2

A

Older Mount Saint Helens mass flow deposits preserved at locality 1 (Alder Creek Bridge). The bipartite sequence blanketing the pre-flow surface (marked), is composed of a coarse grained inversely graded lower unit and an upper finer grained unit. Note the conspicuous clast fabric developed within the plug zone of the lower unit, where cobble sized clasts (arrowed) have a-axes orientated parallel to flow and with no imbrication. Flow direction was from right to left and the 30 cm scale is circled.

B

Older Mount Saint Helens mass flow deposits preserved at locality 2 (Camp Baker). Note the undulose stratification within the pebbly granule sand deposit, reflecting the topography of the underlying depositional surface. The thin coarse-tail inverse graded sub units that define the stratification have gradational contacts and are not laterally persistent. Note the disorganised inversely graded nature of the debris flow unit above and the fragile clast (arrowed A). Flow direction was normal to the section. The unit (arrowed B), which cuts the inversely graded sub units and is in turn cut by the debris flow unit above, represents fluvial material deposited after the erosion of the inversely graded sub units.


O


A
B

with the a-axes of cobble sized clasts preferentially orientated parallel to flow direction, with no imbrication. The upper finer grained unit, which has a locally gradational contact with the lower unit, is a pebbly granule sand, in which outsized clasts (cobbles) occur preferentially orientated with a-axes transverse to flow. This upper unit is thus sedimentologically very similar in character to the 1984 homogeneous recessional flow deposits. Granulometric analysis of the plug zone of the lower unit (appendix 5), yielded very similar textural characteristics to the 1984 main flow deposits at locality 3.7 (compare appendix 5 with 1A). This textural similarity is also demonstrated using the CM textural discrimination diagram (figure 3.2).

The sedimentological and textural characteristics of the upper and lower units are directly analogous to those of the 1984 flow depositional sequence, preserved between localities 3.7 and 6.5. The lower unit, therefore, represents deposition from a flow that was transforming from debris flow to hyperconcentrated flow. The plug zone/basal zone arrangement is well developed, but the contact is diffuse, indicating that shear occurred through a large thickness of the flow and was not restricted to a thin zone at the base (compare with the 1984 flow deposits at locality 0.0, section 2.3.2). In addition, clasts were able to move under shear and became preferentially orientated. The particle support mechanisms can be inferred from the discussion in section 2.6, to consist of a combination of cohesive matrix strength, buoyancy and dispersive pressure. Turbulence can be ruled out as an important mechanism because of the lack of scour of the pre-flow surface (Enos, 1977) and the highly concentrated nature and high yield strength of the flow, which is implied from the similarity to the 1984 flow deposits. The upper unit can be attributed to a hyperconcentrated recessional flow, as its sedimentological characteristics are very similar to those of the homogeneous recessional flow deposits, produced in the wake of the 1984 mass flow.

3.3.2. Locality 2, Camp Baker

At this locality, a pebbly granule sand unit with undulose stratification occurs between two boulder conglomerates (figure 3.4, plate 3.2B). The base of the lower conglomerate bed is not seen, but the upper conglomerate shows slight coarse-tail inverse grading and contains fragile clasts. Both beds are very poorly sorted, unstratified and matrix to clast-supported.

The pebbly granule sand unit blankets the lower conglomerate and has been eroded prior to the deposition of the upper conglomerate. The undulose stratification is defined by stacked thin coarse-tail inversely graded sub units that follow the hummocky configuration of the deposit base. The sub units do not persist laterally for more than 2 m, but pass into homogeneous pebbly granule sand. Pebble

Figure 3.4. Representative descriptive log of the depositional sequence at locality 2 (Camp Baker) and the clast a-axis orientation analysis conducted on several inversely graded sub units.

sized clasts within these units are preferentially orientated with their a-axes parallel to flow direction (figure 3.4).

Texturally, the thin inversely graded sub units are similar to the 1984 main flow deposits at locality 9.2 and to the inversely graded sub units which form part of the 1984 recessional flow deposits at locality 3.4 (compare appendix 5 with 1A). On a CM textural discrimination diagram, these three groups of inversely graded sub units all plot in the same vicinity (figure 3.2).

Such similarity in sedimentological and textural characteristics, indicates similar depositional processes, with this pebbly granule sand deposit being inferred to have been produced at the base of a hyperconcentrated flow where shearing, associated with the production of dispersive stresses, allowed the formation of traction carpets (the sub units) in a manner discussed in section 2.6.5 (after Lowe, 1982; Hiscott and Middleton, 1979). During formation, the traction carpets "hugged" the pre-flow topography (the hummocky surface of the underlying boulder conglomerate) and upon collapse and freezing, the original bed topography was preserved throughout the sequentially produced stack of inversely graded sub units, thereby causing the undulose stratification. The lateral discontinuity of the inverse grading in the sub units indicates, as in the case of the main flow deposits at locality 9.2, that the dispersive pressure at the base of the deposit producing flow was not maintained spatially as the carpet formed. Thus locally, sediment fell from suspension onto the bed without being affected by dispersive stresses. This stacked sequence of inversely graded sub units does not clearly exhibit a decrease in grain size as was indicated for the 1984 main flow deposits at locality 9.2 and which was demonstrated within the 1984 recessional flow inversely graded sub units at locality 3.4, but it does exhibit a general decrease in thickness of the units upward in the stack. This indicates that the hyperconcentrated flow that produced these sub units at Camp Baker was slowing and losing yield strength as deposition occurred (after Hiscott and Middleton, 1979). Based upon the very similar structure and composition of these sub units with the 1984 main flow deposits at locality 9.2, the suggestion can be made that this hyperconcentrated flow had a sediment concentration of between 50 and 60% by weight and was moving in the order of several metres per second.

The upper conglomerate bed was sampled and point count analysis was conducted. The resulting grain size distribution characteristics (appendix 5), its position on a CM textural discrimination diagram (figure 3.2), together with the sedimentological characteristics (figure 3.4), indicate great similarity between this deposit and the proximal 1984 main flow deposits. Therefore, it may be inferred that this unit was deposited from a highly concentrated viscous debris flow, which could be described in terms of Johnson's (1970) Coulomb-viscous model, in which a plug moves over a basal zone of shear. The random clast fabric and the presence of fine grained masses that were once fragile clasts, suggest that shear or collisions between clasts was minimal and hence the plug was rigid and non-deforming.

3.3.3. Locality 3, Tower Road

At this locality, there is a seven metre thick sequence composed predominantly of horizontally stratified pebbly granule sands with subordinate pebble and cobble horizons. Two metres of the sequence were logged, with additional information derived through clast orientation and granulometric analysis (figure 3.5, plate 3.3A).

The pebbly granule sands are composed of laterally persistent inversely graded sub units which are up to twenty five centimetres in thickness (plate 3.3B). The grain size distribution characteristics are very similar to the inversely graded sub unit sampled at locality 2 and the inversely graded sub units that form the 1984 flow event deposits at localities 9.2 and 3.4 (compare appendix 5 with 1A). This textural similarity is best displayed on the CM textural discrimination diagram (figure 3.2). These horizontal sub units, which are generally thicker than those at locality 2 (Camp Baker), persist laterally for up to 10 m, but several units "die out" to be replaced by structureless granule sand. Unlike the sub units at Locality 2 and those formed in the 1984 flow event, they do not exhibit an upward

Figure 3.5. Representative descriptive log of the depositional sequence at locality 3 (Tower Road) and the results of clast a-axis orientation analysis conducted on an inversely graded sub unit.

PLATE 3.3 [OVER]

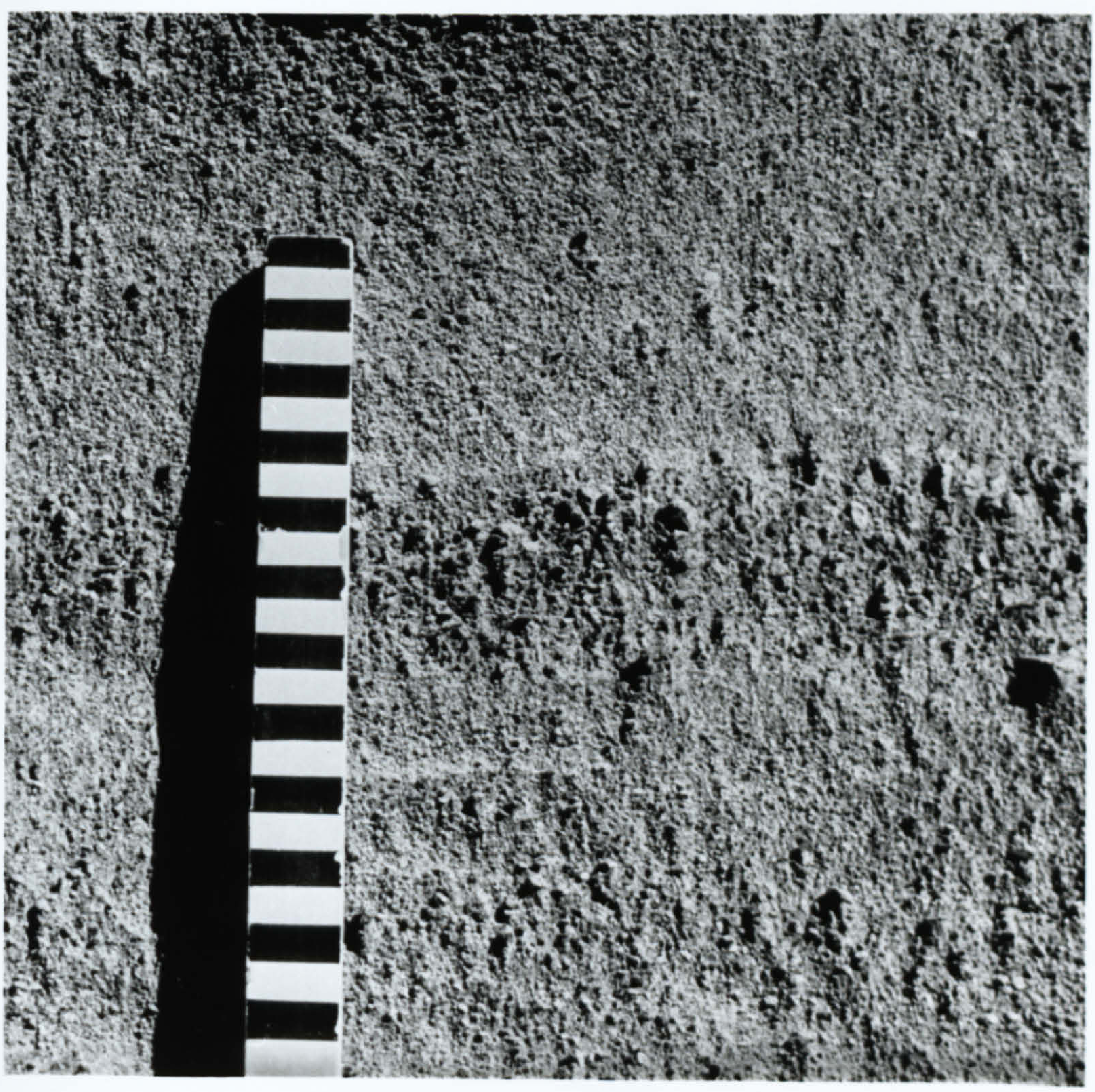
PLATE 3.3

A

Older Mount Saint Helens mass flow deposits preserved at locality 3 (Tower Road). The sequence is predominantly composed of horizontally stratified pebbly granule sands with subordinate clast supported cobble and pebble horizons. The stratification within the pebbly granule sand is defined by stacked thin inversely graded sub units, note their lateral persistence. Flow was from right to left, the 30 cm scale is circled.

B

Close up of the stack of inversely graded sub units at locality 3 (Tower Road), A above. Of note is the coarse-tail nature of the inverse grading and the gradational contacts between the sub units. Flow was from right to left.



decrease in thickness throughout the stack. The a-axes of pebble sized clasts within the inversely graded sub units are orientated parallel to the flow direction.

The pebble and cobble horizons which are clast supported, have sharp contacts with the sequence of inversely graded sub units and well developed a(t) b(i) fabric. This fabric indicates rolling of the clasts along the bed immediately prior to deposition (Johansson, 1965; Walker, 1975a; Rust, 1972) and represents stream flow deposition. In contrast, the sequence of stacked inversely graded sub units bound by the pebble and cobble horizons can be regarded as sequentially produced traction carpets which were formed at the base of a hyperconcentrated flow, as described for the analogous units at locality 2 (section 3.3.2) and for the 1984 flow event deposits at localities 9.2 and 3.4 (sections 2.6.5 and 2.6.6.3 respectively).

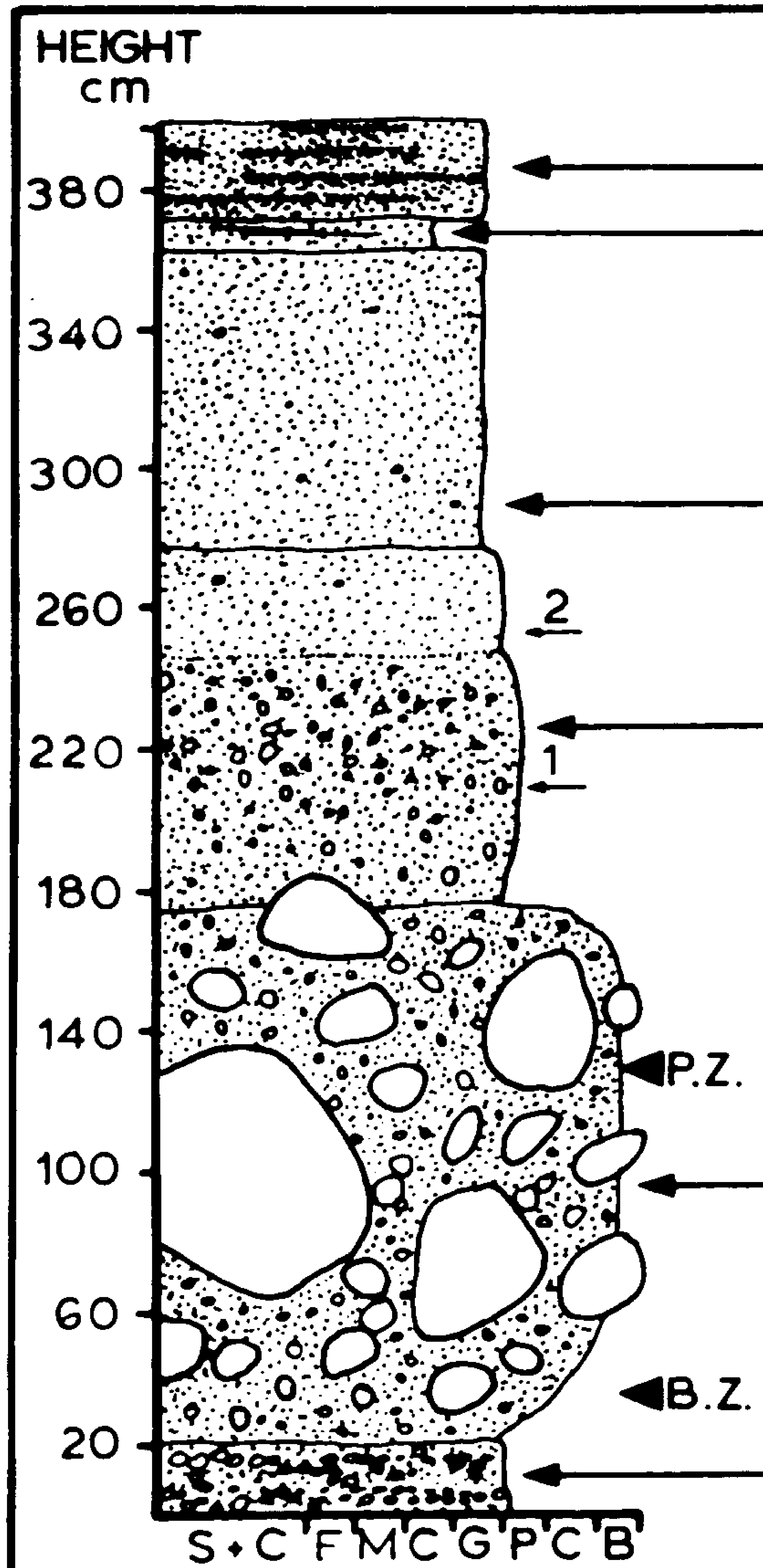
There is no decrease in thickness of the traction carpet layers upward in the stack, or any decrease in the amount of larger sized clasts. This suggests that the flow that produced these sub units did not lose yield strength or velocity during their deposition, as inferred for the 1984 flow event inversely graded sub units, or for those at locality 2 (Camp Baker), (after the work of Hiscott and Middleton [1979]). The horizontal nature of the sub units reflects the horizontal character of the depositional surface.

Most of the seven metres of the section above this logged sequence, which was inaccessible, appears to represent stacked inversely graded sub units that formed as traction carpet layers at the base of a hyperconcentrated flow or flows (plate 3.3A). The pebble and cobble horizons represent deposition under normal stream flow conditions, between periods of hyperconcentrated flow.

3.3.4. Locality 4, Coal Bank Bridge

At this locality several well defined units produced in separate flow events between 13,700 and 9,200 years ago (Scott, in press), occur in a stacked sequence (figure 3.6, plate 3.4). This has been described by Scott (in press) who attributed the lower units to deposition from "lahars", with the top unit being the result of "lahar runout flow", a term which Scott (1988a, in press) uses synonymously with hyperconcentrated flow. The result of this study has shown that this generalisation is most likely correct if Scott's terminology is accepted, by which "lahar" and "lahar runout flow" are synonymous with debris and hyperconcentrated flow respectively. However, important refinements can be made, in order that each unit in the sequence can be interpreted to represent deposits of specific flows in the debris flow to stream flow deposit continuum.

The lowermost unit (A. on figure 3.6, plate 3.4) has a basal zone with a well defined unstratified plug zone above, which contains fragile and rafted clasts. This unit is



DEPOSIT CHARACTERISTICS	INTERPRETATION
- POORLY SORTED GRANULE SAND COMPOSED OF STACKED INVERSELY GRADED SUB UNITS. THESE HAVE GRADATIONAL CONTACTS, ARE NOT LATERALLY PERSISTENT AND FOLLOW THE CONFIGURATION OF THE BED BASE.	TRACTION CARPETS FORMED AT THE BASE OF A HYPERCONCENTRATED FLOW
- LAMINATED SAND, THE LAMINAE WHICH ARE DEFINED BY LAYERS WITH AN INCREASED SILT CONTENT, OCCASIONALLY INTERSECT IN A DOWNSTREAM SENSE.	STREAM FLOW
- POORLY SORTED UNSTRATIFIED GRANULE SAND, WITH VERY RARE PEBBLE SIZED CLASTS	HYPERCONCENTRATED FLOW
- POORLY SORTED AND UNSTRATIFIED PEBBLY GRANULE SAND, WHICH IS DIVISIBLE INTO TWO UNITS THE LOWER ONE BEING COARSE-TAIL INVERSELY GRADED - THERE IS NO VISIBLE FABRIC WITHIN EITHER OF THE TWO UNITS	HYPERCONCENTRATED FLOWS:- 1 = MAIN FLOW 2 = RECESSIONAL FLOW
- VERY POORLY SORTED AND UNSTRATIFIED MATRIX TO-CLAST SUPPORTED BOULDER CONGLOMERATE, WITH SLIGHT COARSE-TAIL INVERSE GRADING AND LARGE FRAGILE CLASTS - VISIBLY CHAOTIC FABRIC	DEBRIS FLOW WITH A PLUG ZONE (P.Z.) AND AND BASAL SHEAR ZONE (B.Z.)
- STRATIFIED AND CLAST-SUPPORTED PEBBLY GRANULE SAND	STREAM FLOW

Figure 3.6. Representative descriptive log of the depositional sequence and its interpretation at locality 4 (Coal Bank Bridge).

PLATE 3.4 [OVER]

PLATE 3.4

The depositional sequence preserved at locality 4 (Coal Bank Bridge) which was produced by different flow events from Mount Saint Helens between 13,700 and 9,200 years ago. Note the large fragile clast within the plug zone of the lower unit (arrowed). Individual units or sequences of units discussed in the text, are lettered. Flow was from left to right.


E
D
B
A

directly analogous to the proximal 1984 main flow deposits and can be regarded as a highly concentrated debris flow which may be described in terms of Johnson's (1970) Coulomb-viscous model. The apparently random fabric and the presence of the large fragile clasts indicates that the plug was rigid and non-deforming.

The bipartite sequence (B. in figure 3.6, plate 3.4) is composed of an inversely graded, unstratified deposit (unit 1), with a superimposed finer grained unit (unit 2), above a sharp to gradational contact. Their general sedimentological characteristics are directly analogous to the 1984 flow bipartite depositional sequences in the vicinity of locality 8.5, albeit with a thicker recessional flow deposit. This suggests that these units were produced by hyperconcentrated flows, with the main flow lacking a plug zone/basal zone arrangement. Following the discussion of the 1984 main flow at locality 8.5 in section 2.6.4, it can be inferred that the flows which deposited sequence B were highly concentrated dispersions, in which cohesive matrix strength and dispersive pressure were the dominant particle support mechanisms. Deposition by the main flow (unit 1) was probably not simultaneous, because of the lack of a plug zone/basal zone arrangement as inferred within the 1984 main flow at locality 8.5. Hence deposition may have taken place, in which a surface separating stationary from moving particles, moved rapidly up through the flow (after a mechanism postulated by Carter [1975a]).

Unit C (figure 3.6, plate 3.4) is not directly analogous to any other 1984 flow deposit, however, its sedimentological characteristics indicate that it may well represent a fine grained corollary of the 1984 main flow deposit at locality 8.5, as reviewed in sequence B.

Unit D (figure 3.6, plate,3.4), which could not be accessed directly, is composed of laminated sands. The laminae are generally horizontal, however, some of the laminae, which are subhorizontal, intersect, or merge in a downstream sense. These are analogous to the 1982 flow deposits described in section 3.2.2. and to the laminated 1984 recessional flow deposits at locality 3.7. These were both attributed to deposition as low amplitude bedforms in a stream flow, in which turbulence was important in sediment transport and deposition.

Unit E (figure 3.6, plate 3.4) is composed of weakly coarse-tail inversely graded granule sand sub units. They are very similar to the units described at locality 2 (Camp Baker), and like those sub units, their undulose nature reflects the curved topography of the depositional surface. These sub units thus represent traction carpet layers formed at the base of a hyperconcentrated flow. The lack of laterally persistent inverse grading indicates that the dispersive stresses were locally ineffective.

This stacked sequence represents elements of the debris flow to stream flow deposit continuum. At the base of the sequence there is a debris flow deposit; at the top there is the intimate association of laminated sand and inversely graded granule sand sub units, which represent deposition on either side of the hyperconcentrated flow/stream flow boundary. In the middle of the sequence, unit C and the bipartite sequence B can be inferred to be hyperconcentrated flow deposits.

3.4. SUMMARY

Examination of remnants of the 1982 flow deposits, combined with the findings from the 1984 flow deposits, has allowed the delineation of the hyperconcentrated flow/stream flow deposit boundary. It can be suggested, that with decreasing sediment concentration in a transforming flow, en masse deposition gives way to the formation of traction carpets (chapter two). With a further decrease in sediment concentration and yield strength, stream flow conditions are developed under which low amplitude bedforms develop. This transition from traction carpets to bedforms delineates the hyperconcentrated flow/stream flow deposit boundary.

Depositional elements of the debris flow to stream flow deposit continuum can be recognised among the eroded remnants of older Mount Saint Helens mass flow deposits. In addition, the processes of sediment transport and deposition can be inferred by the comparison of the various units with their corollaries in the 1984 flow depositional continuum. It has been possible at locality 2 (Camp Baker), to infer the sediment concentration and velocity of the hyperconcentrated flow that produced inversely graded sub units, through the extrapolation of the findings of the 1984 main flow deposits at locality 9.2.

CHAPTER 4

CRITERIA FOR THE RECOGNITION OF VOLCANICLASTIC HYPERCONCENTRATED FLOW DEPOSITS AND THEIR APPLICABILITY TO OTHER SEDIMENTARY ENVIRONMENTS

4.1. INTRODUCTION

Chapter two presented the findings from a sedimentological investigation of deposits produced at Mount Saint Helens in 1984, from a diluting and transforming mass flow. From these investigations it was possible to delineate the debris flow/hyperconcentrated flow deposit boundary. However, due to the lack of downstream exposure the continuum was not complete and so the hyperconcentrated flow/stream flow boundary expressed in the depositional record of the flow was not observed, although it was inferred from the examination of 1984 recessional flow deposits.

An investigation of laminated sand deposits produced by the 1982 flow, presented in chapter three, allowed the complete delineation of hyperconcentrated flow deposits within the debris flow/stream flow continuum, inferred to have been exhibited by the 1984 flow sequence beyond locality 9.2, prior to erosion. It has also been demonstrated in chapter three, that elements of the debris flow/stream flow deposit continuum are well displayed in mass flow depositional sequences produced in the 40,000 year history of Mount

Saint Helens.

The aims of this chapter are to propose criteria for the recognition of hyperconcentrated flow deposits based on the combined findings of Chapters two and three and to discuss their applicability in the delineation of hyperconcentrated flow deposits within the debris flow/stream flow depositional continua of other sedimentary environments.

4.2. CRITERIA FOR THE RECOGNITION OF VOLCANICLASTIC HYPERCONCENTRATED FLOW DEPOSITS AT MOUNT SAINT HELENS

Through analysis and discussion of sedimentology and flow properties, the transformation from debris flow to hyperconcentrated flow was indicated to occur within the 1984 flow beyond locality 3.7, with the result that at locality 7.3 and beyond, hyperconcentrated flow deposits were produced. This delineation includes the stacked inversely graded sub units at locality 9.2. The homogeneous recessional flow deposits and the recessional flow deposit composed of stacked inversely graded sub units at locality 3.4, are also attributed to hyperconcentrated flow deposition. However, the laminated recessional flow deposits were attributed to deposition from bedforms produced under more dilute stream flow conditions. The delineation between hyperconcentrated flow deposits and stream flow deposits with inversely graded sub units forming in the former and bedforms in the latter, was confirmed by the examination of the 1982 flow deposits. At this stage criteria can be proposed for the recognition of hyperconcentrated flow deposits for this particular sedimentary environment, based upon the combined findings of chapters two and three. These criteria are presented in figure 4.1.

Smith (1986), presents in a similar manner, some characteristics of hyperconcentrated flow deposits, based largely upon investigations of volcaniclastic mass flow

DEPOSIT ORIGIN / CHARACTERISTICS	STREAM FLOW	HYPERCONCENTRATED FLOW	DEBRIS FLOW
	C R	I T E	R I A
SORTING	>HF+DF	HF < SF, HF > DF	<HF+SF
SUPPORT	VARIABLE BUT PREDOMINANTLY CLAST SUPPORTED	MATRIX - SUPPORTED (the matrix is polymodal)	MATRIX TO CLAST - SUPPORTED (the matrix is polymodal)
STRATIFICATION	HORIZONTAL AND CROSS-STRATIFICATION	NON, OR DEFINED BY SUB UNITS	NON
GRADING	VARIABLE	NON, OR WEAK COARSE-TAIL INVERSE GRADING WHICH MAY BE DEVELOPED AS SUB UNITS. (MAY HAVE THE REMNANTS OF A PLUG ZONE)	NON, OR WELL DEFINED COARSE-TAIL INVERSE GRADING REPRESENTING A PLUG ZONE AND BASAL ZONE ARRANGEMENT
FABRIC CLAST A-AXIS ORIENTATION + IMBRICATION	TRANSVERSE TO FLOW AND USUALLY WELL IMBRICATED	NON, OR BIMODAL AS A FUNCTION OF CLAST SIZE, WITH NON OR POORLY DEVELOPED IMBRICATION	NON, OR UNIMODAL WITH A-AXES PARALLEL TO FLOW AND NO IMBRICATION
GENERAL	EXHIBITS BEDFORMS	CONTAIN NO OUTSIZED OR FRAGILE RAFTED CLASTS	CAN CONTAIN OUTSIZED RAFTED CLASTS, SOME FRAGILE

ESTIMATED SEDIMENT CONCENTRATION VALUES (IN WT.%) AT FLOW BOUNDARIES FOR THE 1984 FLOW: <55 (stream flow / hyperconcentrated flow boundary); 60-70 (hyperconcentrated flow / debris flow boundary)

Figure 4.1. Criteria for the recognition of hyperconcentrated flow deposits within the debris flow/stream flow deposit continuum, in the volcaniclastic environment of Mount Saint Helens. The estimated sediment concentration values are peculiar only for the 1984 mass flow and the characteristics of stream flow are after Smith (1986).

deposits in the geological record. Smith (1986) indicates that hyperconcentrated flow deposits lack cross stratification, have polymodal matrix and exhibit bimodality within the clast population, in which large clasts occur orientated transverse to flow direction and smaller clasts are orientated parallel to flow, with imbrication poorly developed. Although these characteristics are broadly similar to those of this study, there are some important differences. Smith (1986) indicates that hyperconcentrated flow deposits are clast supported, can have horizontal stratification and are frequently distribution normal-graded. This is at odds with the findings of this study. Furthermore, Smith (1986), does not attempt to put estimates of sediment concentration limits between members of the flow continuum, or give an indication of the intermediate sorting characteristics of hyperconcentrated flow deposits as found in this study (illustrated in figure 2.14 and on the textural discrimination diagram, figure 2.17). Despite the differences between this study and that of Smith (1986), Smith's list of characteristics is a good attempt, derived without the benefit of a modern depositional sequence as displayed by the 1984 flow deposits.

The main point of difference between the results of this study and that of Smith (1986), is Smith's observation that hyperconcentrated flow deposits can have horizontal stratification. Stratification was rarely developed in the 1984 flow deposits and was restricted almost entirely to a group of recessional flow deposits, that were attributed to bedform formation under stream flow conditions. The only other stratification exhibited by the 1984 depositional sequence was defined by the stacked inversely graded sub units at locality 9.2. The fine coarse-tail inverse grading of similar stacked inversely graded sub units may have been unnoticed by Smith (1986) and thus such hyperconcentrated flow deposit units as a whole, may have been termed "stratified" by Smith. This suggested lack of observation by Smith, is very strongly supported when considering Smith's (1988) figure 6, which according to Smith, depicts "crudely stratified hyperconcentrated flow deposits". Examination of the figure reveals that the stratification is defined by stacked inversely graded sub units, identical in appearance to the sequence at locality 3 (Tower Road), in chapter 3 (plate 3.3A). If Smith's (1986) characteristic of horizontal stratification can be translated as stacked inversely graded sub units, then there are only two significant points of difference in the characteristics of hyperconcentrated flow deposits established in this study and that of Smith. These differences are concerned with clast support and grading.

Normal grading, which is attributed to the preferential settling of clasts in a flow (Schultz, 1984; Smith, 1986), was not present within any of the depositional units of the 1984 flow deposits remaining at the time of study. In addition it was not recorded by Pringle and Cameron (in press). Since Smith (1986) did not examine a modern depositional sequence exhibiting a continuum of deposits, as conducted in this study, it is likely that the distribution normal graded deposits noted by Smith were not produced from hyperconcentrated flows. In addition to normal grading, clast support was not present in the 1984 depositional continuum. This suggests that its use as a characteristic of hyperconcentrated flow deposition according to Smith (1986) is unlikely.

Smith (1986) does not indicate that hyperconcentrated flow deposits have sorting characteristics intermediate between debris flow and stream flow as in this study, but intermediacy in sorting is described by Costa (1988) and Scott (1988a). Both Costa (1988) and Scott (1988a) state that hyperconcentrated flow deposits have sorting values in the range 1.1 to 1.6 ϕ, with Scott indicating that mean grain size is greater than approximately 2.5 ϕ. The hyperconcentrated flow deposits defined in this study are more poorly sorted and coarser grained than those defined by Scott (see appendix 1A). This is not surprising, as the deposits Scott defines as hyperconcentrated, are generally composed of sands (see figure 2.36), directly analogous to the 1982 flow deposits investigated in chapter two.

According to Costa (1988), hyperconcentrated flow deposits are very difficult to separate from those of water floods. Costa states that they can be massive, have primary sedimentary structures, including horizontal stratification, cross bedding, clast imbrication and may have normal or reverse grading. The hyperconcentrated flow deposit characteristics presented by Costa (1988), are largely incompatible with those of this study: namely the cross bedding and the normal grading. Costa does not elaborate on the term "massive", or detail the type of imbrication or grading and thus a comparison with this study is difficult. However, as Costa indicates, the characteristics he presents are based on the findings of Scott (1988a), who in turn bases his 1988(a) work on the findings of Pierson and Scott (1985). As discussed in chapter two (section 2.7), Pierson and Scott's (1985) delineation of hyperconcentrated flow deposits based on the 1982 Mount Saint Helens mass flow, appears to have been quite erroneous and thus any criteria established by researchers, developed on this delineation (including Scott [1988a] and Costa [1988]), must therefore be dubious.

Nemec and Muszyński (1982) described a range of volcaniclastic deposits in the Sophia district of Bulgaria and although they do not present criteria for the discrimination of hyperconcentrated flow deposits, they do attributed their "Facies C" deposits to deposition from hyperconcentrated flow. Nemec and Muszyński's "Facies C" deposits are generally distribution normally graded and show crude or cross stratification. However, massive and unstratified deposits also occur, which have an a(p) a(i) fabric (following Walker's [1975a] notation) or a planar fabric (with clast a-axes orientated parallel to flow and no imbrication). By applying the criteria presented in figure

4.1, the "Facies C" deposit characteristics are in general, incompatible with deposition from hyperconcentrated flow. However, the massive and unstratified deposits may have originated from hyperconcentrated flows. A more detailed and systematic sedimentological analysis of Nemec and Muszyński's (1982) "facies C" could therefore yield deposits that fully satisfy the criteria in figure 4.1 which would indicate deposition from hyperconcentrated flows.

4.3. THE APPLICABILITY OF THE CRITERIA FOR THE RECOGNITION OF HYPERCONCENTRATED FLOW DEPOSITS, ESTABLISHED AT MOUNT SAINT HELENS, TO OTHER SEDIMENTARY ENVIRONMENTS

The criteria for recognising hyperconcentrated flow deposits developed in chapters two and three, were used to show that elements of the debris flow/stream flow deposit continuum could be discerned within depositional sequences produced in the last 40,000 years at Mount Saint Helens. The question thus arises, whether or not these criteria can be used to delineate hyperconcentrated flow deposits in other sedimentary environments. Such a suggestion seems distinctly possible when it is considered that mass flow deposits as indicated in chapter one, occur in several different sedimentary environments worldwide and especially when researchers, for example Bull (1962), note the occurrence of flows that are "intermediate in character between mud flow and stream flow". In addition, throughout chapters two and three, references were made to the results of investigations conducted on depositional sequences produced in widely varying sedimentological environments that yielded similar results to those of the 1984 flow deposits. Johnson's (1970) Coulomb-viscous model for the description of debris flow was applied to the 1984 main flow deposits, despite the fact that it was derived by Johnson, in part, through the observation of non volcaniclastic mass flows. The processes suggested in this study for the formation of clast fabric in the 1984 main flow, in the vicinity of locality 8.5, were postulated after considering the results of fabric analyses conducted by Hein (1982), on what were deep marine conglomerates. The processes responsible for the formation of the stacked inversely graded sub units at localities 9.2 and 3.4 were inferred through consideration of Lowe's (1982) and Hiscott and Middleton's (1979) work on turbidity current deposits. In addition, the BTh/MPS relationship of the 1984 main flow deposits (figure 2.26), yielded similar results to BTh/MPS studies conducted on subaerial and subaqueous fan conglomerates by Gloppen and Steel (1981) and on subaqueous fan delta successions by Porebski (1984). These analogous findings indicate that similar processes are operable in many different environments.

Although pan environmental processes of mass flows can be invoked through the similarity of the results of this study with other studies worldwide, subtle variations in sediment transport and depositional processes are likely to occur between environments. Variation will arise, for example from differences in clast composition (Smith and Smith, 1985) and clay content of the flow (Pierson and Costa, 1987). This suggests that the delineation of hyperconcentrated flow within a debris flow/stream flow continuum will also vary. As shown by Pierson and Costa (1987) and illustrated in figure 1.2, the rheological boundaries between stream flow, hyperconcentrated flow and debris flow, based on rheology, will vary according to the composition of the flow.

Thus the sediment concentration limits between the various flow types of the 1984 flow in figure 4.1 may only be peculiar to that particular flow. In addition, every flow that occurs in a volcaniclastic environment may not have the same boundary limits (Smith, personal communication, 1987), despite their being produced under the same conditions (for example as the result of a volcanic eruption) and having the same source of sediment. These indications of variation in flow character, not only between different environments, but also between flows produced in the same environment, lead to concern over the widespread applicability of the criteria established in 4.2. In addition to this concern, the criteria were established through the examination of coarse grained deposits and hence this negates their use in the interpretation of deposits composed of sand, silt and clay.

Although this work has implications for the interpretation of deposits within deposit continua in subaqueous environments, it is beyond the scope of this investigation. Thus, application of the criteria in this study is confined to subaerial environments and in particular to the alluvial fan environment where a variety of coarse grained mass flows occur (Nemec and Steel, 1984; Smith, 1986) and where Smith (after Bull, [1964, 1972]), postulates hyperconcentrated flows may be important, albeit on a smaller scale than the volcaniclastic environment.

4.4 SUMMARY

This chapter has presented the conclusions of the findings of chapters two and three, in the form of a set of criteria (figure 4.1) for the recognition of hyperconcentrated flow deposits in the volcaniclastic environment of Mount Saint Helens. The criteria of no stratification (except where defined by sub units), clast bimodality and polymodal matrix are similar to characteristics defined by Smith (1986). In addition the criterion of intermediate sorting characteristics between debris flow and stream flow is a conclusion in common with Scott (1988a) and Costa (1988). However, neither clast support and distribution normal grading, which Smith states as being characteristic of hyperconcentrated flow deposits, nor the characteristics noted by Costa (1988), which include cross bedding, are compatible with this study.

The interpretation of the processes of sediment transport and deposition within the transforming 1984 flow, produced similar findings to researchers in sedimentary environments elsewhere. This demonstrates that processes can be pan environmental and hence the criteria established in this study can be applied elsewhere in other sedimentary environments, for example, alluvial fans. However, processes may vary even between two flows produced under the same circumstances in the same environment and so the sediment concentration limits set in figure 4.1 may be peculiar only for the 1984 flow.

CHAPTER 5

DELINEATING HYPERCONCENTRATED FLOW DEPOSITS IN PERMO-TRIASSIC ALLUVIAL FAN SEQUENCES ON LEWIS THE OUTER HEBRIDES, SCOTLAND

5.1 INTRODUCTION

Chapter four presented criteria for the recognition of hyperconcentrated flow deposits in the volcaniclastic environment of Mount Saint Helens and the question arose whether the criteria could be used to enable the recognition of hyperconcentrated flow deposits within other sedimentary environments. Alluvial fans in particular were singled out as likely environments of hyperconcentrated flow deposition, although, Smith (1986) indicates that such deposits may not cover as much area and would be less readily preserved than in volcanic areas.

Alluvial fans form at the base of a mountain front, or other upland area, where an emerging mountain stream deposits a sedimentary body whose sloping surface forms the segment of a cone (Nilsen, 1982). Deposition on the fan results from the deceleration of sediment carrying flows due to an increase in flow width and decrease in flow depth as the flows emerge from the confines of the feeder canyon or fanhead canyon (Bull, 1964; Denny, 1965). Much of an alluvial fan surface is inactive and is the site of weathering, pedogenesis and erosion (Bluck, 1964; Denny, 1965; Lustig, 1965; Hooke, 1967, 1968). However, through time, the incision, infilling, migration and abandonment of channels, results in even sedimentation on the fan (Beaty, 1963, 1970; Bull, 1972; Denny, 1965; Hooke, 1967, 1968; Lustig, 1965). Classic descriptions of modern alluvial fans are mostly from the mountainous semi-arid regions of the south western U.S.A. (for example, Bull, 1964, 1972; Hooke, 1967), but they have been described elsewhere, for example, in association with glaciers (Church and Ryder, 1972; Wasson, 1977).

Alluvial fans have been divided by Schumm (1977) into "dry or mudflow" fans formed by ephemeral stream flow and "wet" fans formed by perennial stream flow. In dry fans, debris flows result from the interaction of steep slopes, loose debris and heavy rainfall in the catchment area of the fan. However, as pointed out by Koster and Rust (1984), wet fans also produce debris flows, through short term fluctuations in precipitation (Curry, 1966; Broscoe and Thompson, 1969; Winder, 1965).

Alluvial fans can be divided into proximal and distal depositional facies (Nilsen, 1982). Proximal facies are deposited in the upper or inner parts of the fan and contain the coarser grained sediment. Conversely, distal facies are deposited on the lower or outer parts of the fan and contain the fine grained sediments (Nilsen, 1982). According to Nilsen, stream flow deposits are generally characteristic of distal fan sequences and debris flows are characteristic of proximal fan facies. In addition to deposits produced from debris flow and stream flow, other deposits have been described on modern alluvial fans. These are: mudflows, which consist wholly of fine grained material (Bull, 1963); sieve deposits which consist of permeable lobes of gravel (Hooke, 1968) and sheetflood deposits which can be considered spatially intergradational with stream channel deposits (Koster and Rust, 1984), except that the sheetflood deposits, as defined by Hogg (1982), form from an unconfined flood of water. Sheetfloods occur in the mid fan area below the intersection point (Mack and Rasmussen, 1984), which is the point where the main fan channel intersects the surface of the fan (Hooke, 1967). In addition to these deposits mentioned above and as mentioned in chapters one and four, Bull (1963, 1964 and 1972) notes the occurrence of deposits intermediate between mud flow and stream flow on alluvial fan sequences, which could be interpreted as hyperconcentrated flow deposits.

The aim of this chapter represents the second aim of this entire study, which is, to use the criteria established in chapter four to determine whether hyperconcentrated flow deposits as found in the volcaniclastic environment of Mount Saint Helens, can be recognised within the depositional sequences of other environments. It is not an attempt to produce another set of criteria or modify those established, based on alluvial fan deposits and in addition it is not an attempt to present a detailed analysis of alluvial fan deposition.

As noted in chapter four, differences in processes can be expected between flows in different environments. In particular, hyperconcentrated flows produced in the alluvial fan environment may not be generated through flow dilution and transformation of debris flows, as occurred in relation to the 1984 volcaniclastic flow. However, as stated in section 2.8, the examination of the mechanism by which flows transformation is outwith the scope of this study.

5.2 THE CHOICE OF THE STORNOWAY FORMATION ON LEWIS, SCOTLAND AS A FOCUS FOR INVESTIGATION

Ideally, application of the criteria established in chapter four to depositional sequences in other sedimentary environments would initially involve the examination of recent deposits which would exhibit a relatively complete depositional sequence. In addition, freshly deposited unconsolidated deposits would: 1) facilitate the examination (through excavation) of the sequence in three dimensions, 2) allow the removal of sediment samples for grain size distribution analyses, 3) permit a thorough examination of clast fabric, as conducted in the analysis of the volcaniclastic deposits in chapter two. If hyperconcentrated flow deposits were found in the recent sedimentary environment, the criteria could be applied to a corollary of the sequence preserved in the geological record.

In this study, financial and time constraints have limited the application of the criteria to ancient alluvial fan sequences without the intermediate stage involving the analysis of recent deposits. However, in the light of Bull's (1963, 1964 and 1972) findings which indicate the presence of hyperconcentrated flow deposits on recent alluvial fans, the exclusion of an intermediate step involving the analysis of recent fan deposits in this study is valid.

In choosing an alluvial fan sequence in which to apply the criteria, several conditions had to be satisfied. The sequence had to be extensive, be of good quality (yield well exposed depositional units) and show minimum tectonic disturbance. In addition, the sequence had to show strong evidence of having been produced by alluvial fans. The Stornoway Formation on the Isle of Lewis off the west coast of Scotland, which has a supposed Permo-Triassic age (Steel and Wilson, 1975), satisfied these conditions (figure 5.1). It is extensive, with an apparent thickness of 4000 m and has an outcrop area of at least 150 square km (Steel and Wilson, 1975). It affords excellent well exposed coastal sections that exhibit only minor tectonic deformation with no strata dipping at an angle of more than 45°. In addition it has been established by Steel and Wilson (1975) that the Stornoway Formation represents alluvial fan deposition within the Permo-Triassic North Minch Basin. This basin was fault bounded and the sediment was derived from the elevated basement gneiss areas adjacent to it. Steel and Wilson (1975) divided the Formation into three major units, lower, middle and upper, based on lithology and sediment dispersal direction, which corresponds to the changing palaeogeography as the fault zones at the margins of the basin shifted north west. During periods of fault quiescence, floodplain systems developed in the basin producing fine grained sequences which occur interbedded with the coarser grained alluvial fan sequences. Steel and Wilson's (1975) reconstructed palaeogeography of the North Minch Basin with the changing position of its north western boundary faults through time

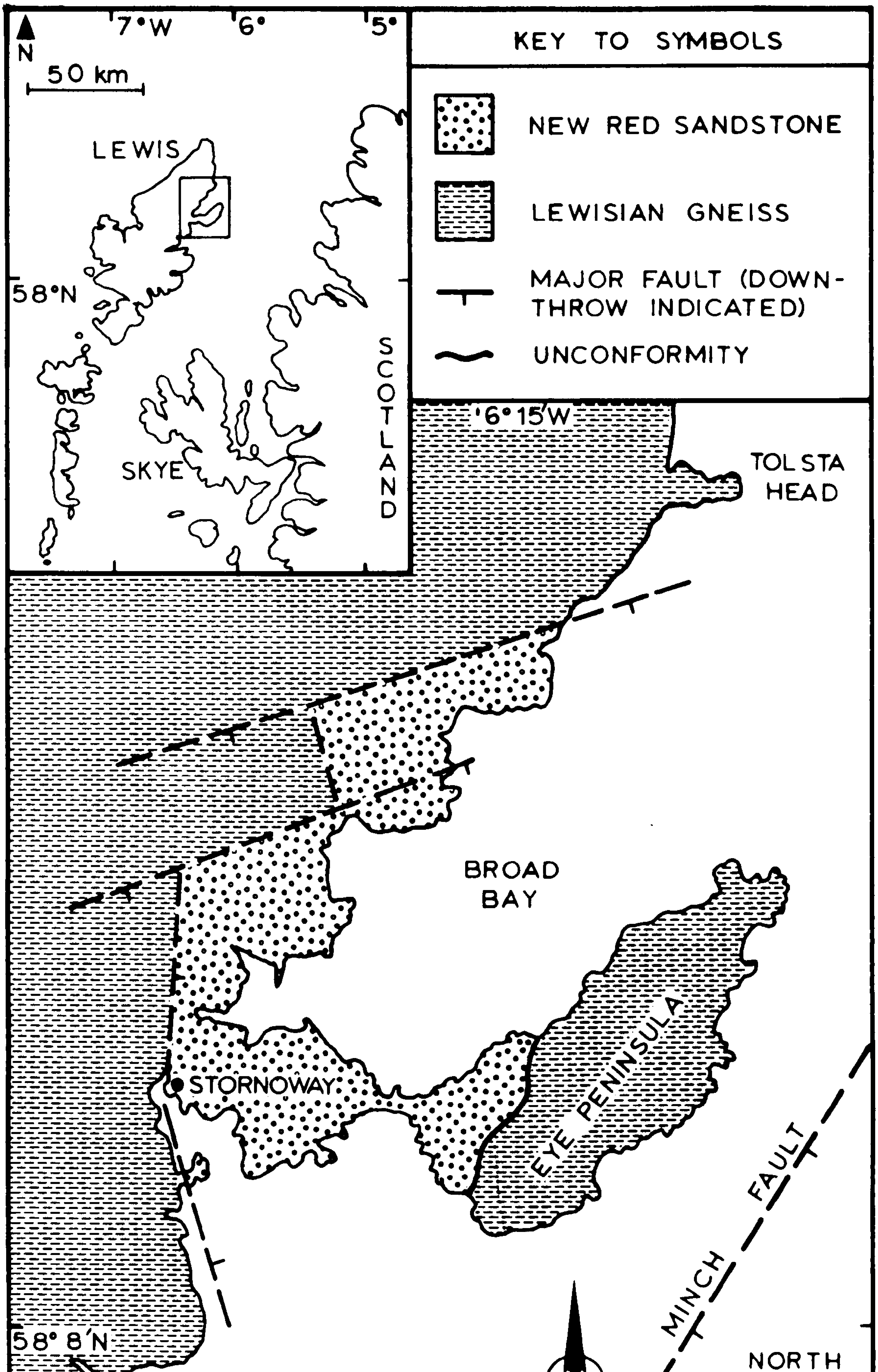


Figure 5.1. Map of the ?Permo-Triassic Stornoway Formation with respect to the north west coast of Scotland (after Steel and Wilson [1975]).

and the positions of the alluvial fans, are illustrated in figure 5.2.

Steel and Wilson (1975) present details of the depositional sequences of the formation and present criteria to distinguish deposits of mud flow, stream flow and braided stream. However, there is no mention of deposits intermediate in character between debris flow and stream flow. This is not surprising when considering that Steel and Wilson's (1975) work is an overall view of sedimentation and tectonism in the basin and so this factor did not affect the decision to apply the criteria in chapter four to this ancient alluvial fan depositional sequence.

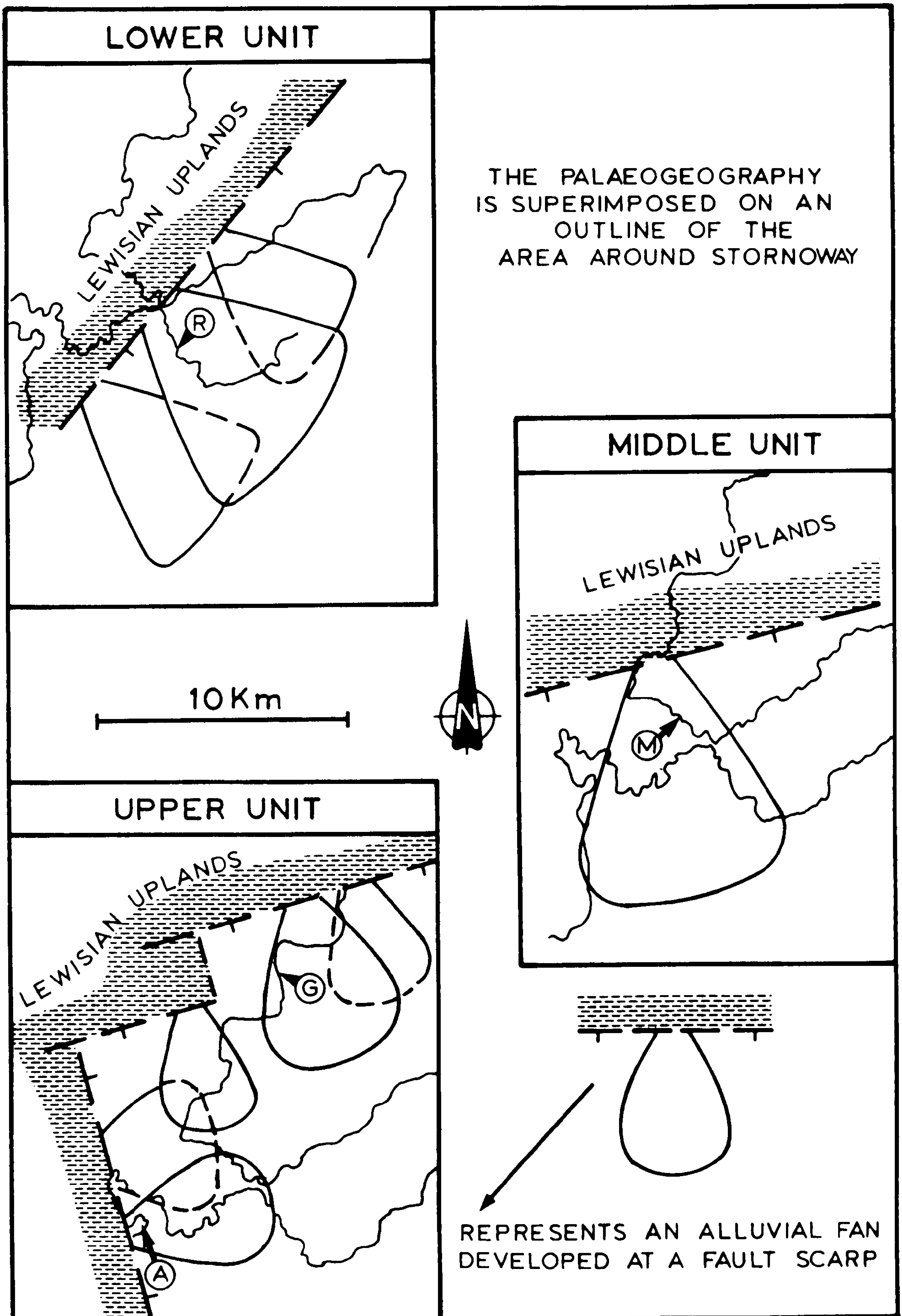


Figure 5.2. Reconstructed palaeogeography of the Stornoway Formation during the deposition of the lower, middle and upper units (after Steel and Wilson [1975]). A, G, M and R represent localities, Arnish Peninsula, Gress Sands, Melbost Point and Ramadale Point respectively.

5.3. METHOD OF INVESTIGATION

5.3.1. The choice of specific field localities

All the accessible coastal exposure of the Stornoway Formation was examined in this study in order to locate the best exposure for detailed sedimentological analysis. Clean, laterally continuous beds with exposed flow parallel and normal sections and exposed upper surfaces were sought. Of primary importance in the initial investigation was the location of depositional sequences that literally had the appearance of the investigated volcaniclastic deposits. This rather objective approach is valid when considering that the aim of this part of the study is to apply the criteria established in chapter four, which in effect is to recognise essentially identical deposits. During the initial examination, the generalised logs of the Stornoway Formation as presented by Steel and Wilson (1975) were found to be correct. However, deposits termed "mudflow" by Steel and Wilson, were in this study found to be coarse grained debris flow deposits, but this is merely a difference in nomenclature.

Despite the amount of exposure, only four localities yielded deposits of sufficient clarity and general visual similarity to the volcaniclastic sequences that merited detailed examination. The sequences at the selected localities were described and analysed as far as the consolidated nature of the deposits allowed.

5.3.2. Techniques

The consolidated nature of the deposits precluded straightforward grain size distribution analysis by sieving as conducted in chapters two and three. In addition, disaggregation of the sediment, which may be conducted in certain circumstances (Folk, 1980), was also precluded due to the presence of fused grain-grain contacts observed in thin sections. An alternative to sieve analysis is point count analysis, which was successfully used in combination with sieve analysis in chapters two and three, to obtain the grain size distribution analysis of particularly coarse grained deposits (section 2.4.1.1). Point count analysis was therefore conducted in this part of the study, not only on the coarse fraction of a deposit but also using thin sections of the finer grained matrix. The point count technique of clasts in the field was similar to that described in section 2.4.1.1, but there were two differences. Firstly, clasts of less than 2 mm were counted as matrix, rather than 6.4 cm as in chapter two, as the small areal extent of thin sections of the matrix would have an unrepresentative component of the granule to cobble size range. The second and more important difference was that as a result of the consolidated nature of the deposits, clasts could not usually be removed for the precise measurement of the b-axis, which is the generally accepted measure of grain size (Lindholm, 1987). Thus, only the apparent long axis of clasts protruding from the deposit was measured.

Samples of the matrix of deposits which had been point counted in the field were sectioned and the grain size distribution was determined petrographically. The apparent long axes of 200 grains were measured along one dimensional transects made across the slides (following the method of Friedman, 1958). The measured values were then grouped into 1 phi classes and the resulting grain size distribution data were combined with that derived from point counts of the coarser material. However, Lindholm (1987) states that point counting using thin sections "is fraught with serious problems" because the method involves the measurement of apparent long axes rather than the intermediate axes.

The inaccurate measurement of clast sizes in the point count analysis in both the field and thin section, questions the validity of such grain size distribution analyses. However, as it was the only method available, it was used in order to gain a measure of the grain size distribution of selected beds only. Ideally, a comprehensive programme of such analyses is desirable, in order that a spectrum of sorting and mean grain size values from deposits in the debris flow/stream flow continuum, as found in chapter two, may be reproduced.

Clast orientation analysis was conducted following the method outlined in chapter two (section 2.4.2.1). This involved the measurement of the compass bearing of clast a-axes and the angle between clast a-axes and bedding (imbrication), on clasts with a:b ratios of 1.5:1 or greater. In addition, the same clast size groupings of cobble, 2 cm to cobble and less than or equal to 2 cm, as used in the volcaniclastic deposits of Mount Saint Helens in chapters two and three, were adopted. These limits were adopted in order that a comparable set of results would be produced. However, in contrast to the volcaniclastic deposits studied, the consolidated nature of the alluvial fan deposits meant that access to levels within a depositional sequence for the measurement of a-axes was limited. Despite the differences in the collection of data compared to chapters two and three, statistical analyses to test for preferred clast orientations were conducted in an identical manner following the procedure in appendix 2.

A feature not observed in the volcaniclastic environment of Mount Saint Helens was tectonic deformation of the sequences. However, in the Stornoway Formation beds dipped up to 45°. Lindholm (1987) (after Potter and Pettijohn, 1963), states that if beds in a sequence dip less than 25°, orientational measurements do not need to be reorientated. However, although two localities in this study had an angle of dip greater than 25°, no attempt was made to reorientate a-axes orientation measurements because the relationship between the a-axis orientation and flow direction was of primary interest rather than the establishment of the direction of source. Thus at each locality, several measurements of palaeoflow from cross beds or imbricated large discoid clasts were obtained and statistically analysed to determine the palaeoflow direction without being reorientated to account for dip.

5.4 THE SEDIMENTOLOGY OF SELECTED DEPOSITIONAL SEQUENCES

5.4.1. Introduction

The sequences examined are dominated by cobble and pebble conglomerates with subordinate pebbly sandstones. The clast population of the sequences was derived from the Lewisian Gneiss highlands that bordered the basin (Steel and Wilson, 1975) and thus consists of quartzo-feldspathic, hornblendic and pegmatitic gneiss. In addition, the sequences all have a red colouration which is an indicative feature of deposition in arid conditions (Nilsen 1982).

The precise location of each sequence, together with details of the strike and dip of the beds examined is presented in figure 5.3. Each sequence was logged as conducted in the volcaniclastic environment, but although some depositional units were laterally continuous (for up to fifty metres), no lateral logging of the units was conducted, as the units did not show sedimentological variation within the length of their exposure. The descriptions of sequences herein do not present complete accounts of the water-laid deposits which are generally composed of either clast-supported pebble and cobble beds with an a(t) b(i) fabric, or cross bedded/horizontally bedded pebbly sandstones, because as stressed in section 5.1, this part of the study is not a detailed analysis of alluvial fan deposition. The descriptions instead, concentrate on deposits that have the

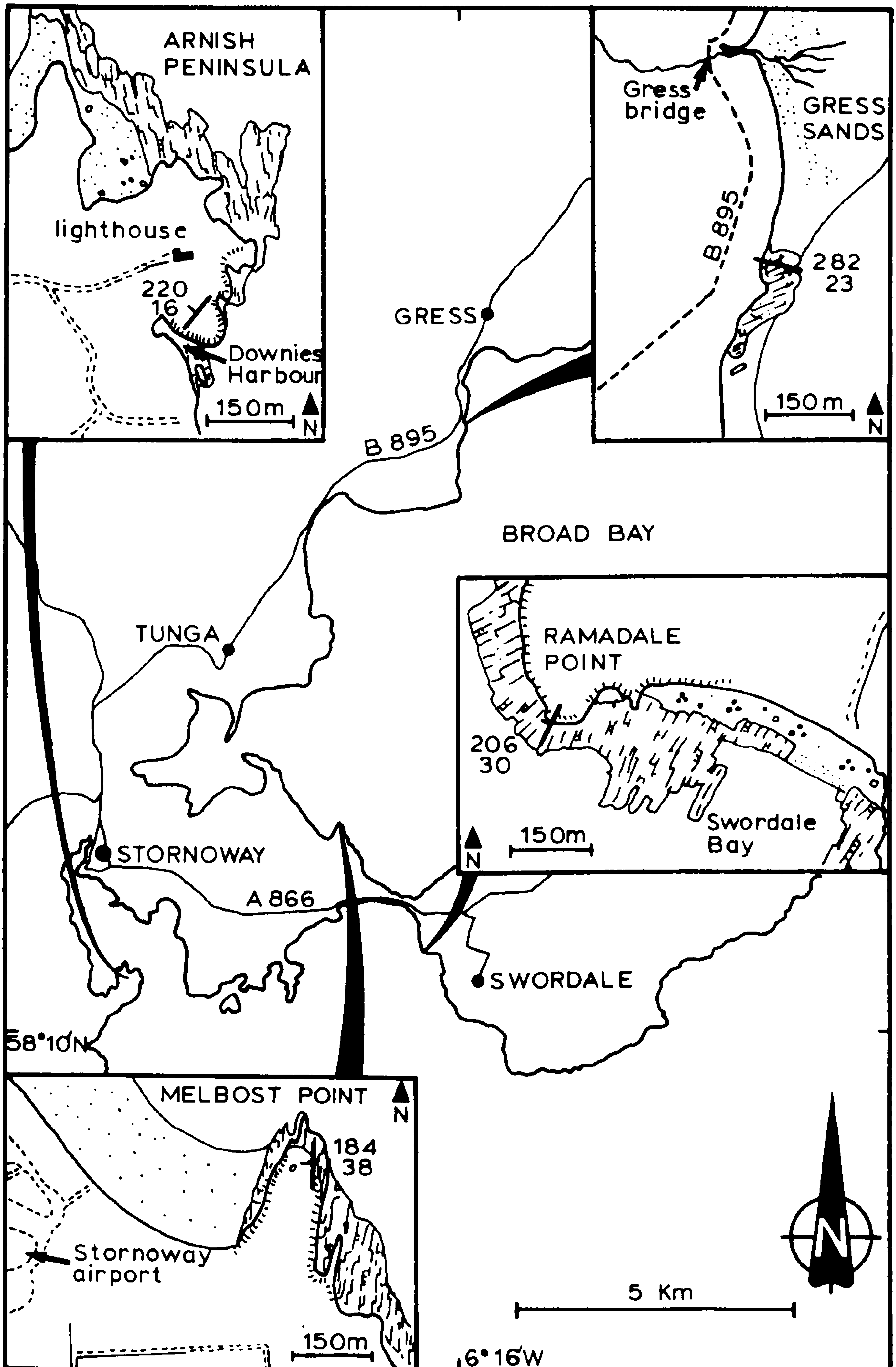


Figure 5.3. Map showing the precise locations of the depositional sequences of the Stornoway Formation investigated in this study. O.S. maps used.

attributes of mass flow deposition. In effect, the selection of depositional units for detailed analysis is based on the criteria presented in chapter four, which indicate that hyperconcentrated flow deposits do not have any stratific-ation (except where defined by sub units) or exhibit an a-axis transverse to flow clast fabric (except when clast orientation is bimodal).

Unlike the modern volcaniclastic environment, where the 1984 mass flow deposits were superimposed upon the Toutle River system, no well defined channels or channel/channel margin topography was discernible within any of the sequences examined. Thus it is extremely difficult, or impossible, to ascertain the position of the examined mass flow deposits in relation to channel systems or the intersection point of the fan. The question arises whether the deposits were produced within a channel system or were spread out on the fan surface.

In this chapter as in chapter three, the descriptions and corresponding data on clast fabric and grain size distribution are discussed together. In addition, it has been possible with some beds to make estimates of palaeoflow velocity and yield strength of the flow that produced them. Using the combined information and by applying the criteria established in chapter four, the deposits in the following sections are assigned to positions within the debris flow/stream flow deposit continuum.

5.4.2. Arnish Peninsula

Arnish Peninsula (figure 5.3) occurs at the boundary between the Permo-Triassic and the Lewisian Gneiss and illustrates a sequence within the lower unit of the Stornoway Formation as defined by Steel and Wilson (1975). The alluvial fan that produced the sequence may have had a radius smaller than 5 to 10 km, according to Steel and Wilson (figure 5.2). The locality yielded one section (at Downies Harbour) that contained mass flow deposits that were sufficiently exposed for thorough examination (figure 5.3). The entire sequence is illustrated in plate 5.1 and the descriptive log of the most relevant segment is presented in figure 5.4.

Figure 5.4 illustrates three mass flow deposits interbedded with stream flow deposits. The latter are largely cobble or boulder clast-supported conglomerates, in which clasts show an a(t) b(i) fabric and weak, locally developed stratification which is defined by a vertical variation in grain size distribution (plates 5.2A and B). The clast fabric exhibited by these deposits is indicative of a grain-by-grain mode of deposition, with clasts rolling on a bed as found by Rust (1972), in braided fluvial deposits and in glacier associated outwash fan deposits by Houmark-Nielson (1983). The measurement of strike and dip values from large well imbricated clasts within these stream flow deposits has allowed the determination of palaeoflow direction. This indicated flow toward the E.S.E. (appendix 6), which is

PLATE 5.1 [OVER]

PLATE 5.1

A view, looking toward the north east, of the depositional sequence at Downies Harbour on the Arnish Peninsula. The actual vertical section logged is marked and the 30 cm scale bar is circled. Note the lateral continuity of the depositional units and the quality of the exposure.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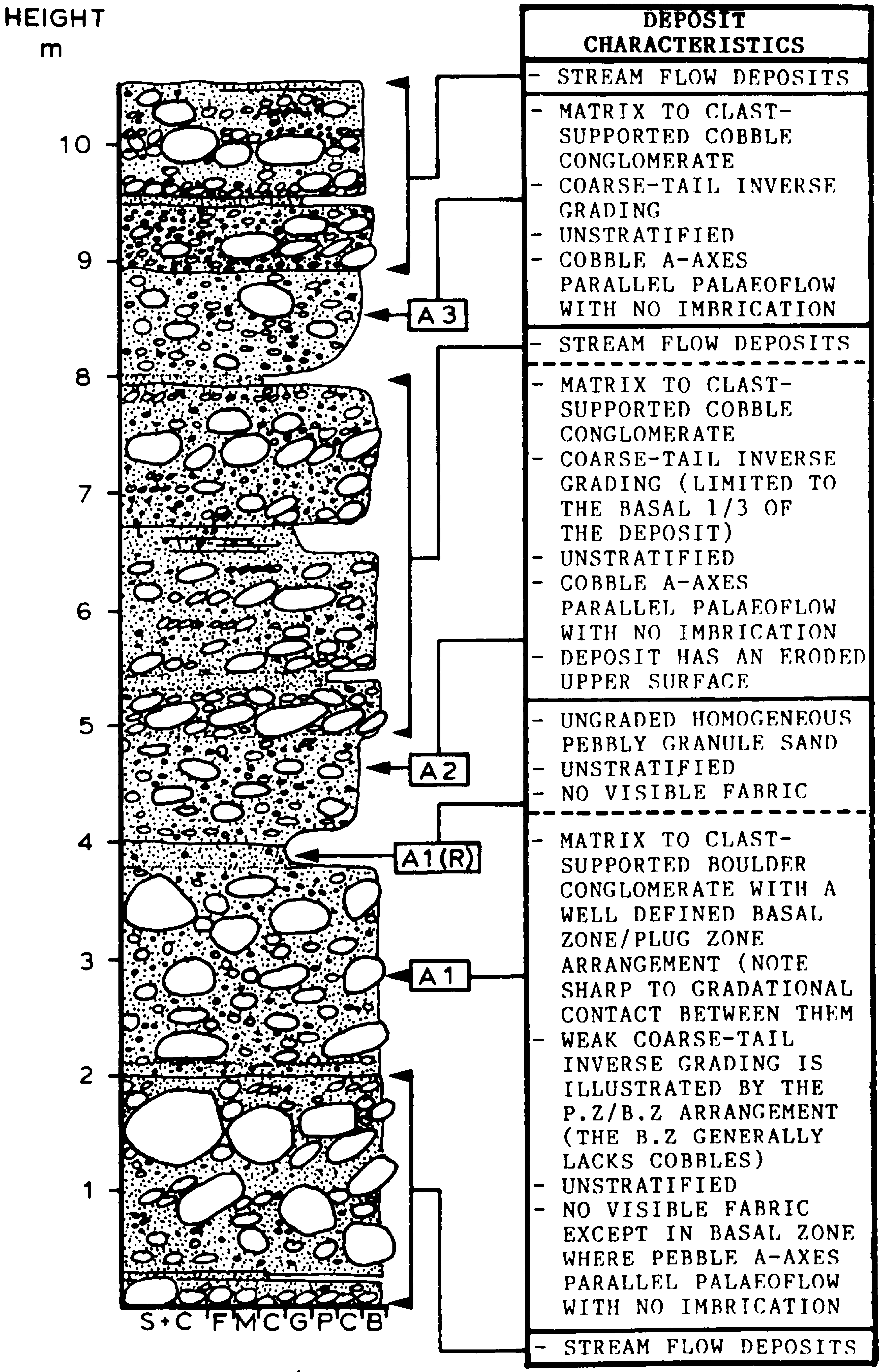

Figure 5.4. Representative descriptive log of the depositional sequence at Downies Harbour, Arnish Peninsula.

PLATE 5.2 [OVER]

PLATE 5.2

A

Stream flow deposits within the logged sequence at Downies Harbour on the Arnish Peninsula. Note their generally stratified and clast supported nature, in addition to the well developed a(i) b(t) fabric. Flow was from left to right.

The white material (arrowed) is sparry çalcite filling the voids in an open framework gravel.

B

The top surface of the sequence illustrated in A above. Note the large discoid clasts, these were used in the investigation of palaeoflow direction. Flow was toward the top of the plate.

similar to that determined by Steel and Wilson (1975).

The mass flow deposits illustrated on figure 5.4 (A1, A2 and A3) are all coarse grained, polymodal, matrix to clast-supported, unstratified units, that exhibit coarse-tail inverse grading. In addition, grain size distribution analyses indicate that these units are very poorly sorted (figure 5.5, appendix 7). The three units thus have very similar characteristics to the volcaniclastic deposits in chapter two, which were attributed to debris flow. In addition they have the characteristics of other deposits in alluvial fan sequences elsewhere (for example, Heward, 1978; Larsen and Steel, 1978) which were also attributed to debris flow. In more detail: unit A1 (plate 5.3A and B) has a well defined plug zone/basal zone arrangement (in similarity with deposits described elsewhere by Johnson [1970] and as illustrated in figure 2.12), with a gradational to sharp contact between them. In contrast to A1, units A2 (plates 5.3A and 5.4A) and A3 (plate 5.4B) exhibit a more diffuse plug zone/basal zone arrangement, with the basal zone in A2 being more pronounced than in A3. The clast fabric developed within the three units illustrates the parallel alignment of a-axes with palaeoflow direction and no imbrication (figure 5.6 and appendix 8). However, the plug zone in A1 shows no preferred clast orientation, with only the basal zone having clast a-axes orientated parallel to flow. In addition, clasts smaller than or equal to two centimetres in size measured in the basal zone and clasts between 2 centimetres

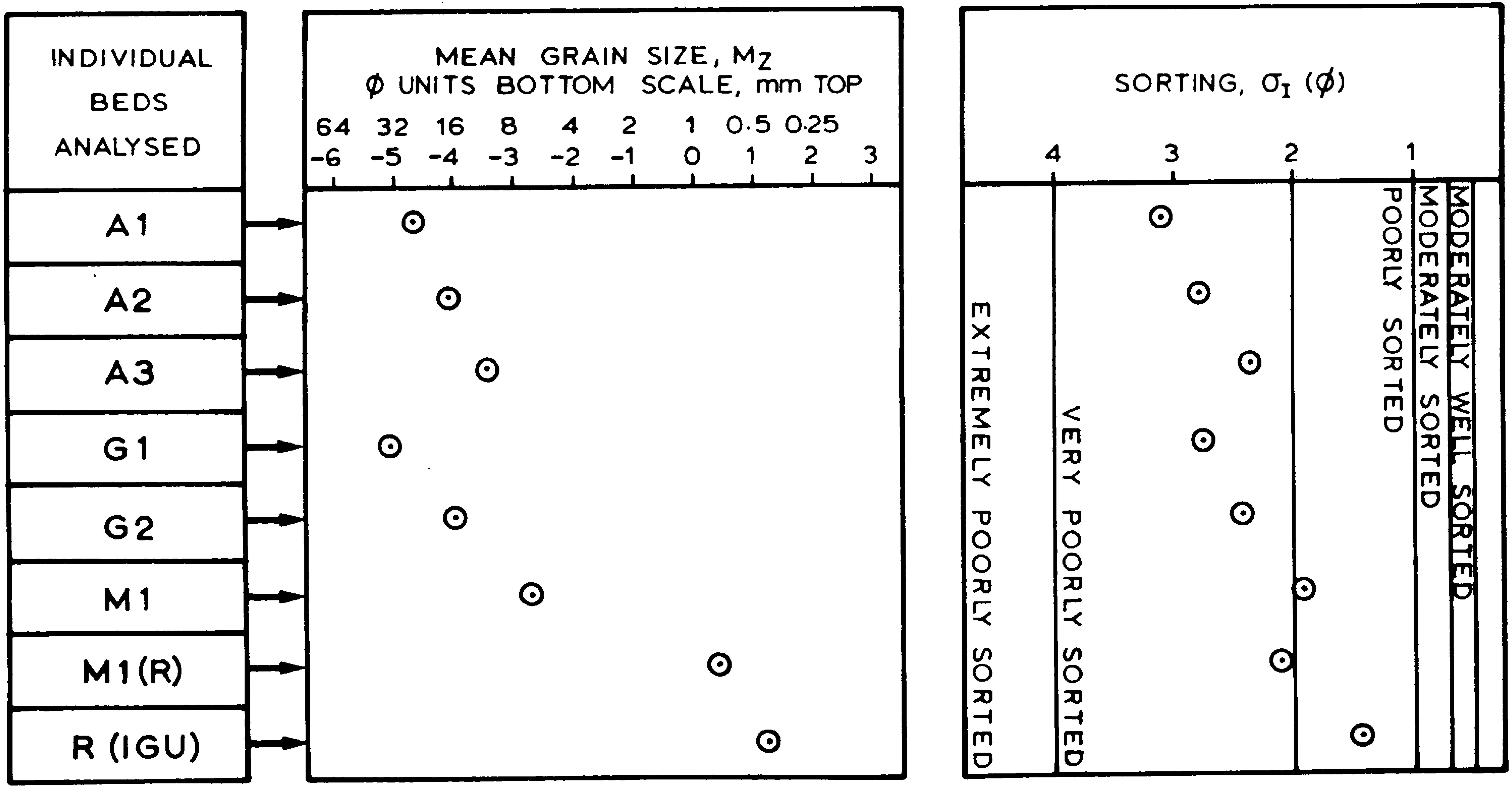

Figure 5.5. Tables showing the range of mean grain size and sorting values of individual depositional units analysed in detail.

PLATE 5.3 [OVER]

PLATE 5.3

A

A view of the bottom two thirds of the depositional sequence described in figure 5.4 (marked on plate 5.1). A1 and A2 refer to the units A1 and A2 respectively. Flow was from left to right.

B

The basal portion of unit A1 (rests with a sharp contact upon fine grained sediment), note the absence of cobble sized clasts in the first ten to fifteen centimetres from the base and the orientated pebbles. The pebbles show a planar fabric with a-axes parallel to flow direction which was from left to right.


A2
A1

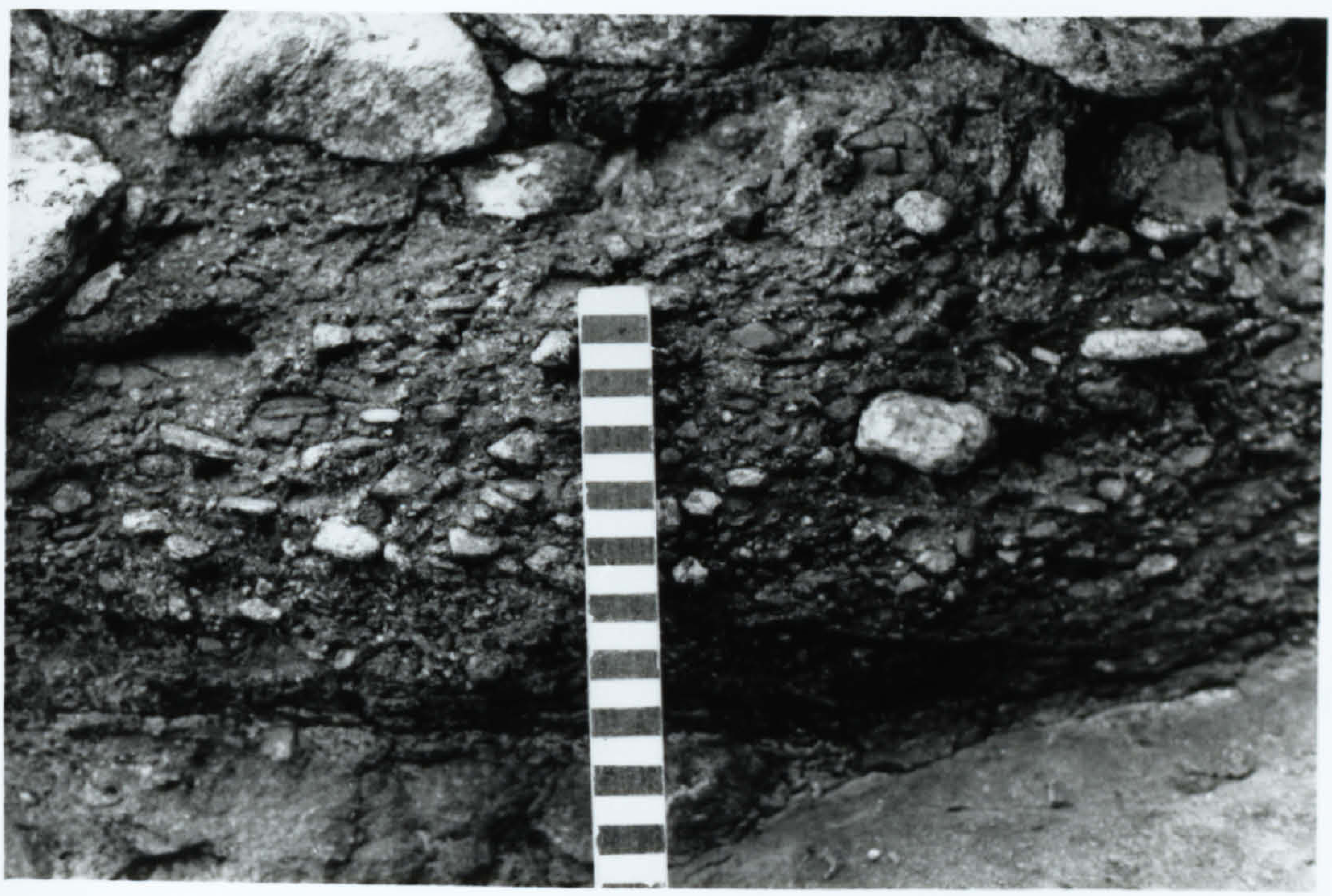

PLATE 5.4 [OVER]

PLATE 5.4

A

A view of unit A2 which shows the basal inverse grading and clasts with a-axes orientated parallel to flow direction (left to right), with no imbrication. The unit is cut by stream flow deposits, which in contrast to unit A2, have a well defined imbricated clast fabric. The contact between the two units is marked.

B

A view of unit A3, the upper and lower contacts are indicated by arrows. Note the inverse grading and the planar clast fabric. The stream flow deposits below A3 show horizontal, stratification and a well developed a(t) b(i) clast fabric.

Figure 5.6. Rose diagrams representing clast a-axis orientation analyses conducted on mass flow deposits at Downies Harbour on the Arnish Peninsula.

and cobble size in the plug zone of A2, showed no preferred orientation. The results of investigations of clast fabric on these three units endorse the view above, that they are similar to those of the 1984 main flow as described in chapter two and therefore can be attributed to debris flow. In particular, unit A1 is directly analogous to the 1984 main flow deposits described at locality 0.0, with units A2 and A3 being analogous to the deposits described in the vicinity of locality 3.7.

It should be noted that the preferred a-axis orientations derived through fabric analyses of A1, A2 and A3 indicate a palaeoflow direction that differs slightly from the one derived through the examination of imbricated clasts. This could indicate that the debris flows were emplaced on the fan from a direction that was slightly oblique to that of the stream flow deposits.

The flows that produced A1, A2 and A3 can be regarded in terms of Johnson's (1970) Coulomb-viscous model in which a rigid non deforming plug moves over a basal zone of shear, as described for the deposits in the debris flow end of the deposit continuum described in chapter two. By using a simplification of this model, that is the Bingham model, the yield strength of the original debris flows can be calculated, as performed in chapter two. As described in section 2.5.2.1 there are three methods established by Johnson (1970) to estimate yield strength. Two of these cannot be applied to A1 and A3 because information regarding either the unconfined thickness of the debris flow, or the channel dimensions plugged by the debris, are not available from the exposure. In addition, since A2 has an eroded top surface it cannot be used in any calculation. Hence, as in chapter two, yield strength estimates are calculated using equation 1 (section 2.5.2.1) based on the largest clasts supported within the debris. Clast density values were determined using the method outlined in section 2.5.2.1. However, due to the consolidated nature of the deposits, the density values of the debris matrix could not be determined through reconstitution and hence a major assumption had to made. Since A1 and A3 have been compared to the 1984 main flow deposits at locality 0.0 and in the vicinity of locality 3.7 respectively, the values of flow density from these localities have been applied to these deposits. The data used in the calculation of the yield strength estimates are given in appendix 9. By using this method the average estimates of yield strength are 1.13×10^4 dyne/cm^2 for A1 and 8.91×10^3 dyne/cm^2 for A3. These values are similar to those obtained for the 1984 flow downstream to and including locality 4.5 (compare appendix 9 with appendix 4).

In order to obtain an indication of the velocity of the debris flows represented by A1 and A2, an empirical equation used in flume experiments on debris flows by Tsubaki et al., in Takahashi (1981), has been used. It has the form,

$$vf = 2.5 \, (g \, y \sin S)^{0.5} \qquad \text{------ equation 3.}$$

where vf is the velocity at the front of the flow, g is acceleration due to gravity, y is the depth of the flow and S is the slope of the surface under the flow. Following Postma (1986), the depth of the flow (y) is estimated to be approximately equal to the thickness of the deposit. Another estimate used in equation 4 is the slope. Since it is not known, the average value of the slope of alluvial fans in general was used. This is equal to 5° (after Nilsen, 1982). The values obtained are around 3.18 m/s for A1 and 2.35 m/s for A3 and the data used for their calculation are in appendix 9. The validity of these velocity estimates is very much open to debate because of the two major assumptions that have been made. The slope of the fan may have been much greater and therefore the velocities of the debris flows may have been larger than the estimates above. However, the estimates do indicate that the debris flows were moving in the order of a few metres per second and the values are similar to observed flows (Sharpe and Nobles, 1953; Curry, 1966; Morton and Campbell, 1974).

The flows that produced A1, A3 and by implication A2 through its sedimentological similarity with A1 and A3, can thus be regarded as debris flows that had considerable yield strength and were moving in the order of a few metres per second. Following the discussion in chapter two section 2.6, cohesive matrix strength, buoyancy and dispersive pressure were operating within these debris flows as particle support mechanisms. However, there was a difference in the relative importance of these mechanisms when the sedimentological differences between the units are considered. The lack of inverse grading throughout A1, compared to A2 and A3, indicates that in the latter two flows clasts were more able to move with respect to one another than clasts in A1. This suggests that dispersive pressure was not as important in A1 as it was in A2 and A3. The variation in clast mobility between the different flows is also indicated by the fabric analyses which show that only unit A1 has no preferred a-axis orientation in the plug zone. The variation in clast mobility may, as it does in the 1984 main flow, reflect variation in sediment concentration between flows, whereby the debris flow that produced A1 would be more highly concentrated than either A2 or A3.

An accurate estimate of the amount of silt and clay present in the deposit producing flows, based on the examination of thin sections of the samples of matrix used in the point count analysis, was precluded due to the presence of iron stained calcareous cement in the sections. In each of the three units the estimated percentage of silt and clay was less than five percent. This estimate indicates that these units are very similar sedimentologically, to the volcaniclastic deposits analysed in chapter two. Thus, the degree of cohesivity between these flows and the 1984 volcaniclastic flow may have been directly comparable, although the clay type in this fan environment is not known.

Despite the concerns expressed in chapter four over the applicability of the results from the volcaniclastic environment to alluvial fan sequences, the striking similarities between the deposits of the two environments indicate that very similar processes were operable. However, in this fan environment a particular mass flow produced from the interaction of water on loosely consolidated material may not undergo flow transformation as demonstrated by the 1984 flow at Mount Saint Helens. The 1984 flow inundated the North Fork Toutle River which was filled with flood water and this contributed in the flow transformation (see section 2.8). In contrast, the fan on which A1, A2 and A3 were emplaced formed under arid conditions (Steel and Wilson, 1975) and could thus be regarded as a "dry" fan (after Schumm, 1977). In such an arid environment, water could be lost from a flow into the pre flow deposits (as found by Hooke, 1967), rather than being incorporated into the flow. As mentioned in section 2.8 and 5.1, this study is not an attempt to understand the flow transformation mechanism and so this phenomenon and how it varies between environments is not dealt with further. However, it can be stated that the flows that produced A1, A2 and A3 were produced from debris flows, with A1 being deposited from the most highly concentrated flow, but how the variation in concentration was produced is speculative.

This sequence at Arnish Peninsula has demonstrated the presence of debris flow deposits on this ancient alluvial fan sequence, but no deposits fitted the criteria which would indicate deposition from hyperconcentrated flow. The only possible candidate is unit A1(R), which is a homogeneous, pebbly granule sand with no visually apparent clast fabric, that caps unit A1 (figure 5.4). Based on its intimate association with the underlying mass flow, it most likely represents the recessional flow phase of the debris flow that produced A1. A lack of exposure precluded clast fabric analysis and therefore only a few criteria that would indicate hyperconcentrated flow deposition are fulfilled. However, it is reasonable to suggest based on the limited sedimentological information available, that unit A1(R) may represent hyperconcentrated flow deposition.

The importance of this depositional sequence is the fact that mass flow deposits occur which can be inferred to represent deposition from flows having differing sediment concentrations and thus other elements of the debris flow/stream flow deposit continuum could be expected to occur elsewhere in the Stornoway Formation.

5.4.3. Gress Sands

This locality occurs on the north west side of Broad Bay (figure 5.3) and according to Steel and Wilson (1975) represents a sequence within the upper unit of the Stornoway Formation, the palaeogeography of which is illustrated in figure 5.2. Although the deposits represent predominantly stream flow deposition, the locality yielded well preserved and exposed mass flow deposits which are illustrated in figure 5.7. The palaeoflow direction derived from the measurement of cross bedding (appendix 6), was toward the E.N.E., which is in contrast to the southerly direction obtained by Steel and Wilson (1975).

The lower mass flow unit, G1 (figure 5.7, plate 5.5A), is a generally homogeneous polymodal boulder conglomerate, with local poorly developed coarse-tail inverse grading, no clast fabric (figure 5.8) and very poor sorting (figure 5.5). By applying the criteria proposed in chapter four, it can be stated that this unit represents deposition from a debris flow. In addition, following the discussion in chapter two, it can be stated that the flow was highly concentrated because of the lack of clast mobility which is indicated by chaotic clast fabric and poorly developed inverse grading.

Unit G2 has sedimentological characteristics which are in contrast to those of unit G1. Although very poorly sorted (figure 5.5), G2 has well developed coarse-tail inverse grading, which illustrates an obvious plug zone/basal zone arrangement (plate 5.5A and B). Unit G2 also has a well developed clast fabric in which the a-axes of cobble sized clasts in the plug zone and pebble sized clasts in the basal zone, are preferentially orientated parallel to the direction of palaeoflow (figure 5.8) with no imbrication (appendix 8). However, clasts between 2 cm and cobble in size within the plug zone show no such preferred orientation. The palaeoflow direction indicated by the orientated clasts in G2, is slightly oblique to the palaeoflow direction derived from

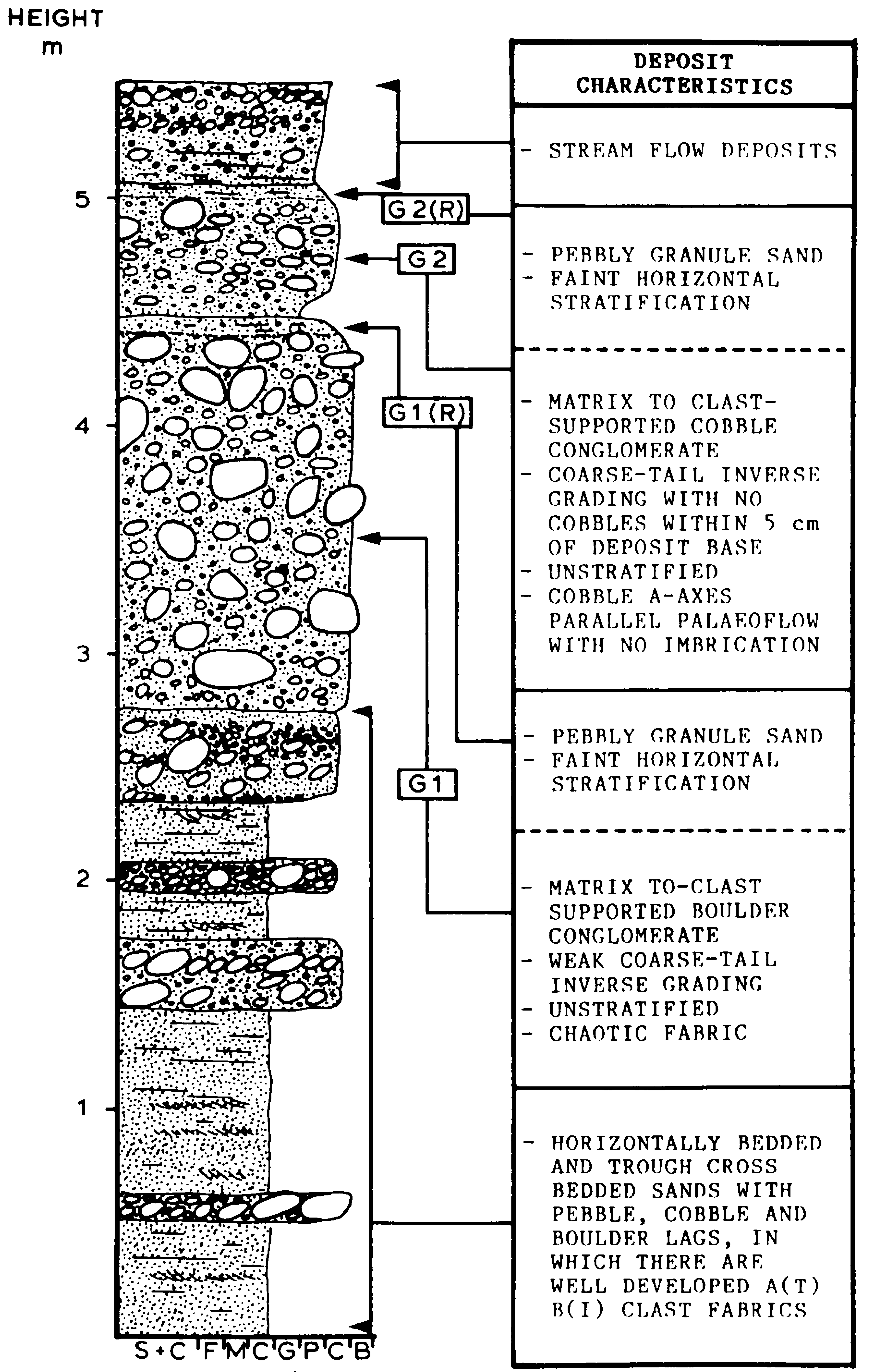

Figure 5.7. Representative descriptive log of the depositional sequence at Gress Sands.

PLATE 5.5 [OVER]

PLATE 5.5

A

A view of units G1 (lowermost) and G2 (above G1). Both units are inversely graded, however it is best developed in unit G2. The clast fabric in unit G1 is chaotic with occasional vertical clasts (arrowed).

B

A close-up view of unit G2, showing the well developed inverse grading and clast fabric in which a-axes of clasts are orientated parallel to flow with no imbrication (flow was from left to right). The sediment between the arrows which is gradational with the matrix phase of unit G2, represents the recessional flow phase of the flow that produced G2.

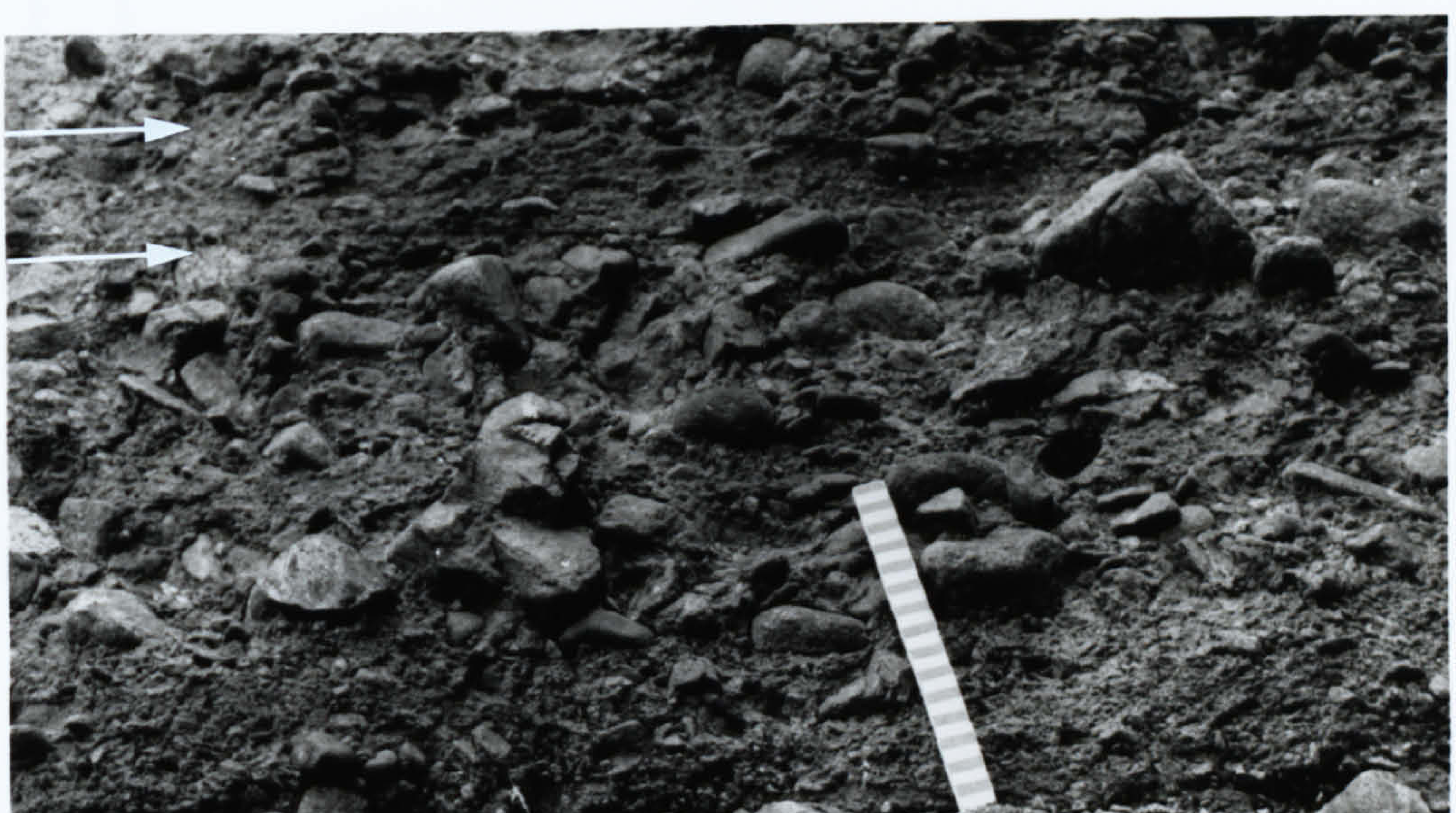

Figure 5.8. Rose diagrams representing clast a-axis orientation analyses conducted on mass flow deposits at Gress Sands.

cross bedding in the fluvial deposits. As at Arnish, this disparity in palaeoflow directions could indicate that the G2 flow was emplaced on the fan from a direction slightly oblique to that of the stream flow deposits. By application of the criteria in chapter four, unit G2 can be regarded as the result of debris flow deposition. However, in contrast to unit G1, the flow that produced G2 was less highly concentrated and clasts were able to move with respect to one another. This mobility is manifested in the formation of clast fabric and inverse grading.

Using techniques identical to those discussed in section 5.4.2, the yield strength of the flow that produced G2 was estimated as 5.14×10^3 dyne/cm^2 and the velocity was approximately 1.8 m/s (the data used in the calculation of these estimates is given in appendix 9). The assumption in the derivation of the yield strength estimate was that the density of the debris matrix was equal to that of the 1984 main flow in the vicinity of locality 3.7, where deposits with similar characteristics to those of G2 occur. The yield strength estimate is comparable to the 1984 main flow at localities 5.2 and 7.3 (appendix 4), but less than that of units A1 and A2 at the Arnish locality, which could indicate that the G2 flow, following the discussion in section 2.6, was less highly concentrated than those which produced units A1 and A2. Estimates of the combined silt and clay content of the flows from thin sections of the matrix were in the order of a few percent for both G1 and G2, the absolute values being indeterminate petrologically due to ubiquitous iron stained calcareous cement in thin section. These estimates are directly comparable to those obtained from the 1984 volcaniclastic flow deposits and the deposits at Arnish Peninsula (section 5.4.2), which may suggest similar flow cohesivity.

Units G1(R) and G2(R) which grade imperceptibly with units G1 and G2 respectively, represent the deposits of recessional flows that followed after the main mass flows. Neither unit is sufficiently well exposed to permit detailed sedimentological analysis, but both units have horizontal stratification which is not characteristic of hyperconcentrated flow deposition, thus indicating a stream flow origin.

5.4.4. Melbost Point

According to Steel and Wilson (1975) this locality (figure 5.3) represents mudflow deposition within the middle unit of the Stornoway Formation, the reconstructed palaeogeography of which is illustrated in figure 5.2. The palaeoflow direction derived from cross bedding was toward the W.S.W (appendix 6), which is comparable to that found by Steel and Wilson. In this study only one thin sequence was sufficiently exposed for thorough sedimentological examination, but this yielded a mass flow deposit with characteristics that were significantly different from those of the debris flow deposits examined at the other localities (sections 5.4.2 and 5.4.3).

The unit M1 (figure 5.9, plate 5.6A) is poorly sorted (figure 5.5), matrix-supported and has weak coarse-tail inverse grading. In addition, it has a well developed clast fabric with cobble a-axes preferentially orientated transverse to flow (figure 5.9) with no imbrication (appendix 8). Further analysis of fabric demonstrated bimodality as a function of grain size, whereby the a-axes of clasts less than or equal to 2 cm were preferentially orientated parallel to palaeoflow; that is normal to the cobble orientation. Clasts between cobble and 2 cm in size showed no preferred orientation.

By comparing the sedimentological characteristics of M1 with the criteria established in chapter four, it can be stated that the flow which produced M1 could be regarded as hyperconcentrated. Although it has not been possible to make an estimate of yield strength, the very striking similarity between the sedimentological characteristics of this unit and those of the 1984 flow in the vicinity of locality 8.5, very strongly suggests near identical modes of sediment transport and deposition, as described in detail in section 2.6.4. Thus, sediment within the flow that produced unit M1 was probably not deposited en masse as in flows with a discernible plug zone/basal zone arrangement. Instead, as the flow slowed, a surface separating stationary from moving particles probably rose rapidly through the flow in a manner described by Carter (1975a). This mechanism as indicated in section 2.6.4, would explain the phenomenon of clast a-axis

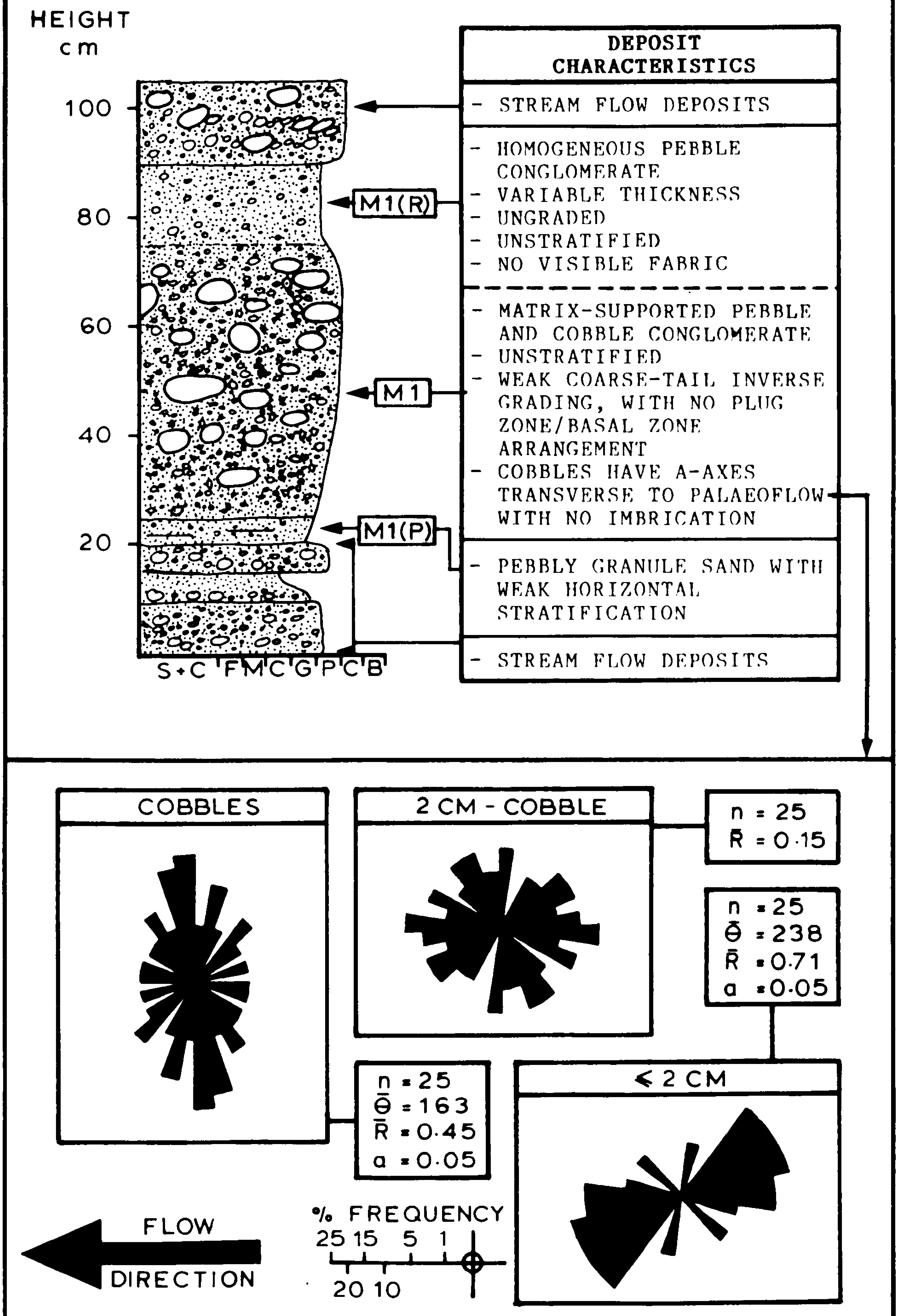

Figure 5.9. Representative descriptive log of the depositional sequence at Melbost Point, together with clast a-axis orientation analyses for unit M1.

PLATE 5.6 [OVER]

PLATE 5.6.

A

A view of unit M1, note the weak inverse grading and the lack of stratification or imbricated clasts. The weakly stratified unit at the base of M1 (arrowed A) was produced by the M1 precessional flow (M1[P]). The homogeneous and irregular unit above M1 (arrowed B), represents deposition from a recessional flow of M1 (M1[R]).

B

The arrowed lines indicate two inversely graded units occurring within reworked debris flow deposits, U represents the upper of the two units, L represents the lowermost unit. Note the lateral persistence of the inverse grading within these units. Flow was from left to right.


B
A


U
L

orientation bimodality as a function of grain size.

Unit M1(P) probably represents deposition from a flow that immediately preceded the M1 flow. The unit M1(R) which is very poorly sorted (figure 5.5), shows variable thickness, has no visually apparent clast fabric and has a sharp to gradational contact with M1, very likely represents a recessional flow that followed in the wake of the M1 flow. Although clast fabric analysis was precluded due to difficulties with exposure, unit M1(R) based on the sedimentological characteristics available, may be regarded as the result of hyperconcentrated flow deposition.

5.4.5. Ramadale Point

According to Steel and Wilson (1975), this locality (figure 5.3) represents mudflow deposits within the lower unit of the Stornoway Formation, the reconstructed palaeogeography of which is illustrated in figure 5.2. The palaeoflow direction derived from imbricated clasts is toward the south west (appendix 6) and is comparable to that found by Steel and Wilson.

The sequence at this locality is dominated by debris flow deposits which have been extensively reworked by stream flow. Thus, laterally extensive individual mass flow deposits with a well defined base and top are extremely rare. However, within this sequence on a relatively flat palaeosurface, there is a thin fine grained unit which represents a complete departure in depositional style from any other deposit observed in this study of the Stornoway Formation, (figure 5.10, plate 5.6B). The unit consists of sub units, two of which are laterally extensive and can be traced for 6.5 m in a down flow direction. These two sub units are coarse-tail inverse graded, but the inverse grading is locally discontinuous. Detailed analysis of the lower inversely graded sub unit (R[IGU]) revealed that it was poorly sorted (figure 5.5) and that the a-axes of pebble sized clasts were orientated parallel to flow direction (figure 5.10), with no imbrication (appendix 8). Sedimentologically, these inversely graded sub units are nearly identical to those described in chapter two which represent traction carpets formed at the base of the 1984 flow when it was hyperconcentrated in the vicinity of locality 9.2. The only apparent difference is that the sub units in this fan environment are locally not gradational with each other. This would indicate that there were breaks in sedimentation of the unit as a whole, which did not occur in the volcaniclastic environment (see discussion in section 2.6.5). However, the locally sharp contact between the sub units could be a function of compaction, diagenesis and subsequent weathering of the depositional sequence.

The origin of the stacked inversely graded sub units investigated in chapters two and three was explained based on the findings of Lowe (1982) and Hiscott and Middleton (1979), who found analogous units in turbidites. However, thin

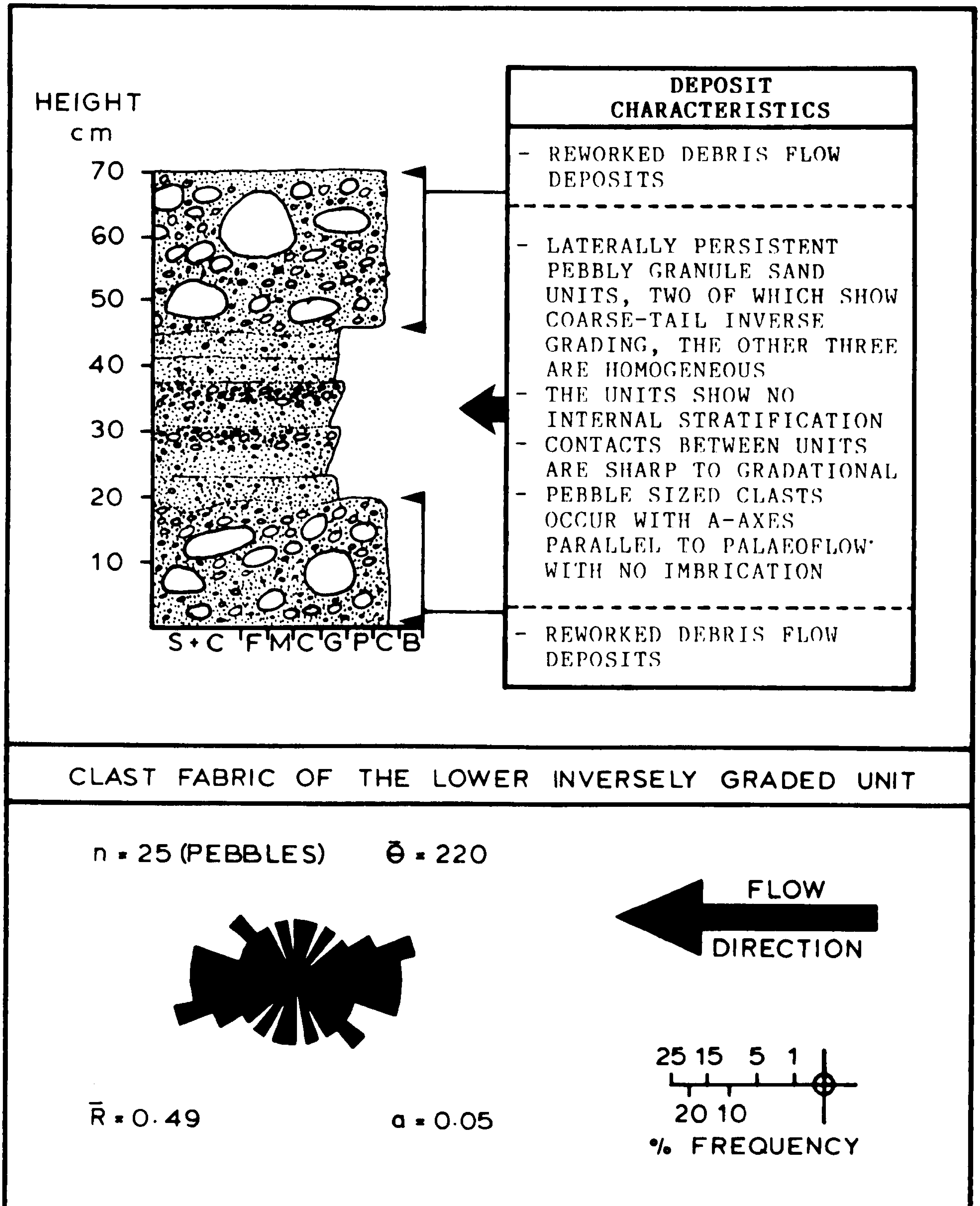

Figure 5.10. Representative descriptive log of the depositional sequence at Ramadale Point, with the clast a-axis orientation analysis for the lower inverse graded sub unit.

inversely graded units have been found elsewhere in depositional sequences attributable to alluvial fans (Nemec *et al*., 1984). Nemec *et al*. (1984) suggest that thin inversely graded units within "Facies C" in the Domba Conglomerate in Norway, represent deposition as traction carpets at the base of sand rich flows. As in this study, Nemec *et al*. (1984) have based their interpretation on the work of Hiscott and Middleton (1979).

Following the discussion in section 2.6, it can be stated that the hyperconcentrated flow that produced the inversely graded sub units at Ramadale Point was less concentrated than the hyperconcentrated flow which produced unit M1 (section 5.4.4) and that the former flow was at the rheological boundary between hyperconcentrated flow and stream flow.

5.4.6. A note on the preservation of the Stornoway Formation alluvial fan hyperconcentrated flow deposits

Smith (1986) indicates that hyperconcentrated flow deposits on alluvial fans would cover less of an area and would be less readily preserved than in the volcaniclastic environment. The results of this investigation tend to endorse Smith's view, as recognisable hyperconcentrated flow deposits in the Stornoway Formation are extremely rare. However, from the depositional record it is very difficult to determine whether their rarity suggests that hyperconcentrated flows are a rare phenomenon in the fan environment, or whether it is a function of preservation of the deposits. Although the presence of reworked mass flow deposits, for example at Ramadale Point (section 5.4.5), does suggest that hyperconcentrated flow deposits would have been subjected to reworking.

5.5. SUMMARY

It was suggested in chapter four, following the establishment of criteria for the recognition of hyperconcentrated flow deposits in the volcaniclastic environment of Mount Saint Helens, that the criteria could be applied to depositional sequences in other sedimentary environments. The Permo-Triassic Stornoway Formation in Lewis, western Scotland was chosen as a site for investigation as it represented an extensive exposure of relatively undeformed alluvial fan deposits.

Despite the good quality and extensive nature of the fan sequences, only a few deposits yielded sufficient sedimentological information to allow their categorisation within the debris flow/stream flow deposit continuum. Of these, only two deposits show sedimentological evidence of being produced from hyperconcentrated flow. Despite the apparent dearth of identifiable hyperconcentrated flow deposits, this part of the study has adequately demonstrated that the criteria established in chapter four can be applied to sequences in other sedimentary environments, in addition to consolidated sequences in the geological record.

Compatibility between the deposits of the two environments suggests not only similar or near identical flow types, but also suggests that the processes of sediment transport and deposition were also similar or near identical.

CHAPTER 6

SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH

6.1 SUMMARY OF THE COMPLETE WORK

In chapter one it was revealed that debris flow and stream flow represent end members of a continuum of flow processes with varying sediment concentration, in which the intermediate flow type is described as hyperconcentrated. It was shown that despite the widespread occurrence of debris flows and debris flow deposits, hyperconcentrated flow deposits have received little attention, although fine grained corollaries of hyperconcentrated flows have been the subject of many experimental investigations. Most of the research on hyperconcentrated flow deposits prior to this study has been conducted in the volcaniclastic environment of the north western U.S.A. and in particular, in the vicinity of Mount Saint Helens. However, much of the earlier work on supposed hyperconcentrated flow deposits lacked detailed and systematic sedimentological analysis. The primary objective of this study was to delineate hyperconcentrated flow deposits within the debris flow/stream flow deposit continuum, within volcaniclastic deposits, with the production of a set of criteria for their recognition. The secondary objective was to determine whether hyperconcentrated flow deposits could be recognised in another depositional environment, by the application of the results from the investigation on volcaniclastic deposits.

Chapter two presented the findings of the detailed and systematic analysis of coarse grained deposits in the North Fork Toutle River, south west Washington State U.S.A., which were deposited from a mass flow that was produced as a result of an eruption of Mount Saint Helens in 1984. The deposits which occurred along a 9.2 kilometre reach of the river, illustrated a downstream thinning, a decrease in mean grain size, a downstream increase in sorting, the development of clast fabric and the formation and subsequent disappearance of inverse grading (although inverse grading was expressed in sub units at the most distal locality). This systematic proximal to distal change, documented the downstream dilution and transformation of the mass flow. From the consideration of sedimentology and flow characteristics (including rheology and the processes within the flow), the boundary between debris flow and hyperconcentrated flow as expressed in the depositional sequence was delineated. The boundary between them was based on the presence or absence of a well defined plug zone/basal zone arrangement. Due to erosion, the depositional continuum produced by the 1984 flow was not complete at the time of study. In particular, the transformation of the 1984 flow from hyperconcentrated flow to stream flow as expressed in deposits was not preserved. However, deposits attributable to stream flow were produced during the recessional flow event that followed in the wake of the main flow.

The delineation of hyperconcentrated flow deposits within the debris flow/stream flow deposit continuum, which was the primary objective of this study, was completed in chapter three, through the examination of deposits produced by a Mount Saint Helens mass flow in 1982. It was suggested that in a diluting and transforming hyperconcentrated flow, deposition, involving a rapidly rising depositional surface, gives way to the formation of traction carpets at the base of the flow. With a further drop in sediment concentration and yield strength, traction carpet formation ceases and bedforms are produced instead, in what becomes a normal stream flow. Thus, the presence of stacked inversely graded sub units produced from the sequential deposition of traction carpet layers represents hyperconcentrated flow deposition, whereas bedforms represent stream flow deposition.

In combining the findings of chapters two and three, chapter four presents a set of criteria for the recognition of hyperconcentrated flow deposits. These are: general homogeneity, matrix-support, no stratification (except where defined by sub units), sorting characteristics intermediate between debris flow and stream flow, bimodal, generally non-imbricate clast fabric which is a function of clast size, and non or coarse-tail inverse grading which may be restricted to sub units.

The study of eroded remnants of older Mount Saint Helens mass flow deposits produced within the last 40,000 years, yielded depositional units that were directly analogous to units within the debris flow/stream flow deposit continuum illustrated by the 1984 and 1982 flow deposits. The characteristics of the modern and ancient deposits were so similar that it was even possible to infer the sediment concentration and velocity values of the flow that produced one particular sequence.

In chapter four the question arose whether the criteria could be applied to sedimentary environments elsewhere and the alluvial fan environment was chosen as a likely site of hyperconcentrated flow deposition in which the criteria could be used. The study was limited to an investigation of Permo-Triassic alluvial fan deposits that form the Stornoway Formation on Lewis. By adopting an objective approach, several depositional units were found that could be positioned within the debris flow/stream flow deposit continuum, with two units satisfying the criteria indicating deposition from hyperconcentrated flow. However, unlike the volcaniclastic sequences studied, it was not clear whether the alluvial fan hyperconcentrated flows were produced through the flow transformation of debris flows. The recognition of hyperconcentrated flow deposits on alluvial fan sequences through the application of the criteria established in the volcaniclastic environment, achieved the secondary objective of this work.

6.2 SUGGESTIONS FOR FURTHER RESEARCH

Throughout this work there are areas that can be identified in relation to hyperconcentrated flows and the debris flow/stream flow deposit continuum, which merit further research, but which are beyond the scope of this work. The purpose of this section is to identify and collate these areas.

The delineation of hyperconcentrated flow deposits was achieved in this study, based largely upon the sedimentological analysis of the 1984 volcaniclastic mass flow event at Mount Saint Helens, with the delineation being completed through the analysis of deposits produced in 1982. Ideally, the delineation should have been accomplished using a single debris flow/stream flow depositional continuum. In addition the study would have benefited from more thorough observations of the flow characteristics, together with systematic sampling of the flow. The combination of a thorough flow characterisation and a complete depositional continuum, may have produced greater refinement of the boundaries delineated in this study.

Due to erosion the 1984 flow deposits at the time of study, were found only in channel margin areas and on the terraces, this gives rise to speculation regarding the sedimentological characteristics of the deposits, that may have been produced further toward the centre of the channel. Central channel deposits could possibly show differences in depositional character between those produced at the channel margins, or on the terraces.

The findings of this study could therefore be considerably enhanced, or even modified, by research conducted on a more complete depositional sequence. This would have to be conducted on a sequence soon after its deposition from a volcaniclastic mass flow event (analogous to the 1984 flow at Mount Saint Helens), which had been thoroughly characterised and sampled.

An important area for future research concerns the investigation of the mechanism by which volcaniclastic mass flows, like the 1984 and 1982 Mount Saint Helens events, transform by sediment loss and water intake, as they progress downstream. One question in particular that arises, is, how does water already in a channel, interact with a highly concentrated mass flow, perhaps composed of several plugs. Research on flow transformation mechanisms would benefit from thorough flow observation and analysis and would be a "spin off" from the other area of research outlined above. However the investigation of the transformation mechanism would probably have to involve accurate scale modelling under laboratory conditions.

Laboratory analysis, could be extended to investigate the processes involved in the transport and deposition of sediment within coarse grained hyperconcentrated flows in general. In particular, laboratory investigations may elucidate the changing processes involved in the transition from hyperconcentrated flow to stream flow, which in this study was found to be documented by the transition from stacked inversely graded sub units to low amplitude bedforms. A laboratory investigation into the processes of the formation of stacked inversely graded sub units, would on its own, form an interesting research project. This study has shown that stacked inversely graded sub units not only occur in the volcaniclastic environment of Mount Saint Helens, but that analogous units occur in association with turbidites in addition to alluvial fans, therefore the results of a detailed investigation of the processes of their formation, would have widespread applicability. Further laboratory analysis could reveal the mechanism by which clast bimodality arises within hyperconcentrated flows.

This study has shown that results from the examination of modern deposits at Mount Saint Helens can not only be applied to ancient deposits in the same volcaniclastic environment, but to ancient alluvial fan sequences. Further research should therefore be conducted on both modern and ancient sequences in other environments, in which depositional continua may occur, in order to achieve a more complete picture of the sedimentology of hyperconcentrated flow deposits.

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APPENDIX 1A

GRAIN SIZE DISTRIBUTION ANALYSES

Phi (ϕ)	SAMPLES AND CUMULATIVE PERCENTAGES						
	1	2	3	4	5	6	7
-9	4.6	1.2					
-8	12.7	3.6	1.4				
-7	24.2	7.2	8.4	8.0	2.5	5.0	
-6	38.0	13.2	23.1	20.0	10.0	13.0	4.3
-5	45.9	18.3	31.2	37.5	23.7	28.5	13.8
-4	56.1	24.3	39.7	53.8	37.5	43.0	26.5
-3	65.6	38.2	48.5	63.6	49.5	54.2	40.3
-2	71.6	49.4	56.6	70.0	58.0	65.2	49.0
-1	76.3	61.6	67.1	76.2	63.5	72.5	55.7
0	82.7	72.8	78.6	82.0	69.7	79.6	64.3
1	87.6	82.9	85.6	87.7	77.2	86.5	74.2
2	92.1	90.7	91.2	93.7	85.0	92.0	82.8
3	95.4	95.6	95.0	95.5	91.3	95.4	89.9
4	97.4	97.8	97.2	98.0	96.0	97.6	95.0
5	98.4	100	100	100	100	100	100
6	99.1						
7	99.5						
8	99.7						
9	99.7						
10	100						

GRAIN SIZE DISTRIBUTION STATISTICS

	1	2	3	4	5	6	7
Md	24250	3860	6960	19030	7730	10200	3610
M_z	-4.00	-2.12	-2.83	-3.40	-2.20	-2.85	-1.48
σ_I	3.79	3.26	3.37	3.17	3.44	3.09	3.26
Sk_I	0.24	-0.07	0.05	0.39	0.30	0.25	0.17
K_G	0.86	1.02	0.78	0.91	0.75	0.89	0.78
C 1%	831750	548750	294070	215270	174850	207940	87430

* Phi (ϕ) = THE NEGATIVE LOGARITHM TO THE BASE 2 OF THE PARTICLE DIAMETER IN MILLIMETRES.
* THE DEPOSIT TYPES AND LOCATIONS FROM WHICH THE SAMPLES WERE TAKEN, ARE GIVEN IN FIGURE 2.13
* Md AND THE OTHER STATISTICAL MEASURES ARE DEFINED IN APPENDIX 1B
* Md AND C 1% VALUES ARE IN MICRONS.

Phi (ϕ)	SAMPLES AND CUMULATIVE PERCENTAGES						
	8	9	10	11	12	13	14
-9							
-8							
-7							
-6	4.3	2.0					3.5
-5	10.3	5.3	2.0				10.0
-4	24.9	12.4	4.4			27.3	21.0
-3	43.3	25.1	7.8	0.4		41.1	34.0
-2	58.6	44.5	12.2	1.4	0.1	52.3	50.0
-1	72.6	60.5	21.8	4.7	0.6	61.4	62.7
0	82.7	74.0	42.2	13.7	9.0	70.9	74.0
1	87.7	83.2	68.5	41.6	48.0	79.5	83.0
2	91.2	88.6	84.5	71.1	74.7	86.8	88.0
3	93.6	93.2	93.5	88.0	87.7	92.3	92.0
4	96.2	96.1	97.8	96.2	94.1	95.7	94.5
5	100	100	100	100	100	100	100
6							
7							
8							
9							
10							

GRAIN SIZE DISTRIBUTION STATISTICS

Md	5860	3140	810	410	480	4600	4000
M_z	-2.28	-1.38	0.23	1.37	1.30	-1.70	-1.77
σ_I	2.62	2.51	1.96	1.37	1.28	2.80	2.91
Sk_I	0.23	0.18	-0.11	0.08	0.36	0.31	0.19
K_G	1.20	1.14	1.15	1.11	1.22	0.76	1.07
C 1%	111430	84450	45260	4930	1800	30910	93700

Phi (ϕ)	SAMPLES AND CUMULATIVE PERCENTAGES						
	15	16	17	18	19	20	21
-9							
-9							
-7							
-6							
-5	4.0		1.0				
-4	15.0	2.3	4.5	2.0	0.8		1.3
-3	30.0	6.5	14.0	6.0	3.8		2.8
-2	47.5	12.0	28.5	26.0	16.6	0.2	5.1
-1	64.0	23.7	47.5	39.0	31.4	1.9	13.4
0	75.0	39.5	67.5	59.5	49.2	18.6	45.2
1	83.0	60.5	82.5	72.9	62.6	44.6	67.7
2	89.0	81.5	92.0	88.0	76.3	69.6	82.0
3	93.0	91.0	96.0	94.9	86.5	84.9	90.0
4	96.0	96.0	98.5	98.0	93.1	92.6	94.7
5	100	100	100	100	100	100	96.5
6							98.1
7							99.0
8							99.3
9							99.3
10							100

GRAIN SIZE DISTRIBUTION STATISTICS

Md	3610	710	1800	1370	970	440	870
M_z	-1.52	0.37	-0.85	-0.40	0.23	1.30	0.50
σ_I	2.58	2.03	2.01	2.00	2.30	1.58	1.71
Sk_I	0.24	-0.09	0.04	0.08	0.16	0.19	0.28
K_G	1.05	1.15	1.01	0.79	1.02	1.05	1.20
C 1%	40790	22630	33130	19700	11710	2140	17750

Phi (ϕ)	SAMPLES AND CUMULATIVE PERCENTAGES						
	22	23	24	25(T)	26(B)	27	28
-9							
-8							
-7							
-6							
-5							
-4			2.6				3.5
-3	3.3	9.0	9.3	0.1	0.7		11.5
-2	11.0	33.7	20.2	1.0	3.4	0.4	24.7
-1	32.0	53.5	39.4	5.0	17.1	5.5	41.0
0	55.0	70.5	60.0	18.0	50.8	26.9	64.3
1	77.5	80.7	77.0	42.7	75.5	60.0	80.8
2	88.0	89.0	88.6	68.4	88.4	81.8	91.3
3	95.0	94.3	95.1	86.2	94.9	92.2	95.6
4	99.0	97.1	98.1	94.7	97.7	96.4	98.3
5	100	100	100	97.4	100	100	100
6				98.7			
7				99.4			
8				99.5			
9				99.5			
10				100			

GRAIN SIZE DISTRIBUTION STATISTICS

	22	23	24	25(T)	26(B)	27	28
Md	1150	2300	1410	410	1000	620	1570
M_z	-0.13	-0.85	-0.42	1.35	0.18	0.82	-0.67
σ_I	1.69	1.98	1.99	1.51	1.40	1.37	1.96
Sk_I	0.09	0.32	0.06	0.07	0.23	0.19	0.02
K_G	1.06	0.95	1.04	1.04	1.21	1.12	1.03
C 1%	12130	12130	21110	4000	5860	2930	22630

* T = THE TOP INVERSELY GRADED SUB UNIT AT LOCALITY 3.4 (LOG A, FIGURE 2.6), 1.35 o = 0.39 mm.
* B = THE BOTTOM INVERSELY GRADED SUB UNIT AT LOCALITY 3.4 (LOG A, FIGURE 2.6), 0.18 o = 0.88 mm.

Phi (ϕ)	SAMPLES AND CUMULATIVE PERCENTAGES					
	29	30	31	32	33	34
-9						
-8						
-7						
-6						
-5						
-4						
-3	1.7					
-2	5.0	0.3	2.0	0.5		
-1	12.0	1.8	5.5	3.5		
0	31.0	14.2	11.5	12.0	0.1	1.0
1	60.1	47.5	30.5	40.0	1.0	5.9
2	82.6	74.7	68.1	77.5	16.6	38.0
3	92.1	88.0	90.5	90.5	61.4	78.8
4	94.5	94.6	96.0	95.0	91.5	96.0
5	100	100	100	100	97.7	100
6					98.8	
7					98.9	
8					99.0	
9					99.0	
10					100	

GRAIN SIZE DISTRIBUTION STATISTICS

Md	640	470	340	440	150	200
M_z	0.68	1.25	1.50	1.27	2.78	2.28
σ_I	1.75	1.34	1.29	1.29	0.83	0.92
Sk_I	0.14	0.23	-0.10	0.14	0.09	0.02
K_G	1.50	1.08	1.41	1.47	1.06	0.95
C 1%	9510	2380	4760	3030	500	1000

* 33 AND 34 ARE SAMPLES OF STREAM FLOW DEPOSITS TAKEN AT LOCALITIES 5.2 AND 9.2 RESPECTIVELY.

APPENDIX 1B

FORMULAS AND SCALES FOR GRAPHIC GRAIN SIZE PARAMETERS

(AFTER FOLK 1980)

Median

Md = the diameter corresponding to the 50% mark on the cumulative curve

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Graphic mean

$$M_Z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Inclusive graphic standard deviation (sorting)

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

<0.35ϕ	very well sorted
0.35 to 0.50ϕ	well sorted
0.50 to 0.71ϕ	moderately well sorted
0.71 to 1.0ϕ	moderately sorted
1.0 to 2.0ϕ	poorly sorted
2.0 to 4.0ϕ	very poorly sorted
>4.0ϕ	extremely poorly sorted

Inclusive graphic skewness

$$Sk_I = \frac{\phi16 + \phi84 - 2\phi50}{2(\phi84 - \phi16)} + \frac{\phi5 + \phi95 - 2\phi50}{2(\phi95 - \phi5)}$$

1.0	to	0.3	very fine-skewed
0.3	to	0.1	fine-skewed
+0.1	to	-0.1	near-symmetrical
-0.1	to	-0.3	coarse-skewed
-0.3	to	-1.0	very coarse-skewed

Graphic kurtosis

$$K_G = \frac{\phi95 - \phi5}{2.44(\phi75 - \phi25)}$$

<0.67			very platykurtic
0.67	to	0.90	platykurtic
0.90	to	1.11	mesokurtic
1.11	to	1.50	leptokurtic
1.50	to	3.00	very leptokurtic
>3.00			extremely leptokurtic

APPENDIX 2

STATISTICAL ANALYSIS OF CLAST A-AXIS ORIENTATION DATA

A-axes orientation with respect to flow direction

Clast a-axis orientation data when plotted on a rose diagram can indicate a general trend. However in order to determine whether there is a statistically preferred trend, the following statistical procedure was conducted using the method of Davis (1986).

1) Firstly, the mean orientation $\bar{\theta}$ which is the angular average of all the orientations in the sample or group of data is obtained using the equation:

$$\text{mean a-axis orientation } \bar{\theta} = \tan^{-1} (Yr / Xr) \qquad ----- (1).$$

where Yr = the sum of sines of the orientation measurements,
where Xr = the sum of cosines of the orientation measurements.
This can allow the comparison to be made between a-axis orientation and the flow direction.

2) Secondly, the measure of dispersion of the measurements (analogous to the variance) is the quantity $\bar{R}$ called the mean resultant length and is calculated as follows:

$$\text{mean resultant length } \bar{R} = \frac{Yr^2 + Xr^2}{N} \qquad ----- (2).$$

where

$Yr^2 + Xr^2$ represents the resultant magnitude R ----(3).

and where N is the number of measurements.

Large values of $\bar{R}$ indicate bunched a-axes orientations,

Small values of $\bar{R}$ indicate widely spaced a-axes orientations.

3) Thirdly, the data is then tested for randomness to determine wether or not there is a preferred orientation. This is called the Rayleigh's test for the presence of a preferred trend, a modern derivation of which is given by Mardia (1972).

The simplest hypothesis that can be statistically tested is that the orientational observations are random, that is, there is no preferred orientation. The statistical test involves using the value of $\bar{R}$ calculated in the second stage. This value is compared to a critical value of $\bar{R}$ for the desired level of significance, α, which in this work is 5%, although data showing a preferred orientation at a significance level of 10% is also presented in this work. The critical values of $\bar{R}$ are obtained from tables in Mardia (1972). If the computed statistic is so large that it exceeds the critical value from the table the null hypothesis must be rejected and the observations may be presumed to come from a population having a preferred orientation.

Imbrication

In order to determine whether there existed a statistically preferred upstream or downstream a-axis dip, an identical procedure to that outlined above, was conducted for measurements of the angle between clast a-axes and the bedding surfaces of a depositional unit.

The dip angles, either upstream or downstream, were treated as orientations on either side of 0 degrees which corresponded to zero dip.

Statistical analysis of bimodal clast a-axes orientations

Some rose diagrams indicated that within certain units there existed bimodal clast a-axis orientations between cobbles and clasts less than 2 cm. Statistical analyses were therefore required to test the orientational quality of the two groups, to investigate whether there is actual bimodality. This was conducted in two stages as follows:

1) The two groups of a-axis orientations were combined and a pooled resultant magnitude was obtained using equation 3.

2) The pooled resultant magnitude was compared with the sum of the two individual group resultant magnitudes. If the mean directions of the two groups were significantly different, (5% level) that is, if bimodality existed, the pooled resultant magnitude would have been smaller than the sum of the two resultant magnitudes. If on the other hand the two groups of orientational data were from the same population then the pooled resultant magnitude should be approximately equal the sum of their two resultants.

APPENDIX 3

FRAGILE CLAST COUNT ALONG STUDIED REACH

(CLASTS ABOVE 10 cm IN SIZE ONLY)

SITE	FRAGILE CLAST COUNT (A)	DEPOSIT DIMENSIONS LENGTH (m)	WIDTH (m)	L.S.A. (m^2) (B)	A/B
0.0	7	14	1.6	22.40	0.313
0.7	12	35	1.4	49.00	0.245
1.0	7	20	1.5	30.00	0.233
1.7	9	40	1.2	48.00	0.188
2.0	4	15	1.1	16.50	0.242
2.7	4	20	1.0	20.00	0.200
3.0	0	5	0.75	3.75	0.000
3.4	1	10	0.70	7.00	0.143
3.7	1	7	0.75	5.25	0.190
4.3	2	T 35	0.40	14.00	0.143
4.5	0	T 10	0.25	2.50	0.000
5.2	2	40	0.55	22.00	0.090

* NO FRAGILE CLASTS ABOVE 10 cm IN SIZE BEYOND LOCALITY 5.2.

* T REPRESENTS DEPOSITS ON THE TERRACE.

* L.S.A. REPRESENTS THE LONGITUDINAL SECTIONAL AREA OF THE DEPOSIT MEASURED = DOWNSTREAM DEPOSIT LENGTH X DEPOSIT WIDTH.

APPENDIX 4

PARAMETERS USED IN THE CALCULATION OF FLOW RHEOLOGICAL CHARACTERISTICS

SITE	CLAST TYPE	UNIT WEIGHTS CLAST (γb) dn/cm³	UNIT WEIGHTS DEBRIS (γd) dn/cm³	CLAST HEIGHT cm	n		YIELD STRENGTH dn/cm²
0.0	DACITE	2450	2009	80	0.65		2.00×10^4
"	"	"	"	65	0.70		1.49×10^4
"	"	"	"	74	0.74		1.56×10^4
"	BASALT	2558	"	83	0.60		2.46×10^4
"	GD	2509	"	55	0.64		1.47×10^4

						AV.	1.80×10^4
3.7	DACITE	2450	1823	35	0.69		9.14×10^3
"	BASALT	2558	"	44	0.89		9.02×10^3

						AV.	9.08×10^3
4.3	DACITE	2450	1793	38	0.71		9.80×10^3
"	BASALT	2558	"	47	0.55		1.62×10^4
"	DACITE	2450	"	54	0.48		1.88×10^4

						AV.	1.49×10^4
4.5	DACITE	2450	1774	26	0.54		8.50×10^3
"	GD	2509	"	25	0.48		9.08×10^3

						AV.	$8,79 \times 10^3$
5.2	PD	2519	1744	22	0.77		5.67×10^3
"	ANDESITE	2391	"	20	0.60		5.89×10^3

						AV.	5.78×10^3

* GD DENOTES GREY DACITE, PD DENOTES PORHPYRITIC DACITE.
* n IS THE RATIO OF SUBMERGED TO TOTAL CLAST HEIGHT.
* THE UNIT WEIGHTS REPRESENT THE DENSITY VALUES X 980 cm/s^2.

SITE	CHANNEL WIDTH m	FLOW VELOCITY cm/s		BINGHAM VISCOSITY poises
0.0	80	980		2.02×10^4
"	"	"		1.52×10^4
"	"	"		1.59×10^4
"	"	"		2.50×10^4
"	"	"		1.50×10^4

			AV.	1.83×10^4

3.7	85	870		1.12×10^4
"	"	"		1.10×10^4

			AV.	1.11×10^4

4.3	75	840		1.09×10^4
"	"	"		1.81×10^4
"	"	"		2.10×10^4

			AV.	1.67×10^4

4.5	85	820		1.10×10^4
"	"	"		1.18×10^4

			AV.	1.14×10^4

5.2	95	790		8.52×10^3
"	"	"		8.85×10^3

			AV.	8.69×10^3

APPENDIX 5

OTHER ST. HELENS GRAIN SIZE DISTRIBUTION ANALYSES

Phi (ϕ)	SAMPLES AND CUMULATIVE PERCENTAGES				
	1982	ALDER	C.B DEB	C.B IGU	TOWER
-9			2.3		
-8			8.0		
-7		4.0	16.0		
-6		10.7	28.5		
-5		23.3	39.4		
-4		36.5	50.2		
-3		48.0	59.0		
-2		60.0	66.9	0.2	
-1	0.1	68.0	74.8	1.2	2.7
0	0.2	74.3	80.1	10.3	12.1
1	3.1	80.0	85.0	44.3	43.8
2	43.5	84.3	89.6	76.0	68.0
3	85.1	89.0	93.6	87.7	84.2
4	97.1	95.0	97.0	94.1	92.4
5	100	100	100	100	100
6					

GRAIN SIZE DISTRIBUTION STATISTICS

	1982	ALDER	C.B DEB	C.B IGU	TOWER
Md	230	7210	16000	450	420
M_z	2.13	-2.13	-3.40	1.33	1.47
σ_I	0.81	3.50	3.75	1.31	1.49
Sk_I	0.07	0.28	0.24	0.28	0.25
K_G	0.91	0.89	0.92	1.26	1.10
C 1%	570	194010	630350	2380	2930

* 1982 = A SAMPLE OF THE 1982 LAMINATED SANDS.
* ALDER = A SAMPLE OF THE LOWER UNIT IN THE BIPARTITE SEQUENCE AT ALDER CREEK
* C.B = CAMP BAKER SAMPLES, DEB = DEBRIS FLOW UNIT AND IGU = AN INVERSELY GRADED SUB UNIT.
* TOWER = A SAMPLE OF AN INVERSELY GRADED SUB UNIT AT TOWER ROAD.

APPENDIX 6

STORNOWAY FORMATION PALAEOFLOW ANALYSES

ARNISH PENINSULA

CROSS BEDDING		PALAEOFLOW
202	24	= 112
201	32	= 111
198	28	= 108
196	16	= 106
195	23	= 105
191	20	= 101
190	28	= 100
186	26	= 96
175	27	= 85
173	31	= 83
	AV.	= 101

GRESS SANDS

CROSS BEDDING		PALAEOFLOW
343	17	= 73
338	24	= 68
333	22	= 63
330	26	= 60
328	21	= 58
327	57	= 57
	AV.	= 63

MELBOST POINT

CROSS BEDDING		PALAEOFLOW
180	46	= 270
176	45	= 266
171	50	= 261
168	51	= 258
165	54	= 255
	AV.	= 262

RAMADALE POINT

IMBRICATION		PALAEOFLOW
300	30	= 210
304	33	= 214
305	36	= 215
308	40	= 218
312	29	= 222
317	32	= 227
320	37	= 230
325	35	= 235
	AV.	= 221

* 202 24, ETC. REFER TO THE STRIKE AND DIP MEASUREMENTS FROM EITHER CROSS BEDDING OR IMBRICATED CLASTS
* 112, ETC. REFER TO THE PALAEOFLOW DIRECTION DERIVED FROM THESE MEASUREMENTS.
* AV. REPRESENTS THE AVERAGE VALUE OF PALAEOFLOW.

APPENDIX 7

STORNOWAY FORMATION GRAIN SIZE DISTRIBUTION ANALYSES.

Phi (ϕ) SAMPLES AND CUMULATIVE PERCENTAGES

Phi (ϕ)	A1	A2	A3	G1
-9	4.0			4.0
-8	10.0	4.0		14.0
-7	24.0	14.0	2.0	26.0
-6	36.0	26.0	14.0	40.0
-5	48.0	40.0	28.0	52.0
-4	60.0	52.0	40.0	64.0
-3	70.0	62.0	56.0	76.0
-2	80.0	70.0	70.0	86.0
-1	88.0	86.0	86.0	92.0
0	91.0	91.8	91.6	95.1
1	93.5	94.8	94.8	97.0
2	96.6	96.9	97.3	98.4
3	99.3	98.7	99.0	99.4
4	100	100	100	100
5				

GRAIN SIZE DISTRIBUTION STATISTICS

	A1	A2	A3	G1
M_Z	-4.65	-4.02	-3.43	-5.05
σ_I	3.10	2.79	2.36	2.75
SK_I	-2.34	1.64	0.10	0.11
K_G	0.96	0.83	0.91	0.94

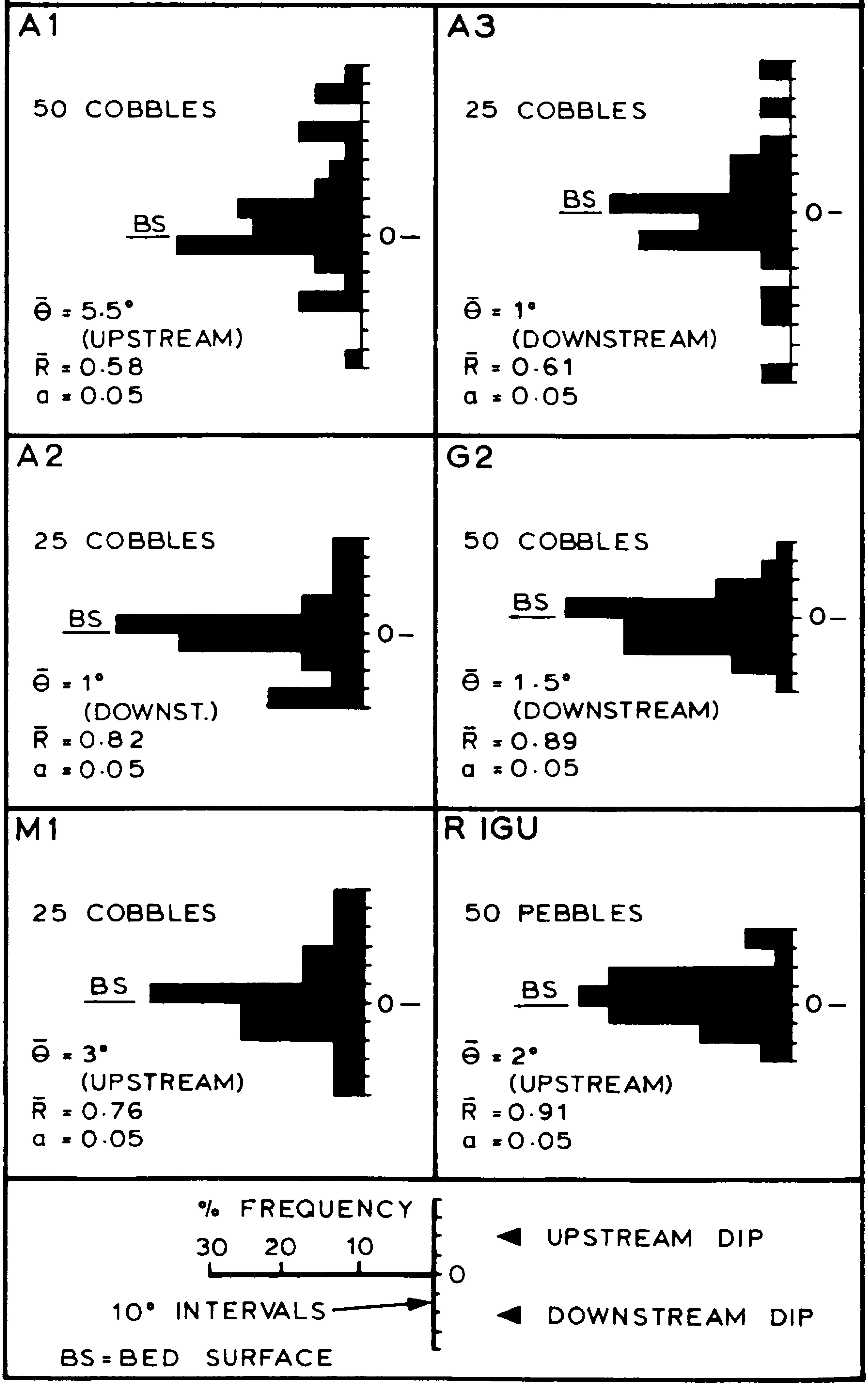
Phi (ϕ)	SAMPLES AND CUMULATIVE PERCENTAGES			
	G2	M1	M1(R)	R(IGU)
-9				
-8				
-7	8.0			
-6	22.0	2.0		
-5	34.0	10.0		
-4	50.0	24.0	1.0	
-3	66.0	42.0	6.0	0.5
-2	78.0	62.0	14.0	3.0
-1	90.0	84.0	24.0	8.0
0	93.8	89.5	37.0	20.0
1	96.4	93.5	57.0	41.5
2	97.8	96.8	79.0	66.5
3	99.1	98.8	90.0	92.0
4	100	100	100	100
5				

GRAIN SIZE DISTRIBUTION STATISTICS

M_Z	-3.95	-2.70	0.42	1.25
σ_I	2.43	1.93	2.08	1.45
SK_I	0.10	0.04	-0.16	-0.16
K_G	0.90	1.12	1.04	0.96

APPENDIX 8

CLAST IMBRICATION ANALYSIS OF SELECTED DEPOSITIONAL UNITS IN THE STORNOWAY FORMATION. THE DATA IS EXPRESSED IN THE FORM OF HISTOGRAMS.



APPENDIX 9

PARAMETERS USED IN THE CALCULATION OF PALAEOFLOW YIELD STRENGTH AND VELOCITY

BED	CLAST TYPE	UNIT WEIGHTS CLAST (γb) dn/cm³	UNIT WEIGHTS DEBRIS (γd) dn/cm³	CLAST HEIGHT cm	n	YIELD STRENGTH dn/cm²
A1	BG	2577	2009	45	0.76	1.03×10^4
"	HG	2626	"	35	0.51	1.23×10^4
					AV.	1.13×10^4
A3	HG	2626	1823	35	0.66	1.09×10^4
"	PG	2489	"	37	0.70	9.83×10^3
"	BG	2577	"	22	0.73	6.00×10^3
					AV.	8.91×10^3
G1	PG	2489	"	16	0.56	5.14×10^3

BED	FLOW DEPTH (cm)	SLOPE	VELOCITY (cm/s)
A1	180	5°	310
"	200	"	327
			AV. 318.5
A3	100	"	231
"	"	"	231
"	110	"	242
			AV. 235
G1	60	"	179

* BG DENOTES BANDED GNEISS, HG DENOTES *HORNBLENDE RICH* GNEISS AND PG DENOTES PEGMATITIC GNEISS.

* n IS THE RATIO OF SUBMERGED TO TOTAL BLOCK HEIGHT.

* THE UNIT WEIGHTS REPRESENT THE DENSITY VALUES X 980 cm/s^2.