Keele UNIVERSITY

This work is protected by copyright and other intellectual property rights and duplication or sale of all or part is not permitted, except that material may be duplicated by you for research, private study, criticism/review or educational purposes. Electronic or print copies are for your own personal, non-commercial use and shall not be passed to any other individual. No quotation may be published without proper acknowledgement. For any other use, or to quote extensively from the work, permission must be obtained from the copyright holder/s.

VOLCANIC AND SEDIMENTARY FACIES OF PART OF THE BORROWDALE VOLCANIC GROUP, CUMBRIA

ROGER JOHN SUTHREN

Department of Geology, University of Keele

Submitted for the Degree of Doctor of Philosophy

1977

VOLUME ONE.

He who, with pocket hammer, smites the edge
of luckless rock, or prominent stone, disguised
In weather stains, or crusted o'er by nature
With her first growths - detaching by the stroke
A chip or splinter, to resolve his doubts;
And, with that ready answer satisfied,
The substance classes by some barbarous name,
and hurries on.

William Wordsworth.

ABSTRACT

Detailed studies of sequences of volcaniclastic rocks, lavas and intrusions have been undertaken in four areas in the Ordovician Borrowdale Volcanic Group in the English Lake District, which together comprise a vertical section some 4km thick. Fieldwork has been complemented by petrographical study of over 300 samples from these rocks.

On the eastern side of Derwentwater, a sequence of blocky lava flows of andesitic and basaltic andesite composition is inter bedded with hyaloclastites, ashfall deposits, and reworked ashfall material. The deposits of mudflows and lacustrine turbidites have also been recognized here.

In the overlying Thirlmere section, a 2500m thick sequence of andesites contains hyaloclastites, local pillows and peperite complexes thought to have been formed by the intrusion of high level andesite sills into wet, unconsolidated volcanic sediments. Ashfall and mudflow deposits are also present. Overlying the andesites is a thick sequence of welded acid ignimbrites, with interbedded ashfall tuffs.

A third section at Sour Milk Gill, southern Borrowdale, spans the contact of the andesites and ignimbrites seen at Thirlmere. A thick bedded ashfall sequence shows evidence of lacustrine deposition, and below the overlying pyroclastic flow deposits, thin units of base surge origin are seen.

Overlying the thick ignimbrite sequence in Langdale, parallel bedded tuffs with well developed sequences of sedimentary structures are interpreted as turbidites, and are sharply overlain by ?sub-aerially reworked coarse tuffs, which are succeeded by blocky andesitic lava flows.

It is concluded that most of the sequence accumulated in an area

of subdued topography, allowing widespread development of the various volcanic units.

Comparisons are drawn between the studied sections and modern volcanic areas such as New Zealand and Mexico.

CONTENTS

Page

CHAPTER 1. INTRODUCTION

1. GENERAL.

The author has undertaken research on the Ordovician Borrowdale Volcanic Group of the Lake District of Northern England (figs 1.1 and 1.3) A wide variety of volcanic rocks has been studied, including lava flows, intrusions and a broad range of volcaniclastic rocks. Rocks of intermediate composition predominate, but there is a range from basic through to acid. Detailed fieldwork and petrography have been undertaken in several geographical areas, which together comprise a section through approximately the lower two thirds of the Group. The aim of the research is to interpret the modes of eruption and the mechanisms and environments of emplacement of the various volcanic and sedimentary facies. Consideration is also given to the petrogenesis of the lavas and intrusions, and to the palaeogeography of the area during the development of the volcanic pile. In a broader context, this work should assist in the interpretation of ancient volcanic environments elsewhere, particularly in discrimination between subaqueous and subaerial environments in volcaniclastic sediments, and in the important distinction between lava flows and high level,contemporaneous intrusions.

Three areas have been examined in detail (fig 1.2)

(1) the area east of Derwentwater, forming the ridge between the Borrowdale and Thirlmere valleys

(2) the area around and immediately to the north of Thirlmere Reservoir

(3) the Chapel Stile - Elterwater area of the Langdale valley.

A shorter term study has been made in the area around Sour Milk Gill, in the Seathwaite Valley of southern Borrowdale.

11. FIELD AND LABORATORY TECHNIQUES.

Approximately thirty weeks fieldwork was undertaken during the period 1973 to 1976. Geological mapping was mostly carried out at a scale of 1:10,560 using Ordnance Survey topographical maps, and aided by O.S. and R.A.F. aerial photographs at scales of 1:6700, 1:8400 and 1:25,800. The detailed survey of the Brown Knotts area, Borrowdale, used aerial photographs enlarged to a scale of about 1:4550 as a base map, whilst enlarged O.S. maps were used in the Langdale area.

Section logging was carried out at different scales, according to the nature of the exposure. Long, partly unexposed sections were measured using both tape and Abney level, and recorded on printed data sheets. Detailed logging was possible in Borrowdale, where differential weathering accentuates sedimentary structures in the bedded tuffs, and in the Langdale quarry sections, where wetting of the rock surface brings out the maximum of sedimentological detail. Such sections were measured with a ruler graduated in mm and recorded in a notebook. Where possible, marker horizons (e.g. a distinctive tuff bed or lava flow) were used to correlate between detailed sections.

Structural and palaeocurrent measurements were made with a Suunto compass/clinometer. Grain size measurements were made on coarse grained clastic rocks in the field by chalking a 10 cm grid onto the rock surface and measuring the maximum clast dimensions at grid intersections. Grains less than 4 mm in diamter were counted as "matrix": the grain size distribution of this finer material was determined later in thin section, and plotted in combination with the outcrop data. Measurements of length/height ratios of fiammé were made on selected coarse-grained welded tuffs in the field. Nearly all the field photographs were taken with a Zenith B single lens reflex camera with a 58 mm f/2 lens. Owing to the low contrast of the features of many exposures it was sometimes necessary to emphasize important details with chalk or a felt-tipped marker prior to photography.

In the laboratory, thick, varnished rock slices were examined under a Vickers zoom stereo microscope, at magnifications from 5x to 45x. In this way, original grain shapes, inter-grain relationships and detailed sedimentary structures and igneous textures are often seen more clearly than in thin section, where they are commonly obscured by alteration, and where secondary mineralogies and textures tend to be more obvious. Approximately 300 thin sections were studied, using a Leitz Wetzlar binocular microscope, with magnifications up to 1250x. Modal analyses were made on this microscope, using a Swift point counter with a spacing of 0.3 mm.

Grain size distribution in thin sections of volcaniclastic rocks was determined by point-counting in conjunction with an eyepiece graticule, or more conveniently with a point counter mounted on a Shadowmaster projecting microscope equipped with a 1 cm grid.

111. REGIONAL STRATIGRAPHICAL AND STRUCTURAL SETTING.

A. The Borrowdale Volcanic Group.

(i) General

The Borrowdale Volcanic Group constitutes a considerable proportion of the thick Ordovician succession of the Lake District, and is the most important of the several Ordovician volcanic units there (figs 1.4 and 1.5). It underlies an area of approximately 900 km^2 in the central mountainous part of the Lake District (fig 1.3), whilst several areas of rocks assigned to the Group occur in the Cross Fell inlier to the east (fig 1.4). Small outcrops are also known from the Langdon Beck and Cautley inliers. Various estimates have been made of the thickness of the main outcrop of the Group: Ingham & Wright (1972) give thicknesses varying between 4.5 km in the southwest and 3.2 km in the east. The stratigraphical compilation of fig 1.8, if correct, suggests that the volcanic pile is 7.5 km thick in the southwest and 3.9 km thick in the east. This is in accord with thicknesses present in the areas studied by the present author and with estimates made by Dr. N.J.Soper (personal communication).

In overall volume, lava flows are slightly subordinate to volcaniclastic rocks, whilst penecontemporaneous intrusions are locally important. Major and trace element abundances of the lavas and ignimbrites suggest that they belong to the calc-alkaline suite (Fitton, 1971). The wide range of volcaniclastic rocks includes ashfall and ashflow deposits, and subaerially and subaqueously reworked material. All the rocks within the Group have been altered to a greater or lesser degree by the effects of diagenesis, hydrothermal activity and low grade metamorphism.

(ii) Stratigraphy.

No consensus has yet been reached on formal stratigraphical nomenclature within the volcanic sequence. "Borrowdale Volcanic Group" superseded the older "Borrowdale Volcanic Series" some years ago when "Series" became a chronostratigraphic term. The present author prefers to follow Soper and Numan (1974) in subdividing the Group into formations, and discontinuing the use of "Group" (e.g. Moseley, 1960) for subdivisions of the volcanic succession. New formations erected by the present writer are described in the relevant chapters below.

Due to the complete absence of fossils within the Group, any attempt at internal correlation must be based on lithostratigraphy. Many attempts have been made in the past to erect an overall stratigraphy for the Group, but it has sometimes been forgotten that, in an area of intermediate and acid vulcanicity, with numerous volcanic centres, many units will be local to their centres of eruption. Pyroclastic flow deposits, however, should be more widespread, and of use in correlation. This is the case in the Borrowdale Volcanic Group, where the major ignimbrite-bearing units, and in particular the Airy's Bridge "Group" outcrop over a large area (fig 1.8). Since the emplacement of a single ignimbrite, or of an accretionary lapilli horizon (A.M.Bell, personal communication) is effectively an instantaneous event, both should be of use as time planes. These are the only tentative time indicators within the volcanic pile, but neither is sufficiently abundant or widespread to allow theerection of a detailed chronostratigraphy. Other extensive rock units are only of lithostratigraphical use, and may well be diachronous.

A compilation of the stratigraphy of the Group has been attempted by the present author (fig 1.8). If the correlations shown are correct, several important inferences may be drawn. The first is the marked decrease in thickness from southwest to east. This is due only in small part to erosion at the base of the Coniston Limestone Group; more important is the greatly reduced thickness of the lower parts of the succession in the east. This could be the result either of original thickness differences, or of the presence of internal unconformities, as yet unrecognized, or a combination of both. The lower parts of the pile are largely andesitic lava, followed by intermediate tuffs in the thick southwestern successions. Overlying the early andesitic rocks over a large area is a thick unit of acid ignimbrites and lavas, the Airy's Bridge "Group" (Oliver, 1954) and its correlatives. This , in turn, is generally overlain by andesitic lavas or tuffs, succeeded in places by further acid ignimbrites. Where the highest remaining parts of the succession are exposed, as at Coniston and Kentmere (fig 1.8), this acid unit is overlain by more andesitic lavas and tuffs, and the sequence is capped by another acid ignimbrite horizon.

(iii) Stratigraphical Age

The sediments of the underlying Skiddaw Group contain Arenig and Llanvirn graptolite faunas, and the youngest so far discovered belong to the Didymograptus murchisoni zone (Wadge et al, 1972) (fig 1.6). This fixes the maximum age of the base of the Borrowdale Volcanic Group in the upper Llanvirn (fig 1.5).

In the Lake District, the oldest sediments seen to overlie the Borrowdale Group are the Actonian Stile End Beds. In the north,however, the Drygill Shales, a small isolated outcrop of Longvillian age, suggests that in places the base of the Coniston Limestone Group is older. This is supported by the occurrence in the Cross Fell Inlier of the lower Longvillian Corona Beds, which overlie acid rocks of the Borrowdale Group (fig 1.4). (Stratigraphical information from Ingham and Wright, 1972). Thus, the minimum age for the top of the Borrowdale Volcanic Group is lower Longvillian (fig 1.5).

A certain length of time must be allowed for deformation and erosion at the unconformable bases of the Borrowdale and Coniston Groups, but it can be concluded that the greater part of the volcanic succession was emplaced during Llandeilo and/or Lower Caradoc times.

(iv) Absolute Age

Absolute dating of the Borrowdale Volcanic Group also poses considerable problems. Radiometric dates from the Lake District are confined almost exclusively to the major intrusions, and none have been obtained from the volcanic rocks.

Recently, the Threlkeld Microgranite, which is intruded into both the Borrowdale Volcanic and Skiddaw Groups, near their junction, has been dated by the Rb-Sr method (Wadge et al., 1974). A whole rock isochron gives the age of the intrusion as 445 $\pm$ 15 m.y.[1] which was interpreted as early Caradocian. They suggested that the Threlkeld intrusion might be co-magmatic with extrusive acid rocks towards the top of the Borrowdale Volcanic pile, thus implying that the younger parts of the pile are Lower Caradocian in age.

The Stockdale Rhyolite, of Actonian–Onnian age, and found in the lower part of the Coniston Limestone Group, has recently been dated at 435 m.y. (R.D.Beckinsale, personal communication). This gives an upper limit for the age of the Borrowdale Volcanic Group.

For further control on the absolute age of the Group, it is necessary to look outside the Lake District. Unfortunately, there is a general paucity of data from the Lower Palaeozoic; all the reliable, stratigraphically controlled data so far published are confined to the Lower Caradocian (points c,d & e in fig 1.6). Fitch, Forster & Miller (1976) have evaluated all the data available up to mid-1974, and have concluded that no satisfactory Ordovician geochronology is possible until many more reliable, stratigraphically controlled dates are available. They have, however, constructed a very tentative "best-fit" geochronology for the Ordovician, which has been incorporated into fig 1.6. Their time scale accords broadly with dates quoted by Phillips, Stillman & Murphy (1976) (although no errors are quoted in the latter publication).

From the data presented, it seems probable that the vulcanicity which gave rise to the Borrowdale Volcanic Group was drawing to a close by 445 m.y. ago. It is not possible to date the onset or duration of the volcanicity, nor of any of the individual volcanic episodes.

[1] All Rb-Sr ages quoted have been standardized using the 4.7×10^{10} yrs. half-life for ^{87}Rb.

B. The Skiddaw Group

(i) General.

The Skiddaw Group comprises a considerable thickness (2 km or 9 km, depending on structural interpretation) of sparsely fossiliferous mudstones, siltstones and sandstones which have undergone polyphase deformation. Its base is not seen, but the lower part of the Group may correlate with the upper part of the Manx Slates of the Isle of Man (Ingham & Wright, 1972).

(ii) Volcanic Units.

Downey and Soper (1972) have proposed on micropalaeontological grounds that the volcanic rocks north of the main Skiddaw Group outcrop (fig 1.3) and formerly thought to belong to the Borrowdale Volcanic group (e.g. Eastwood et al, 1968), are older (early Llanvirn). They were originally underlain and overlain by Skiddaw Group sediments and have been renamed the Eycott Volcanic Group. They consist of up to 2500 m of mainly basaltic and andesitic lavas, petrographically and chemically distinct from those of the Borrowdale Group. A small outcrop of the Eycott Group occurs at the northern end of the Cross Fell inlier (Fitton, 1971).

In the eastern Lake District tuffs and thin lava flows are interbedded with graptolitic mudstones of the D.bifidus zone (Wadge, 1972). These may be the lateral equivalent of the Eycott Group. Tuff bands also occur in the Skiddaw Group northwest of Ullswater (Moseley, 1964). In the Cross Fell inlier, mudstones of the D. Bifidus zone (Milburn Beds) are intercalated with tuffs and andesitic lava flows (Ingham and Wright, 1972). Mudstones higher in the Llanvirn of both the Lake District and Cross Fell are free of volcanogenic material, indicating a cessation of vulcanicity before the onset of the main Borrowdale Volcanic episode.

C. <u>The Junction of the Skiddaw and Borrowdale Volcanic Groups</u>.

For a substantial part of its length the contact is faulted. Both high angle faults and thrusts are seen, the latter interpreted by Moseley (1972) as décollement surfaces between the competent volcanic rocks and the incompetent slates. The traditional view (e.g. Ward, 1876) is that the junction was originally conformable, but a consensus is now being reached that the contact is, at least in part, an unconformity. However, the magnitude of the unconformity remains the subject of vigorous discussion. Three possibilities have been suggested by Moseley (1975) :

(1) an unconformity of orogenic proportions, with polyphase deformation and cleavage development in the Skiddaw Group prior to the emplacement of the Borrowdale Volcanic Group.

(2) a less important unconformity, with limited pre-volcanic deformation of the Skiddaw Group, resulting in an angular discordance in some areas, but apparent conformity in others.

(3) an essentially conformable passage, with local discordances caused by volcanic upheavals.

The traditional view has been opposed by those who argue for a major orogenic unconformity (e.g. Simpson, 1967; Helm, in discussion of Soper 1970). One of the main points of contention is the contrast between the severe polyphase deformation of the Skiddaw Group and the relatively simple structure of the overlying volcanic rocks. Helm believes the Skiddaw sediments underwent three phases of deformation, with cleavage development, before the main volcanic episode. Moseley (1972), however, contends that most of the deformation of the Skiddaw Group is post-volcanic, and that the difference in degree and style of deformation between the two Groups is largely related to their contrasting competence. Although much of the Skiddaw Group consists of strongly deformed, incompetent pelites, more competent, less deformed formations also occur. Conversely, highly deformed, incompetent horizons are found within the largely competent Borrowdale Volcanic Group, and some strongly deformed Silurian sediments are structurally comparable with the Skiddaw Group. Moseley favours an unconformity at the base of the volcanic pile, with some prior north-south folding of the largely unconsolidated Skiddaw Group. The northerly cleavage seen in some parts of the slate outcrop is thought to result from a later post-volcanic, pre-Coniston Group deformation, when the slates were at a deeper structural level; the remainder of the deformation took place during the end-Silurian orogeny.

Controversy also surrounds the contact at several localities where it is exposed. Interbedding of mudstones and mudstone conglomerates with volcanic rocks near the junction has been cited as evidence of conformity in Borrowdale and Black Combe (Soper, 1970) but Helm and Roberts (1971) claim that these interbeds lie within the basal Borrowdale Volcanic Group and are separated from the Skiddaw Group by a major unconformity, lying in unexposed ground. At other localities, an unconformity can undoubtedly be seen (Jeans, 1972; Wadge, 1972). In the eastern Lake District conglomerates (up to 130m thick in the Bampton inlier) occur low in the volcanic pile, but since they consist predominantly of volcanic clasts, they cannot be truly basal (Nutt, in discussion of Wadge, 1972). Wadge concluded that a major regional unconformity is present in the eastern Lake District, with evidence of pre-Borrowdale Group tectonic activity.

The distribution of faunas diagnostic of Arenig and Llanvirn graptolite zones has been used (Helm and Roberts, 1971; Wadge, 1972) to demonstrate the regional nature of the unconformity, truncating a pre-existing fold in the Skiddaw Group. However, the sparse occurrence of these faunas allows considerable ambiguity; whilst Helm and Roberts postulate a north-plunging anticline, Wadge suggests an eastward plunge, and concedes that the pattern might also be the result of faulting or thrusting.

Thus, although the argument has narrowed somewhat, there remains the question of whether the unconformity is an orogenic one, or whether orogeny, involving polyphase deformation and low grade metamorphism, only took place at the end of the Silurian. Moseley's (1972) hypothesis of an angular but non-orogenic unconformity reconciles, to some extent, the conflicting evidence put forward in favour of the two more extreme alternatives, and is preferred by the present writer.

D. The Coniston Limestone Group and Later Sedimentary Rocks.

The junction of the Borrowdale Volcanic Group with the overlying Coniston Limestone Group, not seen in the area covered by the present study, is much less controversial. It is an unconformity related to an important early Caradoc folding episode (Marr, 1916; Moseley, 1972), and is particularly pronounced to the southwest of Coniston, where the basal Coniston Group oversteps progressively southwards onto older units of the Borrowdale Group (Marr, 1916; Smith, 1924; Mitchell, 1954). Just north of Barrow-in-Furness, the Coniston Limestone Group comes to rest directly on the Skiddaw Group (Taylor et al, 1971).

The Coniston Group is up to 135 m thick in the Lake District, whilst thicker, more complete sections are seen in the Cross Fell and Cautley inliers (fig 1.4). Calcareous mudstones and siltstones predominate, with subordinate sandstones, conglomerates and impure, often nodular limestones. Shelly faunas, comprising brachiopods, corals, trilobites and bryozoans define stages which show up important unconformities within the Group (fig 1.5).

At several horizons within the Coniston Limestone Group, there is evidence that volcanism did not die out completely at the end of Borrowdale Volcanic times. In the eastern Lake District, for example, is the Stockdale (or Yarlside) Rhyolite, an acid lava flow up to 30 m thick (fig 1.5). In the Cautley inlier, the acid Cautley Volcanic Formation, of Rawtheyan age, is up to 24 m thick. A 5 m thick tuff bed in the Coniston area may be the lateral equivalent of this formation. Volcanogenic material is found throughout the sediments of the Coniston Limestone Group. (Stratigraphical information from Ingham and Wright, 1972).

Conformably overlying the Coniston Limestone Group is a thick (up to 5 km) succession of Silurian sandstones (including turbidites), siltstones and mudstones. These are separated from the Carboniferous and later rocks by a regional unconformity related to the end-Silurian orogeny.

E. Intrusions

Several large plutons, predominantly of acid composition, are intruded into the Lower Palaeozoic rocks of the Lake District. The Carrock Fell complex consists largely of gabbroic rocks. Minor intrusions range in composition from dolerite to microgranite, and some are associated with the plutons. Except for the Shap Granite, which intrudes Silurian rocks, and fragments of which are included in basal Carboniferous sediments, stratigraphical evidence for the age of the intrusions is lacking. However, the Carrock Fell Complex is older than the Skiddaw Granite, which metamorphoses it, and Fitton (1971) has proposed, on chemical grounds, that the Carrock Fell intrusion represents one of the magma chambers from which the Eycott Volcanic Group was erupted. Radiometric dating supports Harker's (1902) idea of two intrusive suites of different ages. It is suggested that the St. John's - Threlkeld Microgranite (Rb-Sr whole rock age: 445 ± 15m.y.)

(Wadge et al 1974) the Ennerdale Granophyre and the Carrock Fell Complex are of Ordovician age, whilst the Shap, Eskdale and Skiddaw Granites are end-Silurian (Soper, in discussion of Wadge et al, 1974). The individual intrusions of different ages are thought to belong to a composite batholith. A recent gravity survey has shown the existance of a negative Bouguer anomaly extending east-west across the Lake District, with minima associated with the exposed granites (Bott, 1974). From this evidence a composite WSW-ENE trending granitic batholith is inferred, connecting the exposed granites at shallow depth and extending to a depth of 7 - 10 km. Much of the Borrowdale and Skiddaw Groups are thought to be underlain by the roof region of the batholith, which has steeply sloping walls to north and south. To the west, the batholith probably terminates before reaching the coast, whilst to the east, the Shap intrusion may be connected to the Weardale Granite, underlying the Alston Block (Bott, 1974).

Several intrusions close to the present study areas warrant more detailed consideration, and their role as possible volcano sites will be discussed in a later chapter. The first is the St. John's - Threlkeld Microgranite, described by Ward (1876), Hadfield and Whiteside (1936) and Wadge et al (1974). Its three separate outcrops are probably all part of the same laccolith, intruded at the junction of the Skiddaw and Borrowdale Groups, with limited contact metamorphism. Phenocrysts of orthoclase, albite/oligoclaseand quartz are present, and the rock contains around 70% silica. The Armboth/Helvellyn dyke, exposed in the hills on either side of Thirlmere (Ward, 1876; Burton, 1969) is up to 10m wide, and is a pink two feldspar-quartz porphyry, similar in composition to the St. John's - Threlkeld intrusion , and probably related to it. Garnet is an accessory mineral in both intrusions.

At Castle Head, near Keswick, a stock of altered biotite-bearing dolerite, containing about 48% silica (Fitton, 1971) is intruded into the Skiddaw Group, north of its junction with the volcanic rocks. The dyke at nearby Friar's Crag is probably connected to the Castle Head intrusion.

F. Structure

(i) Tectonic History.

The structural history of the Lower Palaeozoic rocks of the Lake District is complex, and various conflicting hypotheses have been put forward. It is recognized, however, that deformation occurred during three major episodes:

(1) post-Skiddaw Group, pre-Borrowdale Volcanic Group

(2) post-Borrowdale Volcanic Group, pre-Coniston Limestone Group.

(3) end-Silurian: the main Caledonian orogeny

The unconformities resulting from (1) and (2) are discussed above. (3) is also represented by an unconformity: the youngest Lake District rocks affected by Caledonian deformation are the Downtonian Kirkby Moor Flags, whilst in the Cheviot Hills, undeformed volcanic rocks of probable Lower Devonian age rest unconformably on folded Silurian sediments. Most workers agree with Moseley (1972) that the end-Silurian episode was the most important, and resulted in polyphase deformation and cleavage formation, accompanied by lower greenschist facies metamorphism.

(ii) Structural Synthesis.

The following summary is based partly on Moseley's (1972) work. The Borrowdale Volcanic Group lies entirely on the southern limb of the Lake District anticlinorium, which has a WSW-ENE Caledonoid trend. The steep, sometimes vertical or overturned northern limb includes the

Eycott Volcanic Group, whilst the ill-defined axis of the fold lies within the main Skiddaw Group outcrop. The more gentle southern limb includes several large open folds (fig 1.7), which may have been initiated in pre-Caradoc times (Soper and Numan, 1974). Minor folds are uncommon in the Borrowdale Volcanic Group, and only one cleavage is usually present, whereas two are commonly seen in the Skiddaw Group. Cleavage intensity is closely related to lithology: it is strongest in fine grained tuffs, and weakest in resistant lavas and ignimbrites.

Due to their brittle nature, the volcanic rocks have a complex history of faulting. Thrusts occur near the base and top of the pile, but high angle faults are common throughout. These are predominantly wrench faults trending between northwest and north, with lateral displacements of up to a mile, but generally much less; corresponding joint sets have been observed. Some faults were involved in normal movement during late Caledonian and subsequent tectonic events. Wide shatter belts are associated with the larger faults, such as the fault which crosses the entire volcanic pile from the Skiddaw Group of St. John's Vale in the north to the Silurian of the Coniston area in the south (Moseley, 1972) (fig 1.7), passing through the present author's Thirlmere study area.

IV. HISTORY OF RESEARCH ON THE BORROWDALE VOLCANIC GROUP.

Jonathan Otley (1820, 1827) first recognized the tripartite division of the Lower Palaeozoic rocks of Lakeland, which he named as follows:

3. Greywacke Division (= Coniston Limestone Group and Silurian)
2. Greenstone Division (= Borrowdale Volcanic Group).
1. Clayslate Division (= Skiddaw Group)

(resting on a granitic basement).

He noted the igneous nature of parts of the Greenstone Division, and distinguished bedding and cleavage in the "roofing slates" of this group. Otley also described the occurrence of garnets, the red breccia near the base of the Division in Borrowdale, and the Armboth Dyke.

Sedgwick (1832, 1848, 1852, 1853) used various names for Otley's Greenstone Division, including "Green Slate and Porphyry" and "Cumbrian Slate Group". He clearly recognized lavas ("plutonic rocks poured out under a deep sea") with associated mechanical breccias akin to those of modern lava flows, and volcanogenic sediments ("quartzose and chloritic roofing slates ... fine aqueous sediment, chiefly derived from erupted matter"). Sedgwick explained the alternation of these lithologies by "the simultaneous action of aqueous and igneous causes long continued." His estimate of the thickness of the volcanic pile as 20,000 to 30,000 feet (6 - 9 km) is remarkably accurate. Sedgwick thought these rocks to be coeval with the "slates and porphyries" of North Wales.

J. C. Ward (1875, 1876) was responsible for the first detailed mapping and petrography of the "Volcanic Series of Borrowdale" (renamed by Nicholson, 1870). The present investigations have shown Ward's field mapping and structural interpretations of the Borrowdale-Thirlmere area to be reliable. He recognized lava flows of intermediate composition with brecciated and vesicular tops and bases, comparing them with lava flows on Vesuvius. His meticulous descriptions of "altered ash rocks" and "felstone-like rocks" enable identification of many of them as welded tuffs, and he reported cross bedding and conglomeratic beds within deposits of "stratified ash". Ward concluded that the vulcanicity was predominantly subaerial, with an initial submarine phase.

He compared some of the bedded tuffs with those of La Solfatara, near Naples, and suggested that they were deposited subaerially or into standing bodies of water. The Castle Head intrusion was thought to represent an important volcanic centre.

Dakyns et al (1897) mapped the eastern part of the volcanic outcrop, and were the first to apply the term "andesite" to the intermediate lavas. Walker (1904) thought the streaky texture of many of the garnetiferous rocks (now identified as welded tuffs) to be the result of alteration, and the garnets to be metamorphic. A cordierite-bearing lava was described by Harker (1906).

The penecontemporaneous nature of small scale faulting in the volcanic "slates" was first recognized by Lomas (1904), who related it to the compaction of ash deposits. The sedimentology of the Langdale "slates" was covered in some depth by Sorby (1908). He concluded that some of the graded beds were deposited by short-lived currents generated by volcanic disturbances. From detailed measurements of ripple-drift lamination, he worked out current velocities and rates of deposition. Other beds he thought to be the result of volcanic ash settling through water. From the degree of disturbance at the bases of some beds, Sorby deduced that depositional events were often separated by only a short interval of time. Much earlier (Sorby, 1880) he had suggested the primary origin of garnets in the volcanic rocks, and recognized pumice.

Postlethwaite (1913) summarized the geology of the volcanic rocks, and postulated several centres of eruption, including one near Ambleside and another at the south end of Thirlmere. He envisaged a large composite subaerial volcano, similar in size to Etna. A more comprehensive summary was made by Marr (1916) who erected a volcanic stratigraphy, recognized rocks ranging from basic andesite to rhyolite, and described "birds' eye slates" (accretionary lapilli tuffs).

Detailed mapping of parts of the volcanic pile was started by J.F.N. Green (1912), who coined the term "Borrowdale Volcanic Series". Despite serious structural misinterpretations, Green (1912, 1917, 1919, 1920) made major contributions to the understanding of the volcanic rocks. He recognized lavas and penecontemporanous intrusions which had interacted with wet sediments, and distinguished "explosion tuffs" (citing the "Purple Breccia" as an example) from "detrital tuffs". He believed most of the pile to be submarine, explaining the wide lateral extent of many lava flows as the result of retention of volatiles under high hydrostatic pressures.

The mapping and description of large areas of the Borrowdale Volcanic "Series" was continued over the next forty years by J. J. Hartley and G. H. Mitchell. Hartley (1925, 1932, 1941) followed Green in interpreting lenticular units as isoclinal folds, and thus grossly underestimated the thickness of the pile. In autobrecciated andesite flows, he noted the incorporation of bedded tuff blocks in the bases of some, and bedded tuff infilling fissures at the tops of others. He distinguished vitroclastic and crystal tuffs, and interpreted graded beds with loaded bases as the result of ash falls through water, but misidentified slumped horizons as tectonic drag folds. Hartley described the occurrence of shallow, penecontemporaneous, intrusive sheets of rhyolite in the Langdale and Thirlmere areas, many of which would now be recognized as extrusive welded tuffs. Although he thought much of the vulcanicity to be submarine, Hartley noted the absence of pillow lavas and the presence of cross-bedding and erosion channels as evidence of the emergence of some areas.

Hadfield and Whiteside (1936) looked in detail at the petrography, geochemistry and field relations of the andesitic lavas and adjacent microgranite intrusion north of Thirlmere. They attributed most of the alteration, including the formation of the garnets in the volcanic rocks, to hydrothermal processes, and thought the garnets in the intrusion to be derived from volcanic xenoliths.

Mitchell (1929, 1934, 1940, 1954, 1963) mapped large areas in the eastern and southwestern parts of the outcrop, and later summarized his work (1956, 1957). He realised in his later papers that the structure was far simpler than originally supposed by Green, Hartley and himself. He made a close study of flow-brecciated lavas, and distinguished those with a matrix of chilled lava from those with interstices filled by fragmental material; he recognized that the nature and extent of the flow brecciation depended on various properties of the lava, including viscosity, velocity, degree of solidification, rate of cooling, thickness and gas content, as well as on the shape of the ground surface. Red flow breccias were thought to be indicative of subaerial weathering. Mitchell (1929) was the first to recognize the occurrence of "palagonite tuffs", and the only worker to find evidence of life in the Borrowdale Volcanic Group; "animal tracks" (possibly of arthropods) in bedded tuffs southwest of Coniston. He thought the volcanic pile to be largely subaerial. In the Kentmere area, he mapped several rhyolite plugs, one of them approximately 500 x 300m, whilst in Upper Dunnerdale he described two large breccia-filled vents, the larger being more than 1100 m long.

The succession and structure of the Western Dunnerdale - Wasdale area was elucidated by Firman (1957), who concluded that the thick development of largely subaerial rocks was derived mainly from the southwest. He thought the garnets in the lavas and tuffs to be xenocrysts, formed by thermal metamorphism of the Skiddaw Slate wall rock of magma chambers and vents.

R. L. Oliver (1953, 1954a & b, 1956, 1961) made an exhaustive field, geochemical and mineralogical study of a large area of the central Borrowdale Volcanic "Series". He recognized the ignimbritic origin of many of the Lake District acid rocks, noting close similarities with welded tuffs from New Zealand. (An earlier suggestion of welded tuffs in the Lake District, based only on Green's written account, had been made by Marshall in 1935). Oliver adduced much field, microscopic and chemical evidence for the almandine-pyrope garnets being phenocrystic, and linked changes in garnet chemistry with the composition of the containing rock. Cordierite of probable primary origin was also observed. Oliver related alteration of the volcanic rocks, including albitization, potassium-metasomatism and epidotisation to the intrusion of the Eskdale Granite. His chemical work,covering both major and trace elements, indicated the calc-alkaline affinities of the Borrowdale Volcanic rocks.

Important contributions to the primary and secondary mineralogy of the andesitic rocks of Borrowdale were made by Strens (1962, 1964), who suggested that most of the alteration was late magmatic or deuteric. He thought the metamorphic grade during this alteration to have been considerably higher than that for the later regional metamorphism, and from consideration of several reactions he proposed temperatures from 250 to 550°C, at depths of up to 1 km. He thought the magmas to be derived from partial or complete fusion of mantle material.

The traditional approach to the mapping and stratigraphy of the Group was continued by Moseley (1960, 1964) and Clark (1964) in the Ullswater and Buttermere-Wasdale areas respectively. Konig (1964) studied the sedimentology, alteration and structural petrology of some of the volcanic rocks, particularly in the Coniston-Kentmere area. He worked mainly on Green's "Middle Tuffs" which almost certainly represent a number of different units both above and below the Airy's Bridge "Group" (fig 1.8), thus rendering most of his palaeogeographical conclusions invalid. Konig recognized ashfall deposits and unwelded ignimbrites, and suggested that some graded beds were turbidites. On dubious sedimentological grounds, he interpreted beach, lacustrine, tidal flat, deltaic, deep water and other sedimentary environments. He thought accretionary lapilli to result from "mud pellet rains" associated with eruptions, noted "auto-intrusion" in wet sediments and recognized the secondary nature of much of the fine-grained matrix of the tuffs. An island arc environment, comparable with that of Sumatra and Java, was thought to be the nearest modern analogue.

The Haweswater area was described by Nutt (1966, 1968, 1970), who observed zoned ignimbrite units with unwelded bases and nodular horizons and thought some ignimbrites to pass laterally into subaqueous bedded tuffs. He proposed rapid accumulation of lavas and volcaniclastics in a predominantly subaerial environment. An important contribution was his identification of rapid lateral facies changes across faults which must have been active during the volcanicity. He recognized several crude volcanic cycles:

acid rocks (mainly ignimbrites)

andesitic lavas

coarse andesitic ashfall tuffs

which he thought reminiscent of sequences in modern island arcs.

From a consideration of the major and trace element chemistry of the calc-alkaline Borrowdale Group (particularly of its garnets) and the transitional tholeiitic/calc-alkaline Eycott Group, Fitton (1971, 1972) proposed models for the evolution of the respective magmas. He thought both to result from the partial melting of oceanic crust along a southward-dipping subduction zone associated with the closing of the proto-Atlantic Ocean (Fitton and Hughes, 1970).

The Borrowdale Group magmas were generated by partial melting at depth (maximum 250 km) and the magma stored in reservoirs at about 30 km depth, allowing the fractionation of zoned garnet; rapid transport to the surface then facilitated the preservation of the garnet. Fitton thought the Eycott Group magmas to be produced by partial melting at higher levels, and stored in relatively shallow magma chambers, permitting extensive fractional crystallization. He suggested that the Carrock Fell Complex represented one such magma chamber.

The Kentmere area was recently remapped by Soper and Numan (1974). They described serpentinized olivine from a dacite, and crude pillow lavas of andesitic and dacitic composition. In two unpublished manuscripts S.M.Smith (pers.comm.) postulated a north-south intravolcanic axis of uplift through the Langdale area, separating two distinct volcanic successions. Subsidence to the east of this structure was thought to have created a basin in which the Langdale Tuffs were deposited.

A recent bibliography of Lake District geology (R. A. Smith, 1975) has proved useful in compiling this review.

V. LATITUDE AND CLIMATE OF NORTHERN ENGLAND DURING THE ORDOVICIAN PERIOD.

It is possible from the published palaeomagnetic data to obtain some indication of the position of the Lake District during the emplacement of the Borrowdale Volcanic Group. The map of Smith et al (1973) for the Cambrian/Lower Ordovician shows northern England at a latitude of about 25°S, whilst that for the Lower Devonian shows a slightly lower latitude, around 23°S. The Lake District therefore lay around 23 - 25°S during the eruption of the Borrowdale Volcanic pile.

Spjeldnaes (1976) has suggested that pronounced climatic zoning, with the presence of polar ice caps, obtained during most of the Ordovician period.

If the distribution of Ordovician climatic zones was similar to that of the present time (Debenham, 1962), Northern England would have had a warm, tropical to subtropical climate, possibly with heavy seasonal rainfall, and may well have been affected by the southeast trade winds.

FIGURE 1.1 Locality Map of the Lake District

KEY:

Place Names

A	Ambleside
B	Barrow-in-Furness
C	Coniston
DM	Dunmail Raise
G	Grasmere
H	Helvellyn
K	Keswick
Kl	Kendal
KP	Kirkstone Pass
M	Maryport
P	Penrith
Sh	Shap Fells
Sk	Skiddaw
SP	Scafell Pikes
T	Threlkeld
W	Workington
Wh	Whitehaven
Wm	Windermere

Lakes

b	Buttermere
bl	Bassenthwaite Lake
c	Crummock Water
cw	Coniston Water
d	Derwent Water
e	Ennerdale Water
h	Haweswater
l	Loweswater
r	Rydal Water
th	Thirlmere
u	Ullswater
w	Windermere
ws	Wet Sleddale Reservoir
ww	Wastwater

Inset Map: the black shading indicates the area covered by the larger map

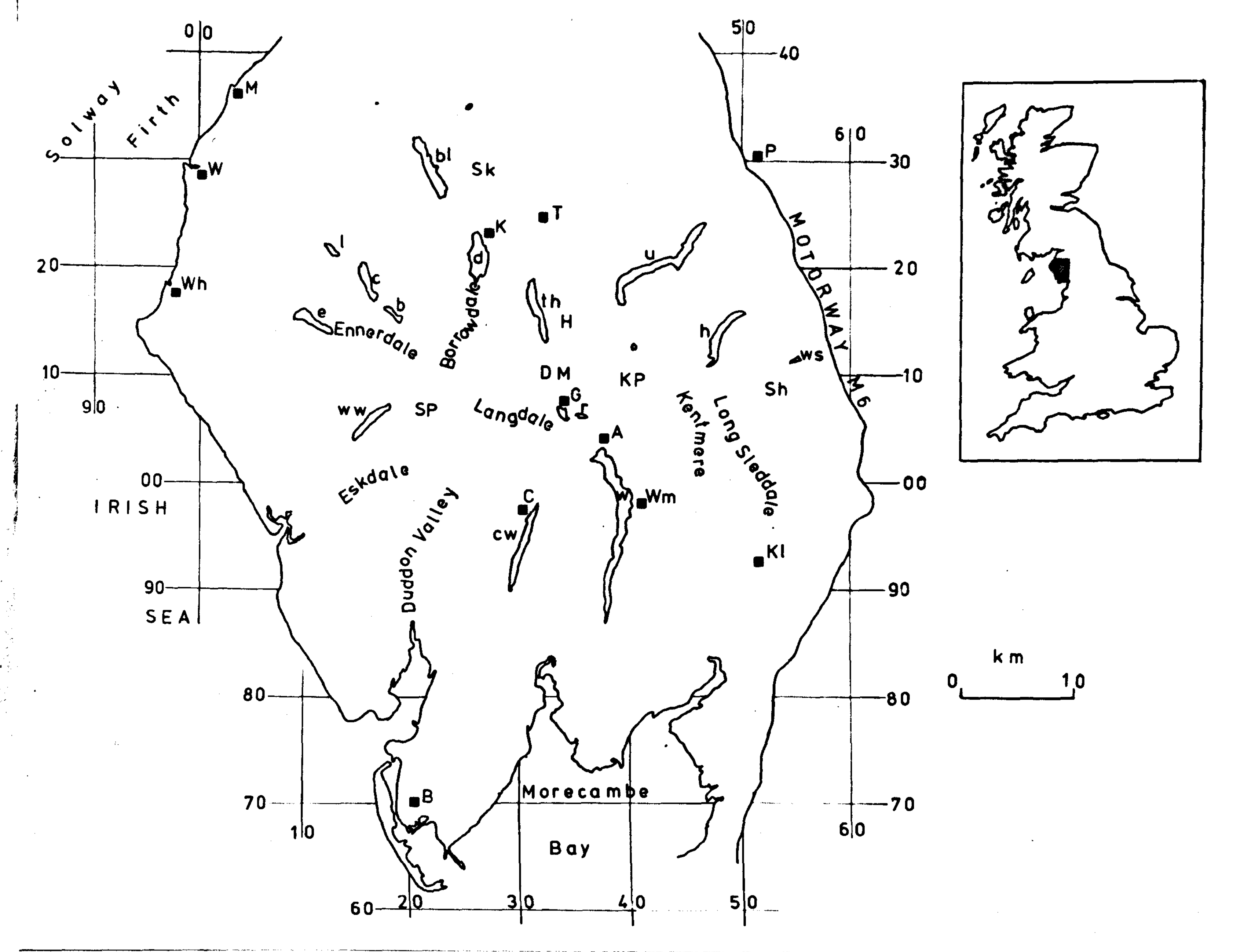

Solway Firth
IRISH SEA
Morecambe Bay
MOTORWAY M6
Ennerdale
Borrowdale
Langdale
Eskdale
Duddon Valley
Kentmere
Long Sleddale
M
W
Wh
bl
Sk
K
T
d
l
c
b
e
th
H
u
h
ws
DM
KP
Sh
G
ww
SP
A
C
cw
Wm
Kl
B
P
km
0
10

FIGURE 1.2

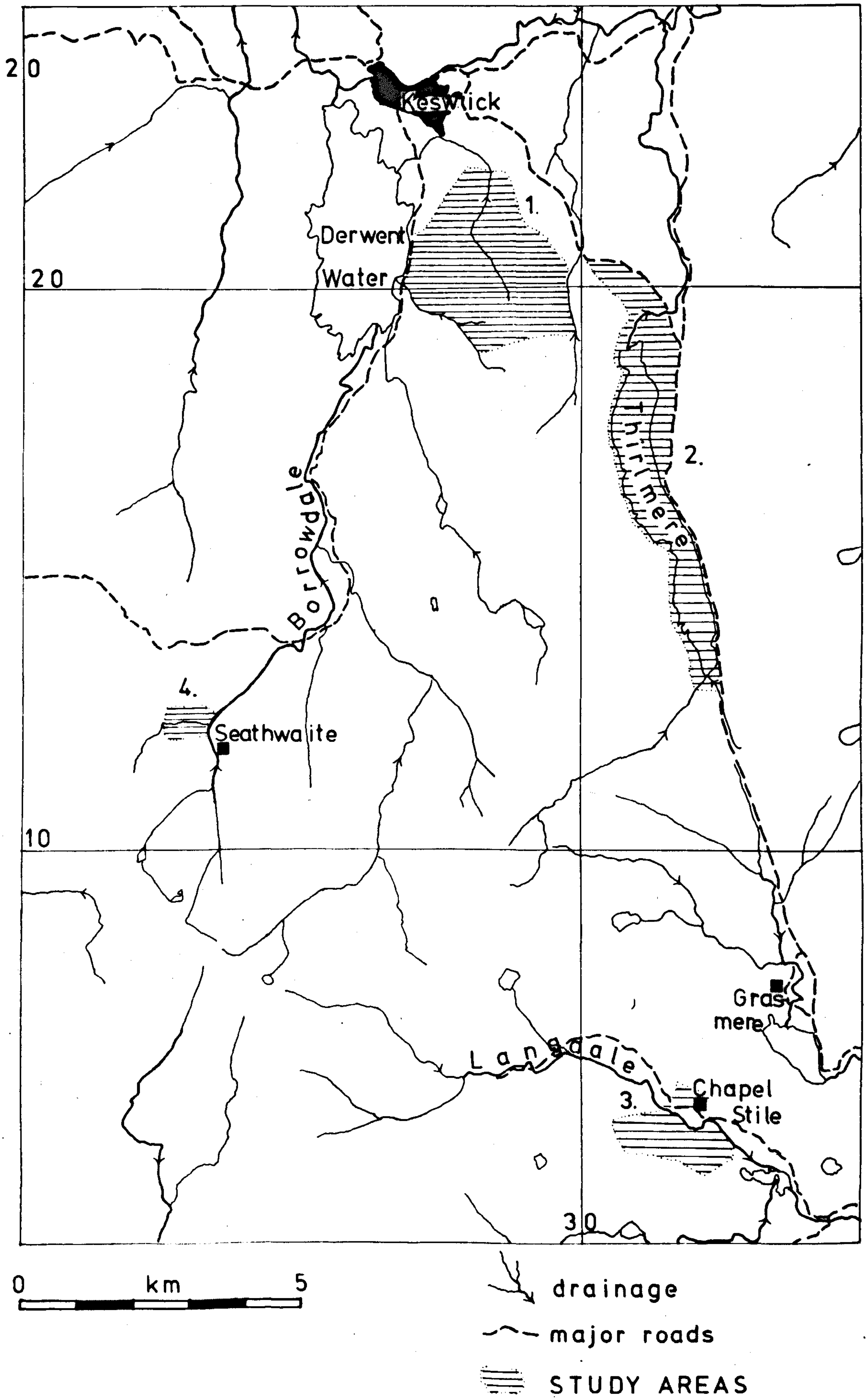
Locality map of the central Lake District, showing the four areas studied.

1. Brown Knotts - Bleaberry Fell area

2. Thirlmere area.

3. Chapel Stile - Elterwater area.

4. Sour Milk Gill area.



20
Keswick
1.
Derwent
Water
20
Thirlmere
2.
Borrowdale
4.
Seathwaite
10
Grasmere
Langdale
3.
Chapel
Stile
30
0
km
5
drainage
major roads
STUDY AREAS

FIGURE 1.3

Geological Map of the Lake District, after Geological Survey
¼ inch sheets
4, 5 and 6. (1907 & 1959)

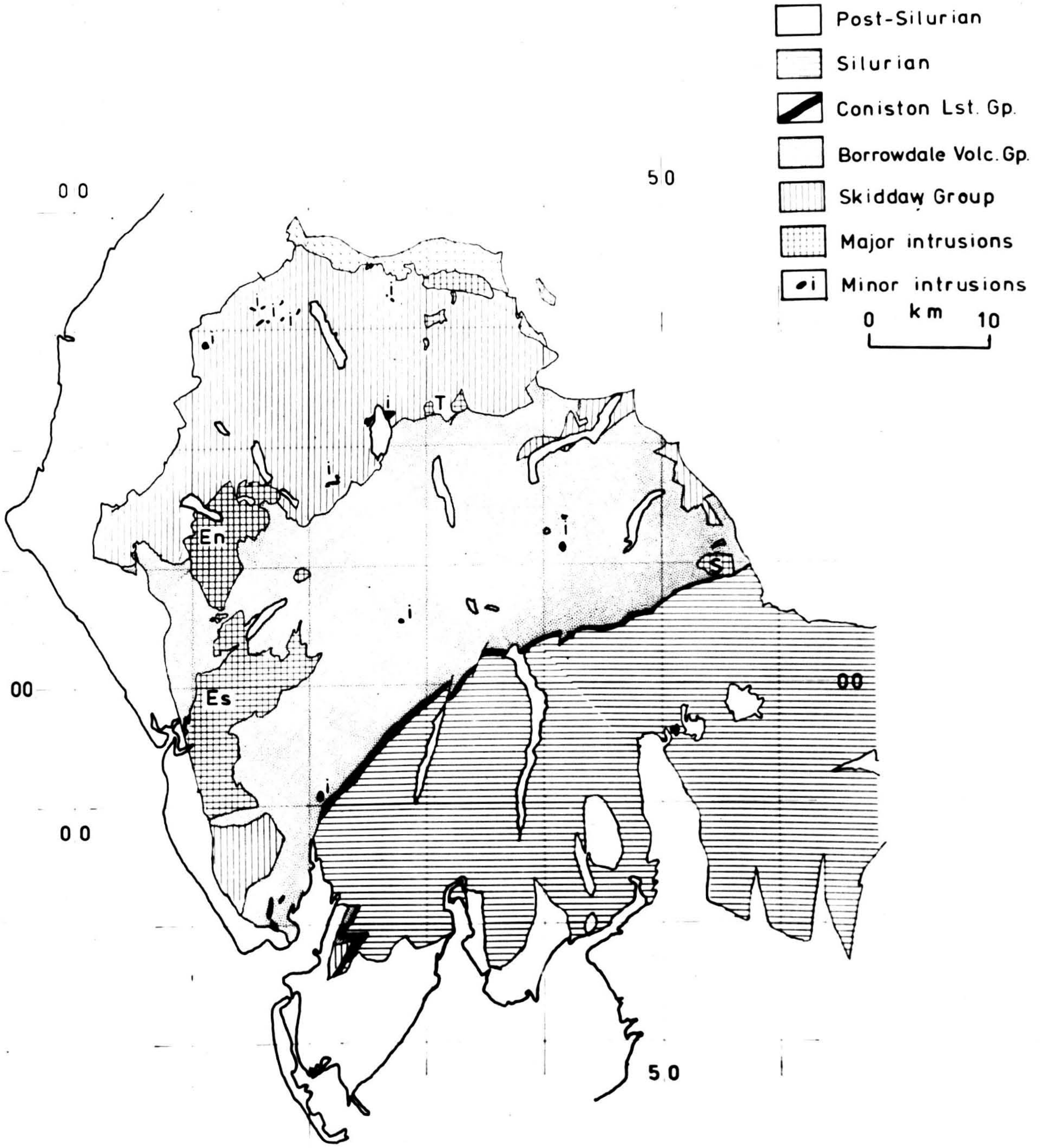
En - Ennerdale Granophyre;

Es - Eskdale Granite

S - Shap Granite

T - St. John's - Threlkeld Microgranite.

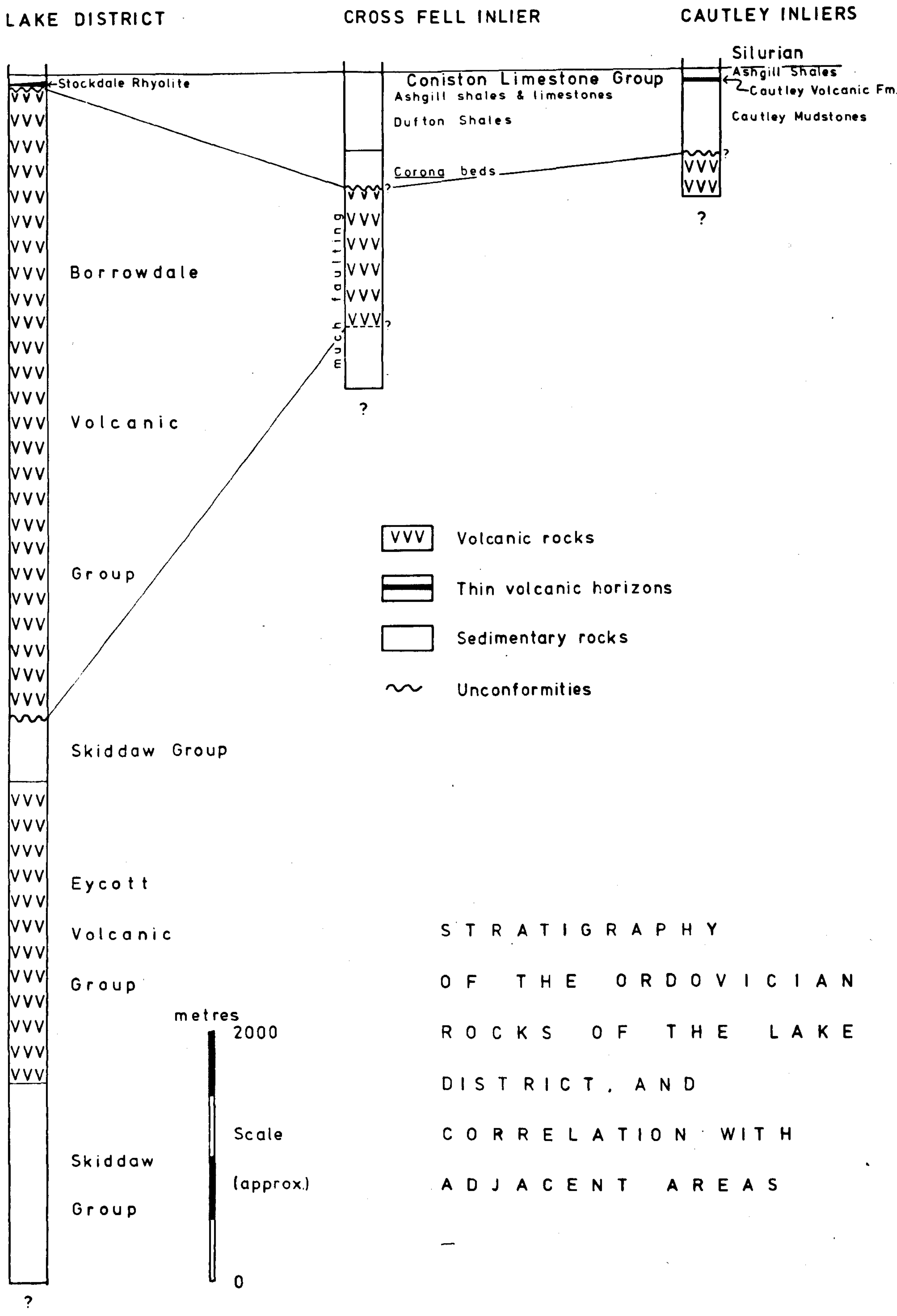
vvv - Eycott Volcanic Group



Post-Silurian
Silurian
Coniston Lst. Gp.
Borrowdale Volc. Gp.
Skiddaw Group
Major intrusions
i Minor intrusions
0 km 10
00
50
En
Es
T
S
i
00
00
50

FIGURE 1.4

Stratigraphy of the Ordovician rocks of the Lake District, and correlation with adjacent areas.



STRATIGRAPHY OF THE ORDOVICIAN ROCKS OF THE LAKE DISTRICT, AND CORRELATION WITH ADJACENT AREAS

FIGURE 1.5

Stratigraphy of the Ordovician rocks of the Lake District.

Not to scale. Thickness variations are not shown.

Dashed lines indicate uncertainty. After Ingham and Wright (1976) and Taylor et al (1971).

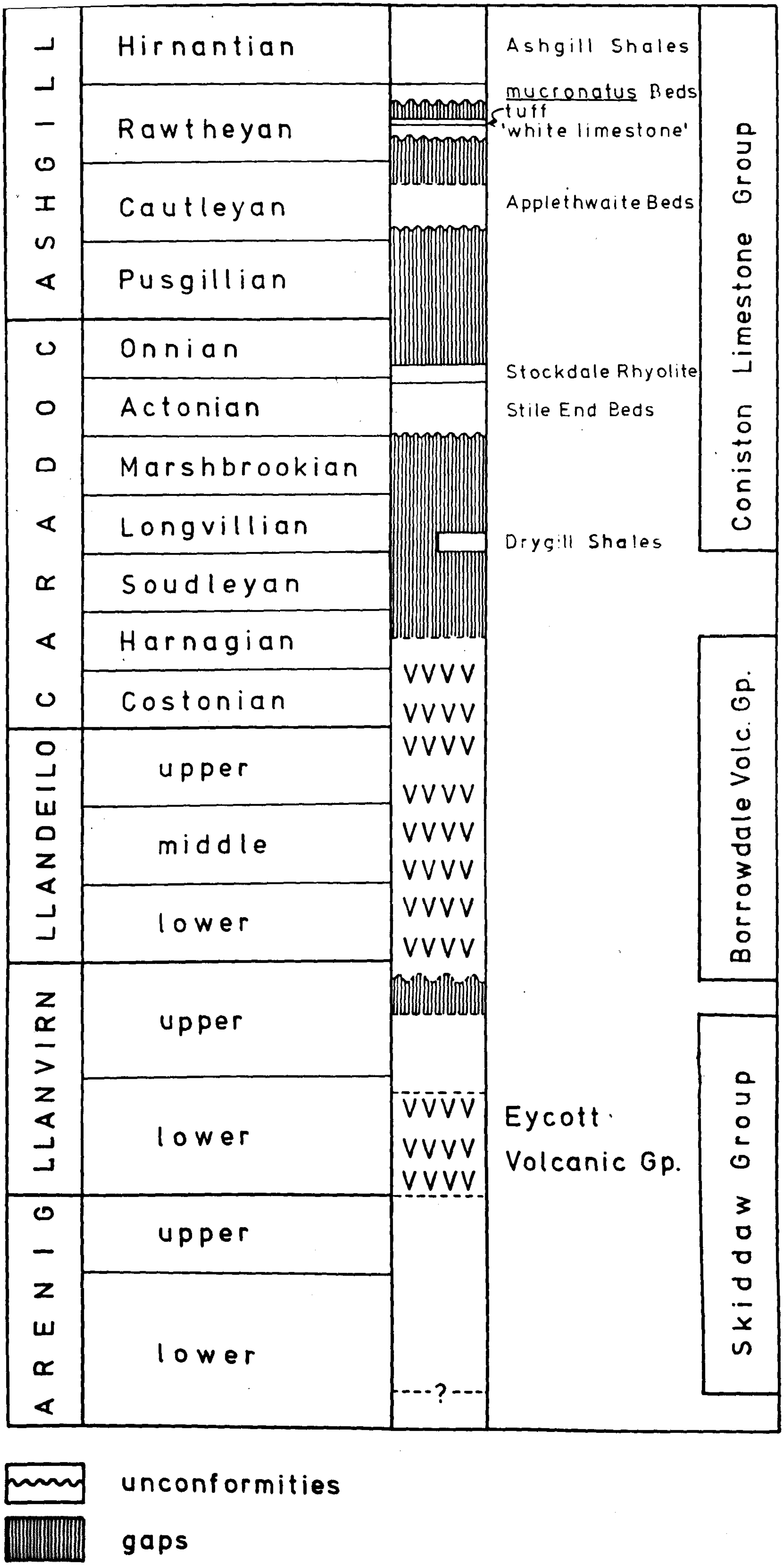

ASHGILL
Hirnantian
Rawtheyan
Cautleyan
Pusgillian
CARADOC
Onnian
Actonian
Marshbrookian
Longvillian
Soudleyan
Harnagian
Costonian
LLANDEILO
upper
middle
lower
LLANVIRN
upper
lower
ARENIG
upper
lower
Ashgill Shales
mucronatus Beds
tuff
'white limestone'
Applethwaite Beds
Stockdale Rhyolite
Stile End Beds
Drygill Shales
Eycott Volcanic Gp.
Coniston Limestone Group
Borrowdale Volc. Gp.
Skiddaw Group
unconformities
gaps

FIGURE 1.6

The stratigraphy of the British Ordovician, showing the correlation of shelly fossil stages with graptolite zones. The diagram is after Williams et al. (1976); radiometric age data from Harland et al.(1964, 1971) (d, e, f), Phillips et al. (1976) (a, c, g, i) and Fitch et al. (1976) (b, h, j) has been added.

a. Date quoted for the end of the Ordovician.

b. A rough estimate for the age of the Ordovician/Silurian boundary, based on the data below, plus the ages of late Caledonian granites thought to be intruded in Silurian times, which have an average Rb-Sr isochron age of 435 m.y.

c. Date quoted for the boundary of the upper and lower Caradoc.

d. K-Ar date on biotite from a mica-andesite in the Bail Hill Volcanics, Dumfriesshire.

e. ^{238}U-^{206}Pb date on zircons from a bentonite in the Carter's Limestone of Tennessee, U.S.A. An Rb-Sr date on biotite from the same horizon is 447 ± 7 m.y.

f. K-Ar dates on biotite and sanidine from bentonites in the Chasmops Limestone, Kinnekulle, Västergötland, Sweden.

g. Date quoted for Lower Caradocian.

h. The maximum age suggested for the base of the Caradocian, based on:

(i) a date of 477 ± 7 m.y. from Ingletonian slates underlying Caradoc/Ashgill shales at Horton-in-Ribblesdale, Yorkshire (Rb-Sr whole rock age),

(ii) a gabbro in Ayrshire, which is post-middle Arenig and pre-lower Caradoc, and gives a K-Ar biotite age of 475 ± 24 m.y.

(iii) the Newer Gabbros of Aberdeenshire, which are in trusive into the Macduff Slates (containing microfossils of probable Llanvirn/Llandeilo age) and give concordant Rb-Sr and K-Ar isochrons around 470 m.y. (from both minerals and whole rocks)

i. Suggested age for the Arenig.

j. Maximum age for the Cambro-Ordovician boundary, based on the age of a basic intrusion in Connemara, emplaced towards the end of the high-grade M_1 Dalradian metamorphism, which is thought to predate the deposition of the D. bifidus zone. (U-Pb date from zircons).

All Rb-Sr ages have been standardized, using the 4.7 x 10^{10} yrs. half-life for ^{87}Rb.

Broken lines indicate uncertainty. The bracket associated with a radiometric date shows the stratigraphical range within which the dated rocks lie.

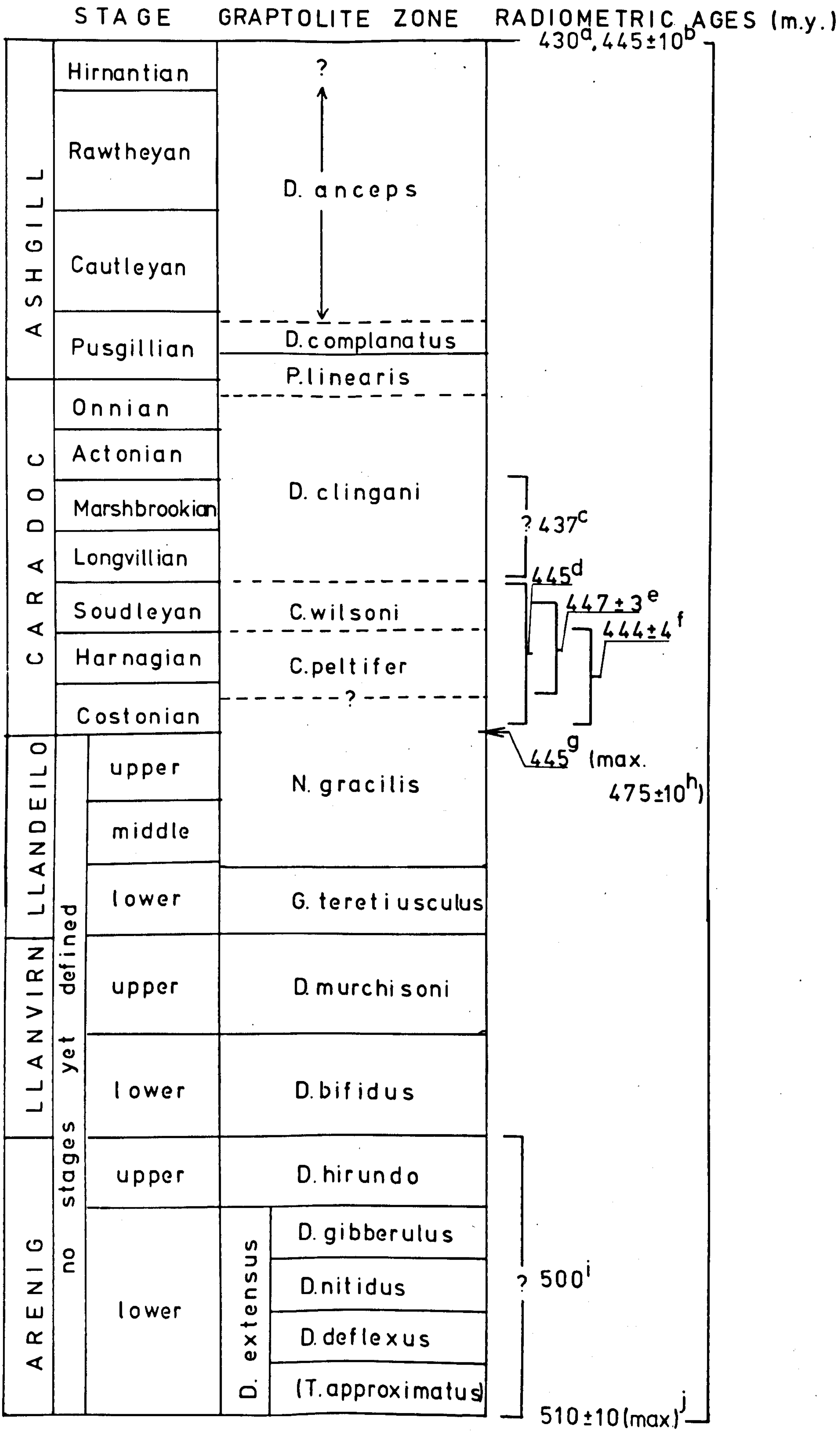
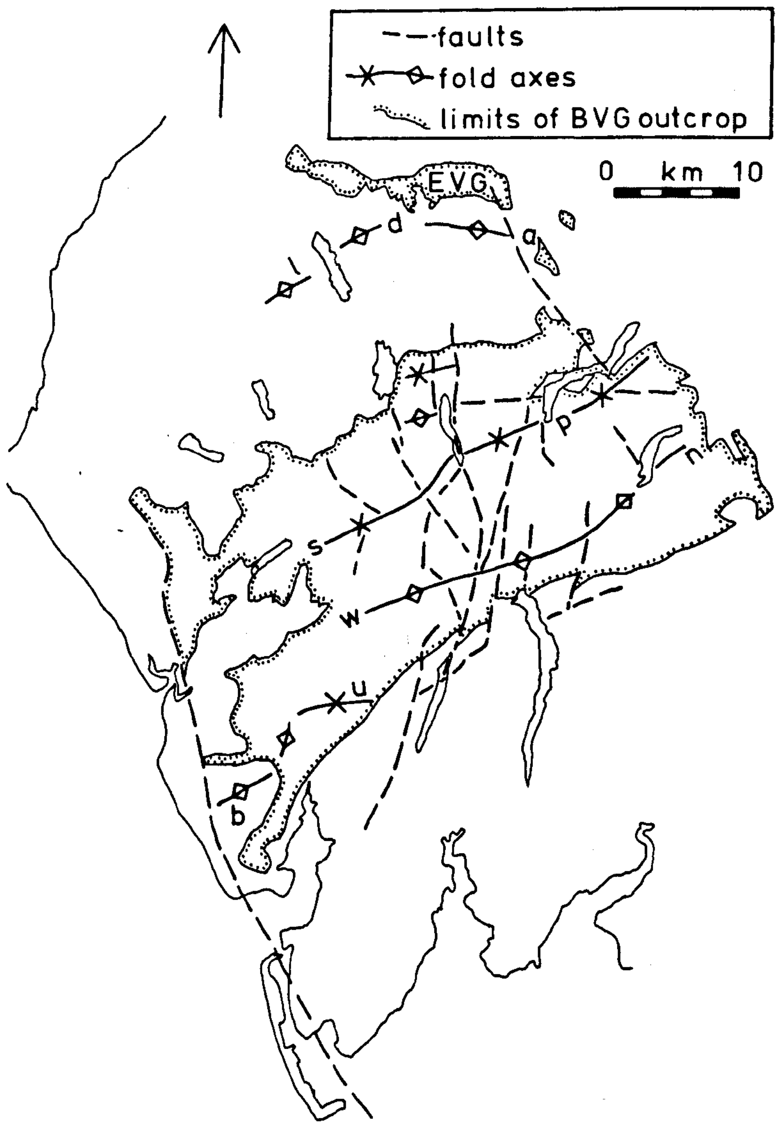

STAGE
GRAPTOLITE ZONE
RADIOMETRIC AGES (m.y.)
ASHGILL
CARADOC
LLANDEILO
LLANVIRN
ARENIG
Hirnantian
Rawtheyan
Cautleyan
Pusgillian
Onnian
Actonian
Marshbrookian
Longvillian
Soudleyan
Harnagian
Costonian
upper
middle
lower
upper
lower
upper
lower
no stages yet defined
?
D. anceps
D. complanatus
P. linearis
D. clingani
C. wilsoni
C. peltifer
?
N. gracilis
G. teretiusculus
D. murchisoni
D. bifidus
D. hirundo
D. extensus
D. gibberulus
D. nitidus
D. deflexus
(T. approximatus)
430a, 445±10b
? 437c
445d
447±3e
444±4f
445g (max. 475±10h)
? 500i
510±10 (max)j

FIGURE 1.7

Major Structures in the Borrowdale Volcanic Group

After Moseley (1972) and Soper and Numan (1974). Many faults are omitted for reasons of clarity.

l - d - a	Axis of Lake District Anticlinorium
s - p	Scafell - Place Fell Syncline
w - n	Wrynose - Nan Bield Anticline
u	Ulpha Syncline
b	Black Combe Anticline
EVG	Eycott Volcanic Group



faults
fold axes
limits of BVG outcrop
0 km 10
EVG
d
a
p
n
s
w
u
b

FIGURE 1.8

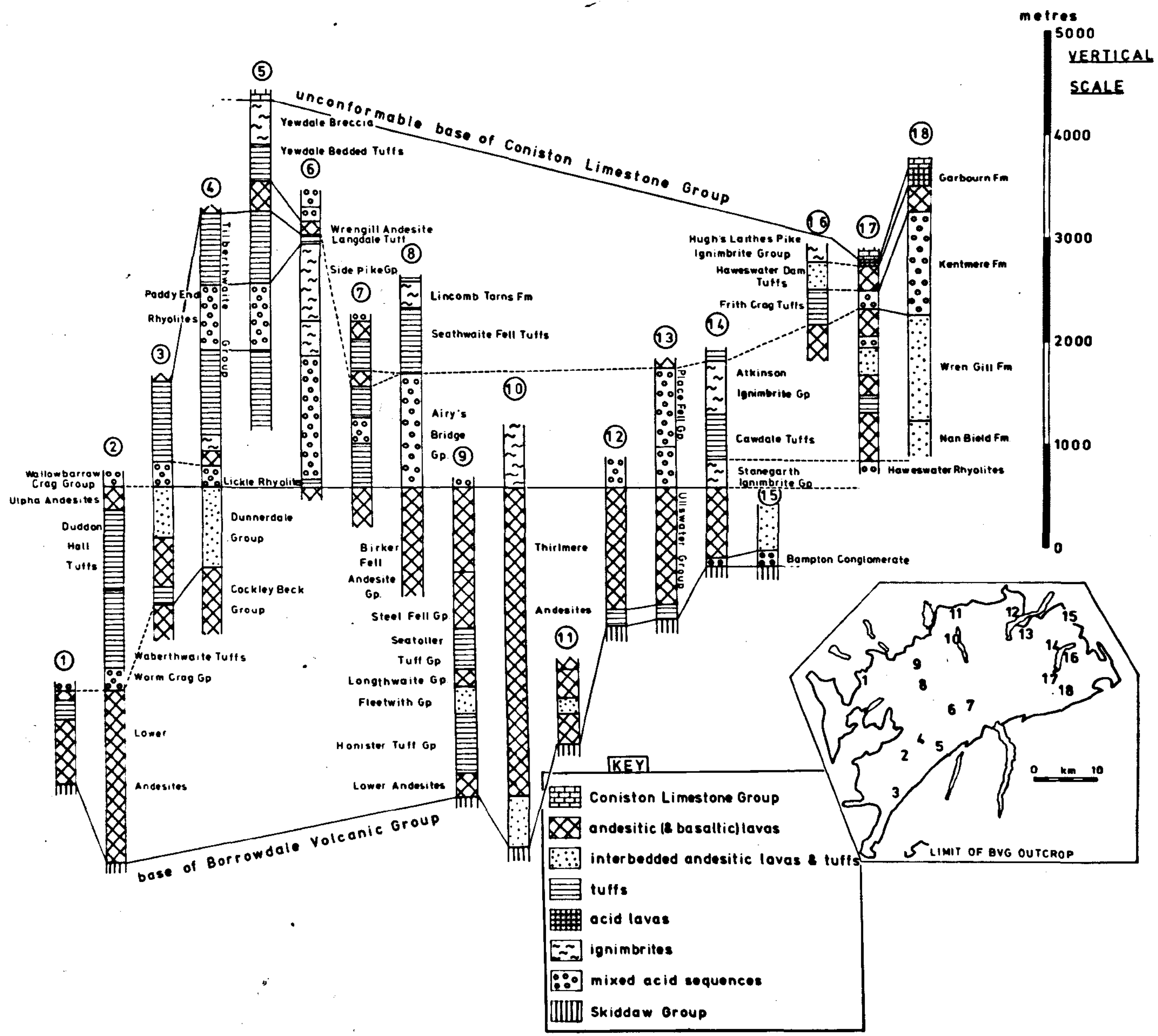
Lithostratigraphical Correlation of Sections in the Borrowdale Volcanic Group

The base of the Airy's Bridge Group and its probable correlatives is used as a datum, since it is the most important marker horizon, and approximates to a time plane (see text for discussion). In each unit shown, the predominant lithology is indicated. "Mixed acid sequences" include lavas, tuffs and ignimbrites. Many unit names are omitted for reasons of clarity. The sections of some earlier workers (e.g. Green) are omitted because they depend on erroneous structural interpretations. The contact with the underlying Skiddaw Group is shown only where it is unfaulted, or where the relevant author believes it to be close to the original junction. Dashed lines indicate uncertainty.

Sections:

1. Buttermere - Wasdale (Clark, 1964)
2. Wasdale - Dunnerdale (Firman, 1957)
3. Dunnerdale (Mitchell, 1954)
4. Seathwaite Fells (Mitchell, 1963)
5. Coniston (Mitchell, 1940 and Suthren, 1973)
6. Central Langdale (S.M. Smith, unpublished)
7. Coniston - Thirlmere (Hartley, 1925, 1932, 1941)
8. Scafell (Oliver, 1961)
9. Borrowdale (Strens, 1962)
10. Borrowdale - Thirlmere (present account)
11. High Rigg (Hadfield & Whiteside, 1936)
12. Northwest of Ullswater (Moseley, 1964)
13. Southeast of Ullswater (Moseley, 1960)
14. North of Haweswater (Nutt, 1970)
15. Tarn Moor Tunnel (Wadge et al, 1972)
16. Southeast of Haweswater (Nutt, 1970)
17. Haweswater - Long Sleddale (Mitchell, 1929 & Nutt, 1970)
18. Kentmere - Long Sleddale (Soper & Numan, 1974)

Inset map shows the location of sections within the outcrop of the Borrowdale Volcanic Group.



metres
5000
VERTICAL SCALE
4000
3000
2000
1000
0
unconformable base of Coniston Limestone Group
base of Borrowdale Volcanic Group
Yewdale Breccia
Yewdale Bedded Tuffs
Wrengill Andesite
Langdale Tuff
Side Pike Gp
Lincomb Tarns Fm
Seathwaite Fell Tuffs
Paddy End Rhyolites
Tilberthwaite Group
Airy's Bridge Gp.
Wallowbarrow Crag Group
Ulpha Andesites
Lickle Rhyolite
Duddon Hall Tuffs
Dunnerdale Group
Cockley Beck Group
Waberthwaite Tuffs
Worm Crag Gp
Lower Andesites
Birker Fell Andesite Gp.
Steel Fell Gp
Seatoller Tuff Gp
Longthwaite Gp
Fleetwith Gp
Honister Tuff Gp
Lower Andesites
Thirlmere Andesites
Place Fell Gp
Ullswater Group
Atkinson Ignimbrite Gp
Cawdale Tuffs
Stanegarth Ignimbrite Gp
Bampton Conglomerate
Hugh's Laithes Pike Ignimbrite Group
Haweswater Dam Tuffs
Frith Crag Tuffs
Haweswater Rhyolites
Garbourn Fm
Kentmere Fm
Wren Gill Fm
Nan Bield Fm
KEY
Coniston Limestone Group
andesitic (& basaltic) lavas
interbedded andesitic lavas & tuffs
tuffs
acid lavas
ignimbrites
mixed acid sequences
Skiddaw Group
0 km 10
LIMIT OF BVG OUTCROP

I.

CHAPTER 2. THE CLASSIFICATION AND NOMENCLATURE OF VOLCANIC PROCESSES AND PRODUCTS

I. LAVAS AND MINOR INTRUSIVE ROCKS

Since Fitton's (1971) classification of calk-alkaline lavas (Figure 2.1) was devised specifically for the Borrowdale Volcanic Group, it has also been employed by the present author. It has been used to describe minor intrusive rocks as well as lava flows. The classification is based on silica content, but the compositional limits of some rock types also coincide with the appearance and disappearance of certain phenocryst phases (Fitton, 1971). Thus, the phenocryst assemblage of some rocks can be used as a tentative guide to their chemical composition. The silica percentages which Fitton chose to delimit the various rock types differ slightly from those of other authors. "Andesite" is also used as a more general field term for intermediate rocks which include some basaltic andesites.

II. VOLCANICLASTIC ROCKS

Various schemes have been erected to describe the grain size of volcaniclastic rocks (e.g. Wentworth and Williams, 1932; Blyth, 1940; Fisher, 1961; Vlodavetz et al, 1963). Features of several of these have been used by the present author, and in order to describe grain size as accurately as possible, the grade size terms of Wentworth, (1922) have been incorporated (Table 2.1). Since the clastic sedimentary rocks described in this thesis are entirely of volcanic origin, terms such as "coarse sand", "sandstone", and "clay" are used purely as grain size descriptors, with no implications as to the composition of the particles.

The composition of volcaniclastic rocks may be indicated by a prefix such as "acid" or "andesitic" where the components are predominantly of these compositions. The constituents can be subdivided into crystal,

FIGURE 2.1

Classification of calc-alkaline extrusive rocks based on silica content.

The diagram shows the range of Borrowdale Volcanic rocks in which the various phenocryst phases occur. After Fitton (1971).

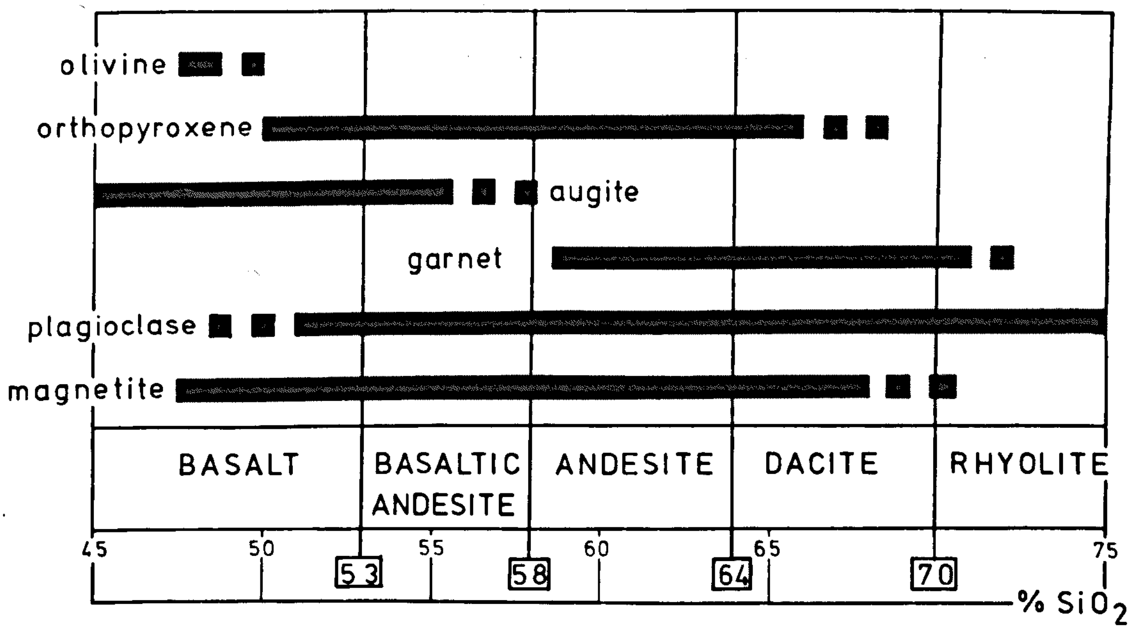

olivine
orthopyroxene
augite
garnet
plagioclase
magnetite
BASALT
BASALTIC ANDESITE
ANDESITE
DACITE
RHYOLITE
45
50
55
60
65
75
53
58
64
70
% SiO2

TABLE 2.1

mm	ø	SIZE DESCRIPTION		PYROCLASTIC PARTICLES	PYROCLASTIC ROCKS	VOLCANICLASTIC ROCKS
		Boulder				
256	-8			Blocks and bombs	Pyroclastic breccia (tuff-breccia if a substantial amount of tuff grade matrix is present)	Volcanic breccia/ conglomerate
128	-7	Cobble		(Bombs are plastic on eruption		
64	-6					
32	-5	Pebble				
16	-4			Lapilli	Lapillistone (Lapilli-tuff if a substantial amount of tuff grade matrix is present)	
8	-3					
4	-2	Granule				
2	-1	Very coarse				
1	0	Coarse				
0.5	1	Medium	Sand	Coarse ash	Coarse tuff	Volcanic sandstone
0.25	2	Fine				
0.125	3	Very fine				
0.0625	4	Silt		Fine ash	Fine tuff	Volcanic siltstone
0.0039	8	Clay				Volcanic claystone

Sources: Wentworth (1922); Wentworth and Williams (1932); Fisher (1961, 1966) lithic and vitric fragments, and these are used as prefixes to indicate the dominant type(s): e.g. vitric tuff, crystal-lithic tuff.

Bed thicknesses have been described using the terms of Reineck and Singh (1975, p.83) (Table 2.2).

TABLE 2.2

Description of bed thickness (after Reineck and Singh, 1975)

cm	
	very thick
100	
	thick
30	
	medium
10	
	thin
1	
	very thin

III. GLOSSARY OF VOLCANIC TERMS

The terminology of volcanic processes and volcaniclastic rocks has suffered particularly from loose and often ambiguous usage. This glossary lists the meanings of the terms as interpreted and used by the present author. Other interpretations are possible.

Aa: basaltic lava flow with a flow brecciated top and base composed of highly vesicular, jagged, spinose fragments.

Accessory: describes material from a volcanic cone which falls or slides into the vent and is re-ejected.

Accidental: describes fragments of earlier volcanic or non-volcanic rocks incorporated in pyroclastic deposits.

Accretionary lapilli: pellets of ash with a concentric structure, formed by accretion round a nucleus, such as raindrops falling through eruption clouds, or fragments rolling along the ground.

Ash: unconsolidated pyroclastic material with a grain size less than 2mm.

Ashfall: volcanic ash deposited on land or into water by gravity, from a subaerial or subaqueous eruption column. Covers a broader range of deposits than airfall

Ash flow: fluidized flow consisting of a turbulent mixture of gas and volcaniclastic material at high temperature, moving downslope under the influence of gravity after explosive eruption from a vent or fissure. Strictly, this term should be confined to flows carrying only ash (q.v.).

Ash flow sheet: sheetlike unit or group of units of ash flow origin.

Aspect ratio: ratio of horizontal extent to height or thickness, with particular reference to lava flows and fiamme

Autobreccia: breccia produced by processes taking place within a lava flow or intrusion: e.g. flow brecciation, explosions.

Autoclastic: applies to fragmental rocks produced in volcanic vents, by friction in flowing lava or by internal gas explosions within lava flows.

Autoclastic explosion breccia: produced by the explosion of gases within a solid or semi-solid intrusion or lava flow.

Base surge: a type of ground surge (q.v.) associated with phreatic eruptions, and first recognized in submarine nuclear tests at Bikini Atoll. Takes the form of a ring-shaped basal cloud moving rapidly outwards from the base of a vertical explosion column. Base surges deposit dunes which are concentric about the crater, and commonly show plane bedding, and cross bedding resembling that of climbing ripples, antidunes and chute and pool structures. Analogies with aqueous flow regimes should not be carried too far, as base surges travel at much greater velocities, and their deposits are often cohesive, because of steam entrained in the flow. Accretionary lapilli commonly form.

Block lava: lava flow in which flow breccias composed of regular angular blocks are developed, particularly at the base and top.

Bombs: masses of magma with a diameter greater than 64 mm, which are plastic at the moment of ejection, and whose form is modified by plastic deformation during flight or on landing.

Bouma sequence: Idealized sequence of structures in a turbidite bed:

e. mudstone division

d. upper parallel-laminated division

c. ripple cross-laminated or convolute-laminated division

b. lower parallel-laminated division

a. massive and/or graded division

Cooling unit: a term applied to pyroclastic flow deposits. A simple cooling unit may consist of one or several ash flow units emplaced sufficiently rapidly to cool as a single unit, and either remaining unwelded or forming a pattern of textural zones with different degrees of welding or crystallization. In a compound cooling unit the intervals between flow units are too great for cooling as a single unit, resulting in departures from the expected zonation; however, no part cooled completely before the next flow unit was emplaced above it.

Debris flow: downslope movement of a mixture of granular solids, clay minerals and water under the influence of gravity. The solids are supported in the cohesive fluid phase, which has a finite yield strength.

Ejecta: general term for pyroclastic material ejected from a volcanic vent.

Epiclastic: clastic sediments consisting of weathered products of older rocks.

Epiclastic volcanic rocks: derived by weathering and erosion of lithified volcanic rocks.

Eruption column: the rising column of volcanic gas, pyroclastic material, entrained air (or, in a subaqueous eruption, water and steam) etc., ejected upwards by an explosive eruption.

Essential: refers to erupted material derived directly from the magma, and including lava, pumice, ash, volcanic gases and sublimates.

Eutaxitic structure: a foliation in welded tuffs (q.v.), due to strong flattening of glass shards and pumice fragments by compaction immediately following deposition.

Fall unit: bed deposited by a single ash shower.

Fiammé (singular fiamma): describes lenticles of flattened pumice or glass in a welded tuff, often flame-shaped, with ragged ends (from the Italian for flame).

Flow breccia: breccia formed by the breakage of the congealing surfaces of a lava flow as the more fluid interior continues to move.

Flow unit (lava): a single tongue, lobe, stream or pillow of lava.

Flow unit (pyroclastic flow): the deposit of a single pyroclastic flow.

Fluidization: occurs when a fluid forced up through loose sediment exerts an upward force on the grains equal to the downward force of gravity. The grains may become fully suspended in the fluid.

Glomeroporphyritic aggregates: clusters containing several crystals of one or more phenocryst phase minerals.

Graded bedding: bed showing progressive grain size changes from base to top. This may be one of several types:

Distribution grading: progressive change in overall grain size

Coarse tail grading: only the grain size of the large clasts changes (e.g. clasts may be concentrated at the base or top of a bed, but the finer matrix shows no grain size change).

Combined coarse tail/distribution grading: progressive grain size changes in both the clasts and the matrix.

Normal grading: grain size decreases upwards.

Reverse grading: grain size increases upwards.

Multiple grading: grading occurs twice or more within a single bed

Ground surge: rapidly moving, turbulent gaseous flows, carrying a much lower concentration of solid material than pyroclastic flows (q.v.), and often depositing bedded material. Hot, dry ground surges have been recognized as a component part of nuées ardentes, in which they precede the main flow. Another type of ground surge is the base surge (q.v.).

Hyaloclastite: volcaniclastic rock formed by non-explosive granulation of volcanic glass when magmas are quenched by contact with water.

Hyalotuff: pyroclastic rock formed during explosive phreatic eruptions in shallow water.

Ignimbrite: the deposit of a pyroclastic flow. Although the original definition (Marshall, 1935) is ambiguous, it seems to the present author that the term was meant to include the products of all nuée ardente type flows, and should not be restricted to welded pyroclastic flow deposits.

Lahar: a mudflow consisting mainly of volcanic debris.

Lava flow: a body of lava produced by one volcanic eruption (lasting from a few days to several years). A lava flow may be simple, consisting of a single flow unit (q.v.), or compound, being divisible into flow units which may number up to several hundred.

Liquefaction: occurs when a loosely packed sediment collapses, the grains temporarily losing contact with each other, and settling within their own pore fluid. On resettling, tighter packing is established.

Mudflow: mass flow in which clasts up to several m long are supported by the finite yield strength of the mud/water matrix. Synonymous with debris flow.

Nuée ardente: fast-moving pyroclastic flow, consisting of a concentrated basal avalanche of hot pyroclastic material and volcanic gas, surmounted by a dilute, rapidly expanding ash cloud. Nuées ardentes produce unwelded, topographically confined deposits which have very small volumes compared with pyroclastic flow sheets.

Pectinate: describes the fibrous structure which develops normal to the edges of glass shards during devitrification. As this alteration progresses inwards, the fibres from either side meet to form a central "seam".

Perlitic structure: concentric, onion-like partings in volcanic glass.

Peperite : a breccia of lava fragments, commonly chilled, mixed with sediment, commonly baked, and formed when lava intrudes (from below) or flows (from above) into soft, unconsolidated sediment.

Phreatic explosion: explosion produced when hot magma comes into contact with groundwater.

Pillow: ellipsoidal structure in lava or intrusion. This is a morphological term with no genetic connotation.

Pillow breccia: breccia composed predominantly of fragments of pillow lava.

Pumice: highly vesicular volcanic glass of any composition.

Pyroclastic: rocks produced by explosive or aerial ejection of material from a volcanic vent, or by the reworking of unconsolidated material of this origin. (cf. epiclastic volcanic rocks.)

Pyroclastic fall: pyroclastic material deposited on land or into water by gravity from a subaerial or subaqueous eruption column.

Pyroclastic flow: Synonymous with ash flow (sensu lato).

Pyroturbidite: subaqueous pyroclastic flow, resulting either from a subaqueous eruption, or the passage of a subaerial pyroclastic flow into water.

Rain flushing: process by which fine-grained material is removed from an ash cloud or eruption column by the down washing action of rain falling through it.

Ripple index: ratio of ripple length to height.

Scoriaceous: highly vesicular and rubbly.

Shard: fragments of vitric ash produced by the disruption of highly vesicular magma. Shards commonly have forms (e.g. rod-shapes and Y-shapes) defined by bubble walls.

Strombolian eruption: mildly explosive open vent eruption with a low eruption column, producing a pyroclastic deposit, commonly a cinder cone, whose 0.01 T_{max} isopach encloses an area of between 0.05 km^2 and 5 km^2.

(T_{max} = maximum thickness of deposit).

Subaqueous tuff: non-genetic term which includes all types of hyalotuffs and hyaloclastites, and can be used as a field term (hyaloclastites and hyalotuffs are often very difficult to distinguish in the field).

Surtseyan eruption: subaqueous, usually shallow water explosive eruption, producing ash rings. The eruption column may be several km high, and the deposit contains a high proportion of fine-grained material.

Tephra: volcanic material of any size transported from a crater through the air.

Tuff: consolidated pyroclastic rock with a grain size less than 2 mm, i.e. the lithified equivalent of ash. It is proposed that this term should be extended, at least for field use, to include hyaloclastites (which are not strictly pyroclastic: see also subaqueous tuff).

Vitric: composed of glass. No undevitrified glass remains in the rocks described in the following chapters, and vitric is used as a convenient description of devitrified glass fragments in tuffs.

Vitroclastic texture: texture in which glass shards (q.v.) predominate. (synonymous with bogenstruktur)

Volcanic breccia: any rock composed mainly of angular volcanic fragments greater than 2mm in diameter.

Volcanic conglomerate: any rock consisting largely of rounded volcanic fragments coarser than 2 mm.

Volcaniclastic: describes all clastic rocks composed mainly or entirely of volcanic fragments, regardless of origin.

Volcanic sandstone: any sand grade clastic rock consisting predominantly of volcanogenic material.

Volcanic siltstone: any silt grade clastic rock consisting mainly of volcanogenic material.

Volcanogenic: of volcanic origin

Vulcanian explosion: powerful explosive eruption from a vent blocked by viscous or solidified magma, or by older volcaniclastic material. Low eruption column and high proportion of fine-grained material.

Welded tuff: one that accumulated sufficiently rapidly for the plastic vitric fragments to weld together, and mould themselves around rigid fragments. Welded tuffs commonly show a eutaxitic structure (q.v.), and it is inconceivable that a tuff with eutaxitic structure could be unwelded. Eutaxitic tuffs from the Borrowdale Volcanic Group are commonly too altered for welding to be distinguished in thin section; they are nevertheless referred to as welded tuffs in the following chapters.

This glossary was compiled using the following sources:
Aramaki & Yamasaki, 1963; Beavon et al, 1961; Bemmelen, 1949; Blyth, 1940; Bond & Sparks, 1976; Booth, 1973; Crowe & Fisher, 1973; Fisher, 1960, 1961, 1966; Fitch, 1967, 1971; Francis, 1976; Honnorez & Kirst, 1975; Johnston-Lavis, 1885; Lowe, 1976; MacDonald, 1972; Marshall, 1935; Mattson & Alvarez, 1973; Middleton & Hampton, 1973; Mitchell, 1970; Moore, 1967; Moore & Peck, 1962; Pettijohn et al, 1973; Rast, 1962; Rittmann, 1962; Ross & Smith, 1961; Schmincke, 1967a, 1974; Schmincke et al, 1973; Sheridan & Updike, 1974, 1975; Smith, 1960; Snyder & Fraser, 1963; Sparks & Walker, 1973; Thorarinsson, 1954; G. P. L. Walker, 1971, 1973; R. G. Walker, 1975; Wentworth & Williams, 1932; Wright & Bowes, 1963.

CHAPTER 3. THE BROWN KNOTTS - BLEABERRY FELL SECTION

I. INTRODUCTION

A. General

The area extending from the east side of Derwentwater eastwards, to the Shoulthwaite Valley, and from Rakefoot (NY 284 221)[1] in the north to Ashness Gill in the south, has been mapped at a scale of 1:10,560, using Ordnance Survey maps (Figure 3.2). Exposure is generally good, except in the extensive peat bogs of Low Moss. In the faces of Falcon Crag and the upper part of Brown Knotts (Plates 2, 3, 4,) the well-exposed, gently dipping lavas and volcaniclastic rocks form very marked stepped features. These outcrops have been examined in much greater detail than the rest of the area, involving mapping at a scale of approximately 1:4550 on enlarged aerial photographs (Plate 1, Figure 3.3a) and measurements of many detailed sections.

The only published geological map of the area is that of the Geological Survey (Ward, 1876). This detailed map, and the descriptions in the accompanying memoir, are difficult to fault, except that the relative abundance of "ash" is perhaps overestimated.

B. Structure

The major structural feature of the area is a gentle asymmetrical syncline trending west-southwest - east-northeast. It is best seen at High Rigg (Moseley, 1972: Plate I; Figure 4) east of the present area, and on the west side of the Shoulthwaite Valley. Here the fold has a steeper northern limb, with dips of up to 35° to 40°, and a much gentler southern limb. To the west, at Brown Knotts, the syncline is much less

1 All references in this form are to the National Grid Reference System of the Ordnance Survey

marked, and gentle eastward and southeastward dips predominate (Plate 1). These are steeper at the base of the section than at its top (Figure 3.3b). Brown Knotts appears to be near the western closure of the syncline which has a gentle easterly plunge here. Stereographic projection of structural data from this area (Figure 3.4) does not reveal any well-defined trends. Cleavage is largely absent although a crude cleavage is developed in tuffs at two or three localities on Brown Knotts (Plate 1, Figure 3.4), and in one autobrecciated andesite at Falcon Crag.

Several minor faults have been observed. Although they form prominent features, none shows any substantial displacement of the strata. The gorges occupied by the northern and southern branches of Ashness Gill (Plate 1) follow vertical faults with narrow crush zones and thick quartz veins, but vertical displacements are negligible. Low angle slickensides in the northern gorge indicate lateral motion, at least in the last stages of fault movement. At locality 11 (Figure 3.1b) coarse tuffs are affected by small tectonic faults with 1 to 2cm throws and associated quartz veining. These are probably related to movements along the faults in Ashness Gill. A fault with thick quartz vein s is exposed in the lower part of Brown Knotts (near point A, Plate 1). Two gullies to the north of this (Plate 2), separating the outcrops of Brown Knotts from those of Falcon Crag, may also mark the lines of minor faults. There is no displacement along the fault or master-joint forming the prominent pair of north-south gullies on Brown Knotts (Plate 1). The inaccessible gullies on Falcon Crag are believed to mark the positions of minor faults or master-joints.

C. Relationship with the Skiddaw Group

The contact between the Borrowdale Volcanic Group and the underlying Skiddaw Group (Figure 3.1a) is not exposed in this area. It was interpreted by the Geological Survey (Ward, 1876) as a fault running along the east shore of Derwentwater, but neither the contact nor rocks of the Skiddaw Group are anywhere exposed on this shore. The breccias near the mouth of Cat Gill (NY 269 209), interpreted by E.H. Shackleton (1971) as fault breccias consisting of Skiddaw Slate fragments, are in fact volcanic breccias with clasts predominantly of dark-coloured aphyric andesite. To the northeast, Wadge (1972) interpreted an outcrop (NY 2907 2197) of the contact as a gently angular unconformity with a 4.9m thick conglomerate at the base of the Borrowdale Group. Moseley (1975) expressed doubts on this interpretation, due to poor exposure.

Thus it is not possible to locate with any certainty the original junction between the two groups. The author believes, however, that the lowest exposed rocks in the area, the breccias near the outflow of Cat Gill, are not far above the original base of the volcanic pile.

D. The General Sequence

The rocks of this area are largely of andesitic composition, with lavas predominating over volcaniclastic rocks. The lower 250m of the 800m thick sequence (Figure 3.7) consists of massive, dark coloured aphyric andesites with subordinate bedded tuffs, breccias and hyaloclastites or hyalotuffs. Above this there is a rather abrupt change in lava type to lighter coloured plagioclase-and plagioclase pyroxene-phyric andesites, and several major bedded tuff horizons and a welded tuff unit occur (Figure 3.6). Higher in the section, massive andesites appear, and at least one of these is a shallow intrusive sheet rather than a lava flow. Except for the gorges of Ashness Gill these are poorly exposed, although they form marked features on the moor between Brown Knotts and Bleaberry Fell. The poor exposure may account, in part, for the apparent lack of volcaniclastic horizons in this part of the sequence. A thick garnetiferous andesite and a major bedded tuff horizon occur some 600m above the base of the sequence, and the highest rocks in the section are the andesites on the summit of Bleaberry Fell (NY 286 196).

E. Stratigraphy and Correlation

The lower 550 to 600m of the succession in this area is designated the Falcon Crag Formation (Figure 3.7), following the precedents of Ward (1876) and Marr (1916). The top of Ward's Falcon Crag "Series" was not precisely defined, whilst the upper limit of Marr's Falcon Crag "Group" is rather higher than that of the Formation. The Falcon Crag Formation has been subdivided into three members (Figure 3.7). The lowest of these, The Cat Gill Member (new name) includes the aphyric lavas of Falcon Crag, where it is best seen. Its lowest exposed rocks are the red breccias on the lake shore (described by Otley, 1827; Ward, 1876 and Marr, 1916).

The overlying Brown Knotts Member (new name) is best exposed on the hillside from which it takes its name. Its base is drawn at the base of a thick bedded tuff unit (Figure 3.7), at the level where a change in lava types occurs: the bedded tuff is underlain by a dark, aphyric andesite and overlain by a lighter coloured, plagioclase-phyric lava. The three major bedded tuff units within this Member are informally termed, in ascending order, BT1, BT2 and BT3.

The top of BT3 defines the base of the third Member of the Formation: The Ashness Gill Member (new name), best exposed in the gorges of that stream. Andesitic lava flows predominate in this part of the sequence. The top of the Member is taken at the base of a light coloured, flow jointed andesite with abundant red garnets. This is the lowest horizon in the Borrowdale succession in which garnet occurs in any quantity. It is believed to correlate with very similar garnetiferous lavas exposed near the north end of Thirlmere (Figure 3.8), and its base is defined as the base of the Thirlmere Andesites (see Chapter 4). The well-exposed bedded tuff unit lying some 40m above the base of the garnetiferous lava is informally named BT4.

The described section is laterally equivalent to the lower part of that of Strens (1962). His lowest division, the Lower Andesites (Figure 3.8), consists of massive, dark coloured, aphyric lavas up to 240m thick which are tentatively correlated with the Cat Gill Member. The Lower Andesites in southern Borrowdale are overlain by the Honister Tuff "Group", which is suceeded by the Fleetwith "Group". These two divisions both include porphyritic andesites, and are thought to correspond broadly with the upper two Members of the Falcon Crag Formation. There is, however, a considerable decrease in the importance of bedded tuffs in the Brown Knotts succession, compared with that of Strens. The thickness of the Falcon Crag Formation (550-600m) is rather less than the combined thickness (680-1090m) of Strens' lowest three divisions. His fourth division, the Longthwaite "Group", which includes highly garnetiferous lavas, is tentatively correlated with the lowest part of the Thirlmere Andesites.

3 km east-northeast of Brown Knotts, a similar succession has been described from High Rigg (Hadfield and Whiteside, 1936). The lowest division, the "Basic Pyroxene Andesites" is 300m thick and consists of aphyric, dark coloured lavas comparable with the Cat Gill Member of the Falcon Crag Formation. The overlying "Fine-grained Lavas and Tuffs" (150m thick) and the succeeding "Middle High Rigg Andesites" (more than 280m thick) include feldspar-phyric lavas and are thought to be the lateral equivalents of the Brown Knotts and Ashness Gill Members.

Further east, similar rocks are again seen in the Ullswater Group

(Figure 1.8) of Moseley (1960, 1964). The 150m thick tuffs at the base of the northwest Ullswater sequence have no equivalents at Derwentwater, but they are overlain by some 250m of massive, dark-coloured, sparsely phyric lavas, succeeded by feldspar-phyric andesites. Again, this is strikingly similar to the succession in the Cat Gill and Brown Knotts Members.

It must be emphasised that all the correlations attempted above are lithostratigraphical. Units may be diachronous, and no time equivalence is or can be implied.

II. THE LAVA FLOWS AND INTRUSIONS

A. Lava Flows

(i) General

The lava flows are laterally extensive. Some well-exposed ones can be traced for over 1 km, with negligible changes in thickness (Plate 1). Thicknesses of individual flows range from 6m to 60m, and many are around 20m thick (Figures 3.3b, 3.6). Minimum aspect ratios for three well exposed flows in the Ashness Gill Member are 13, 17 and 45. Occasionally, apparently lenticular lavas occur, such as the one above BT2 (Plate 1). The thicker flows may consist of several flow units, although there is often insufficient evidence to distinguish thin simple lava flows from the flow units of thicker compound flows. Many outcrops show massive, structureless lava.

(ii) Primary Structures

(a) Brecciation

Monolithological andesitic breccias, occurring either as extensive tabular bodies or isolated patches, are commonly interbedded with massive andesites. Their fragments are mostly angular, and from 2 to 10cm in diameter, although clasts up to 50cm across occur, and very small scale brecciation is seen in some thin sections. The breccias are almost entirely clast-supported. Their matrix may be fragmental, or may consist of fine-grained, aphyric lava. In rare cases, the voids are filled with crystalline chlorite and quartz. A lava matrix tends to be lighter in colour than the clasts, and to stand out on weathered surfaces (Plate 5B). In one example, the lava matrix has thin chilled zones at its contacts with the clasts. The fragmental matrix present in many cases consists of angular to subrounded grains of andesite, very similar to that of the clasts. Grain size ranges from lapilli down to medium sand, and sorting is usually poor. Within a single breccia unit, both types of matrix may occur.

The monolithologic character and the distribution of the breccias are characteristic of autobreccias described from recent intermediate lava flows (MacDonald, 1972, p.91-98). The best documented are the andesites and basaltic andesites of Paricutin, Mexico (Krauskopf, 1948; Segerstrom, 1950; Wilcox, 1950). As the lava cools, a solid crust forms on its upper surface and, as the more mobile lava beneath continues to move, the crust breaks up, In andesitic lavas, the clasts thus formed are rather equant, often cuboidal blocks, and the flow is termed a block lava (MacDonald, 1972). As the flow advances, the blocks from its top roll down the steep front, along with pieces spalled off from the viscous magma in the centre of the flow. These are then overridden as the flow continues to advance. As a result, a single flow unit, seen in cross-section, will have a brecciated base, a massivecentre and a brecciated top. This process was observed by the author in an active basaltic aa flow during the April-May 1975 eruption of Etna (Plate 30A).

Where blocks have sunk into the underlying lava, or the lava has flowed into the rubbly part of the flow, an autobreccia with a lava matrix results. In other cases, the interstices are filled with fragmental material, derived either by attrition between the blocks as the flow advances, particularly near the edges of the flow (Kraukopf, 1948) or by ashfall material being deposited onto the lava.

In a sequence of massive and autobrecciated andesites without interbeds of other facies, it may be impossible to decide whether a particular autobreccia is the top of the underlying massive flow (or flow unit) or the base of the overlying one. This difficulty is experienced in the present area and at Thirlmere.

(b) Flow Banding and Flow Jointing

Flow banding occurs in some lavas of the present area, and is best seen on weathered surfaces where it shows as parallel, continuous or discontinuous lineations (Plate 5A). In three dimensions, it is a planar structure, and individual layers are often 1mm or less in thickness. Flow banding seen in hand specimen or outcrop is often not apparent in thin section. In some cases it shows up as discontinuous, diffuse darker and lighter bands, presumably reflecting differences in composition or degree of crystallinity. In others, banding is defined by thin layers of minute vesicles. Trachytic texture may be parallel to the banding or, as seen in one thin section, it may be at a high angle to the lighter bands, and sweep into parallelism with the dark bands. This suggests that movement of the lava occurred by shearing along the darker bands.

Flow banding in modern lavas may result from differences in crystallinity between the layers (e.g. Coats, 1968), or from differences in vesicularity. A good example of the latter is seen in the recent Rocche Rosse flow of Lipari, where 0.5 to 2 cm bands of dense black obsidian alternate with highly vesicular rhyolite layers.

A few lavas in the present section have closely spaced parallel fractures, often 0.5 to 1 cm apart, which are interpreted as flow joints, rather than tectonic joints. In one flow, they are parallel to flow banding in the overlying unit. Such joints have been reported from more recent intermediate and acid lavas in areas including Iceland (Walker, 1959) and Arabia (Gass and Mallick, 1968). Flow jointing and flow banding in Borrowdale are parallel to the tops and bases of the lava flows in which they occur, and to the regional dip. No flow folding has been observed.

These planar fabrics are thought to form by laminar flow, in which the lava moves by shearing along closely spaced planes. They will only be preserved if motion continues until the viscosity is high enough for their preservation, but not so high that the fabric is destroyed by brecciation (Snyder and Fraser, 1973).

(iii) Petrography

(a) Plagioclase Phenocrysts

Plagioclase phenocrysts occur in nearly all the andesites of the present area, and are the predominant phenocryst phase in many. They may form up to 39% of the rock (tables 3.1, 3.2). They are mostly 0.5 to 2 mm in length, but range up to 4 mm. Plagioclase compositions have been determined[1] in thin sections where sufficient unzoned, fresh grains are present. They are all either andesine or sodic labradorite. Those in the Cat Gill Member range between An_{33} and An_{55}, in the Brown Knotts and Ashness Gill Members between An_{33} and An_{40}, and two examples from the Thirlmere Andesites are An_{50} and An_{55}.

Plagioclase commonly occurs in glomeroporphyritic clusters from 1 to 5 mm across, either on its own, or with interstitial clinopyroxene (or its alteration products). In andesites where the composition of

[1] Using the Michel-Levy method (Kerr, 1959). The composition was determined using the maximum of at least six measurements of extinction angle of albite twins in each thin section. Where the extinction angle was less than 20°, ambiguity was resolved by comparison of refractive indices with the mounting medium.

TABLE 3.1

Point counts on andesites from the Cat Gill and Brown Knotts Members of the Falcon Grag Formation
Pseudomorphs are counted as the primary phase which they replace.

SPECIMEN NO:	B2.4	B3.9	BT1.28	B2.17	B2.18	BK26
plagioclase phenocrysts	39.0	24.4	26.0	32.4	30.8	14.4
pyroxene phenocrysts	6.0	5.6	3.8	7.1	6.6	0.3
groundmass plagioclase	-	-	-	-	-	39.7
amphibole	0.2	-	-	-	-	-
opaques	-	2.7	-	-	-	0.3
amygdales/vesicles	5.0	9.8	13.5	4.3	-	7.8
groundmass	49.8	57.5	56.7	56.2	62.6	37.5
TOTAL:	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
number of points counted:	662	997	628	691	727	320

Specimens B2.4 and B3.9 are from lavas of the Cat Gill Member

Specimens BT1.28, B2.17 and B2.18 are from lavas of the Brown Knotts Member

Specimen BK26 is from a large andesite block contained in coarse tuffs of BT2 single plagioclase phenocrysts and plagioclase in clusters can be measured, there is no appreciable difference beteen the two. Zoning is a very common feature: the cores of the plagioclase phenocrysts are frequently altered, with rather thin rims of fresh feldspar. It appears that the centres, now consisting partly of calcite, were originally more calcic than the edges.

Nearly all the plagioclase shows some degree of alteration, and in hand specimen it is often green. Alteration ranges from slight sericitization, causing cloudiness, or thin epidote seams along twin planes, to complete replacement by secondary minerals, sometimes leaving only vague "ghosts" of the original phenocrysts. The commonest alteration products are sericite[1] and coarser-grained white mica, calcite, quartz and epidote. Partial replacement by chlorite also occurs. Alteration has in some cases resulted in rounding and embayment of plagioclase crystals.

(b) Pyroxene Phenocrysts

Pyroxene phenocrysts up to 2 mm long, but generally smaller, are common, although they are generally subordinate, in both size and abundance, to plagioclase (Tables 3.1, 3.2). Most are euhedral or subhedral, and multiple twinning and zoning frequently occur. As described above, pyroxene, or its alteration products, commonly occur in glomeroporphyritic clusters with plagioclase. Sometimes it is the sole constituent of such aggregates. Although unaltered colourless or brown clinopyroxene occurs, no fresh orthopyroxene has been found in the area. Chlorite pseudomorphs, often a single large crystal, show typical pyroxene cross sections and long sections and are more abundant than fresh pyroxene. Some of these are thought to represent orthopyroxene. Other common alteration products

[1] Sericite is used in the sense of Deer et al (1966, p.202) as a general name for fine-grained white micas, including both muscovite and paragonite.

TABLE 3.2: Point counts on andesites from the Ashness Gill Member of the Falcon Crag Formation, and from the Thirlmere Andesites. Pseudomorphs are counted as the primary phases which they replace.

SPECIMEN NO:	B2.26	B2.28	B2.31	B2.33	BK18	BK21	BK47
plagioclase phenocrysts	2.7	27.3	25.0	30.7	19.1	20.8	32.9
pyroxene phenocrysts	-	2.1	12.6	14.4	3.2	13.0	5.4
groundmass plagioclase	33.6	35.0	9.3	1.7	6.1	3.2	1.1
groundmass pyroxene	-	-	-	2.7	-	-	-
K-feldspar	-	-	-	-	-	1.1	-
quartz	-	-	-	-	-	0.2	-
apatite	-	-	-	-	-	0.2	-
garnet	-	-	-	-	-	2.6	-
opaques	7.8	-	3.0	2.4	0.1	1.2	1.3
amygdales/vesicles	-	-			22.6	-	-
groundmass	55.9	35.7	50.1	48.1	48.9	57.7	59.3
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Number of points counted: ..		288	884	1115	677	568	745

Specimen B2.26 is from the centre of the sill at the base of the Ashness Gill Member.

Specimens B2.28, B2.31, B2.33 and BK18 are from lavas of the Ashness Gill Member.

Specimens BK21 and BK47 are from lavas of the Thirlmere Andesites, on Bleaberry Fell.

are calcite, epidote, Fe-Ti oxides and fine-grained brown amphibole. Multiple twinned clinopyroxene is sometimes preserved as alternating layers of chlorite and calcite, or chlorite and epidote. Epidote and opaque minerals often form thin bands parallel to the cleavage of the chlorite pseudomorphs. Some chlorite pseudomorphs preserve the zoning of the clinopyroxene they replace, showing slight but progressive changes in birefringence and extinction position between core and rim. In a few cases, pyroxene is replaced by serpentine.

(c) Other Phenocryst Phases

Rounded blood red garnets up to 5 mm across are a conspicuous constituent of the lava flow at the base of the Thirlmere Andesites. Rare garnets occur lower in the section. In thin section, many have highly irregular margins, sometimes with embayments containing fine-grained groundmass material. Small inclusions of other minerals are common, and include Fe-Ti oxides and chlorite. At least one chlorite inclusion is pseudomorphing pyroxene. Oliver (1956) described both garnet and pyroxene (replaced by chlorite) completely enclosed in plagioclase, in a rock from Bleaberry Fell.

Chlorite also occurs as an alteration product, particularly along fractures which are often present in the garnets. Many garnets are surrounded by a reaction rim consisting of some or all of plagioclase, calcite, quartz and Fe-Ti oxides. Intergrowth of garnet with plagioclase or chlorite (after pyroxene) is present in several thin sections. In some cases, plagioclase appears to be replacing the garnet, as in one example where a thin "finger" of garnet protrudes along the centre of a plagioclase lath. In others, it is possible that a comagmatic relationship exists between the garnet, plagioclase and pyroxene. A small plagioclase-chlorite (after pyroxene) aggregate from the Thirlmere

Andesites of Bleaberry Fell contains small garnets. Garnets from the Borrowdale Volcanic Group have been studied in detail (Oliver, 1956; Fitton, 1972). They are of almandine-pyrope composition.

Small subhedral phenocrysts of opaque minerals occur in some lavas. Some may be magnetite, but others are white in reflected light, and are interpreted as leucoxene replacing ilmenite. They may occur in glomeroporphyritic aggregates with plagioclase and pyroxene. In the Thirlmere Andesites, typical four- and six-sided amphibole cross-sections occur rarely. The original amphibole is always pseudomorphed by chlorite and fine-grained brown amphibole.

(d) The Groundmass

The groundmass, constituting up to 60% or more of the andesitic lavas, may be a holocrystalline mass of felted plagioclase microlites and other minerals, or it may consist entirely of devitrified volcanic glass. In most cases it lies between these two extremes. Plagioclase is the most common primary groundmass mineral. In one thin section from the Ashness Gill Member, where the laths are sufficiently large and fresh, the composition was determined as An_6. The plagioclase microlites may be unoriented, or may show a preferred orientation, often swirling around phenocrysts. This trachytic texture is generally parallel to flow banding or flow jointing, where present.

The groundmass may also contain small grains of pyroxene, either fresh or pseudomorphed by chlorite, and often interstitial to the plagioclase. Small subhedral to anhedral grains of opaque oxides, appearing as white flecks in varnished slices, are thought to be leucoxene replacing ilmenite. In some thin sections, particularly those from the Thirlmere Andesites, small apatite prisms are conspicuous.

Devitrification products are often too fine-grained to be resolved, even at high magnification (1250x). In other cases, they are coarser, and minerals may be identified. These include plagioclase, opaque oxides, chlorite, calcite, epidote, sericite and quartz. Occasionally, formerly glassy lavas show perlitic cracks. In the more altered lavas, secondary minerals, instead of being finely disseminated, become segregated. In particular, the groundmass may be overgrown by patches of chlorite or calcite. Epidote segregations are less common. This patchy alteration is sometimes difficult to distinguish from autobrecciation. Fine, anastomosing veins of haematite, chlorite, calcite or epidote and quartz are a feature of some of the andesites.

(e) Vesicles and Amygdales

Amygdales are common, particularly near the bases and tops of lava flows, where they may form up to 40% of the volume of the rock (Plate 7B). Vesicles are almost invariably filled with secondary minerals, except on surfaces where they have weathered out. They range in size from 0.5 to 20mm. Many are circular or ovoid in section (Plate 7A), and probably formed after the flow came to rest. Others are elongate, or have very irregular, sometimes anastomosing shapes (Plate 7B). This is thought to result from deformation due to continued flowage of the lava after formation of gas bubbles. One lava flow shows a change in amygdale shape from elongate at the base to equant higher up. In some thin sections, many of the amygdales are adjacent to plagioclase phenocrysts, and often wrap around them. The feldspars appear to have provided nucleation points for gas bubbles in the magma. Flow lines defined by plagioclase microlites are sometimes bent around amygdales, possibly indicating expansion of thevesicle after the flow came to rest. Many amygdales are surrounded by a thin zone of altered groundmas material.

Generally, the largest amygdales have the most complex fills, whilst

TABLE 3.3

AMYGDALE FILL SEQUENCES OBSERVED IN THIN SECTIONS OF LAVAS FROM THE AREA EAST OF DERWENTWATER

	rim			core
1.	chlorite (fine-grained, unoriented)			
2.	chlorite (fibrous, radiating, banded)			
3.	coarsely crystalline quartz			
4.	chalcedony (sometimes banded: <u>ie</u> agate)			
5.	chalcedony	chlorite		quartz
6.	chalcedony	chlorite		calcite
7.	chalcedony	chlorite	quartz	calcite
8.		chlorite	calcite	
9.	chlorite	chalcedony		calcite
10.	chlorite	quartz		chlorite
11.	chlorite	chalcedony	quartz	clinozoisite
12.	finely interbanded chlorite and quartz			
13.	quartz		quartz and epidote	
14.	quartz and sericite		chlorite.	

many small ones contain only chlorite or quartz. Chlorite is the most common mineral of vesicle fills. It may be fine-grained, granular and unoriented, or it may have a fibrous, radiating habit and show alternate bands of colourless and green chlorite. It may occur alone, or with thin bands or disseminated grains of fine, granular quartz. Thin rims of fine-grained granular quartz or chalcedony are particularly common; the quartz is thought to represent recrystallised chalcedony. Haematite and chlorite rims also occur. Amygdales may consist predominantly of quartz, chalcedony (Plate 7B) or calcite, often with subordinate chlorite. Calcite often occurs in the centres of large amygdales and, more rarely, as rims or thin bands. Some typical vesicle fill sequences are shown in Table 3.3.

(iv) Composition

If Fitton's (1971) relationship of phenocryst phases to silica content (Figure 2.1) holds true, the fact that most lavas in the present section have phenocrystic plagioclase and pyroxene suggests that most are of basaltic andesite composition. The darker, aphyric lavas of the Cat Gill Member appear to be more basic in composition than the plagioclase-phyric lavas higher in the section. The only analysis of a lava from the study area is given by Ward (1876, p.18). His "Trap No. 12", which appears to be the lava immediately overlying BT4, in the lower Thirlmere Andesites (Figure 3.7), has a silica content of 59.511%. This falls in Fitton's (1971) andesite field (Figure 2.1). The phenocryst phases of the garnetiferous lava indicate a similar composition.

To the southwest, in the Buttermere-Honister area (Clark, 1964; Fitton, 1971), lavas low in the sequence are rather basic in composition. Of six analyses, three are basalts (50.3%, 50.81% and 52.1% silica), two are basaltic andesites (55.28% and 55.4% silica) and one is an andesite (61.65%

UNIVERSITY OF LEEDS

silica). Near the Bowder Stone (NY 253 165), 3.5 km southwest of the present area, a lava near the base of the sequence is a basaltic andesite (55.98% SiO_2).

Ten analyses are available from the equivalent section to the east, on High Rigg (Hadfield and Whiteside, 1936; Fitton, 1971). Three from horizons equivalent to the Cat Gill Member span the basaltic andesite field (Figure 2.1), with silica contents of 53.38%, 55.65% and 57.67%, whilst a fourth is an andesite (58.22% SiO_2). Of six analyses from the level of the Brown Knotts and Ashness Gill Members, one is a basalt (49.63% silica), two are basaltic andesites (54.61% and 57.59% silica) and three are andesites (58.98%,59.60% and 60.01% SiO_2). Further east, on Wanthwaite Bank (NY 321 233) a garnetiferous dacite (69.81% SiO_2) occurs near the base of the Group (Fitton, 1971).

(v) Variations in the Lavas

(a) The Cat Gill Member

The massive lava flows of this Member are dark grey-green or purple in colour, and are commonly weathered red, particularly towards their tops. With few exceptions, they appear aphyric in hand specimen, but sparse, altered plagioclase phenocrysts are visible in most thin sections. Pyroxene, either fresh or pseudomorphed by chlorite, is generally subordinate to plagioclase, but is the predominant phenocryst phase in a few cases. Amygdales are less common than in higher parts of the section, but are occasionally seen near the bases and tops of flows. The lowest exposed lava flow, a few metres above the base of the section, is interbedded with the red breccias near the mouth of Cat Gill (NY 269 209).

Some, at least, of the lava flows appear to be compound, and are composed of several thin flow units. For example, the following section is exposed at localities 5 and 6, Brown Knotts (Figure 3.1b);

top not seen

2m flow banded lava

sharp, planar contact

1m flow jointed lava

sharp contact

1.5m flow brecciated lava

sharp contact

0.05m disturbed bedded tuff

sharp contact

1m amygdaloidal lava

base not seen

The contact between the two upper units can be traced laterally for over 50m.

Flow banding and flow jointing are quite common. Autobreccias are less important than in the overlying Members, but some flows have thin brecciated zones at their tops and bases. These are often local and discontinuous, and brecciated pockets occur within massive andesite. Low in the Falcon Crag Section (Figure 3.3a) the lowest part of an autobreccia below a lava flow has a matrix of dark grey, non-volcanic mudstone. Higher up, it has a matrix of fine-grained, light coloured tuff.

(b) The Brown Knotts and Ashness Gill Members

As the characteristics of these two Members are very similar, they are considered together. In contrast with the Cat Gill Member, plagioclase phenocrysts are abundant in hand specimen (Plate 6B) and in one lava near the base of Ashness Gill Member they are up to 4 mm long.

Subordinate pyroxene phenocrysts are seen in most specimens (Plate 6B). These lavas are medium to dark green in colour, and red weathering is occasionally seen. Flow banding and flow jointing are less common than in the underlying Member, but autobreccias are thicker and more frequent. In some cases, they account for more than half the thickness of a lava flow (Figure 3.6). Autobreccias usually form extensive units at the bases and tops of flows.

Flow tops, and some flow bases, are frequently amygdaloidal or scoriaceous. Where lava flows overlie bedded tuffs, induration and plastic deformation may occur. A good example is seen at locality 3 (Figure 3.1b), where flames of tuff from BT1 extend up into the overlying amygdaloidal andesite.

(c) The Thirlmere Andesites

The lavas of the lower part of the Thirlmere Andesites, exposed on Bleaberry Fell, are lighter in colour than those of the Falcon Crag Formation. They contain abundant plagioclase phenocrysts, with subordinate pyroxene, and, in the lowest lava flow, garnet. Besides the small plagioclase, pyroxene and plagioclase-pyroxene aggregates common elsewhere, this flow contains dark green inclusions up to 10 cm long (Plate 6A). These weather brown, and appear to be more basic than the host lava. They are highly altered, and contain plagioclase and chlorite (after pyroxene) phenocrysts, with interstitial chlorite, calcite, quartz, epidote and opaques. Their texture resembles that of a dolerite. The lava is flow jointed (Plate 6A) and becomes amygdaloidal towards its top.

Lavas higher in the Thirlmere Andesites are very similar in their appearance and petrography, but do not contain garnets or large inclusions.

At the top of the succession, the flow forming the summit of Bleaberry Fell appears spherulitic.

(vi) Interpretation

As discussed above, the andesites and basaltic andesites of this area are interpreted as blocky lava flows. In their shape and size, they are comparable with block lavas and aa flows of similar composition from Central America and other areas (Table 3.4). Such flows, although often channelized near their sources, spread into broad lobes near their lower ends (Krauskopf, 1948; Macdonald, 1972). Besides the thick, extensive simple lava flows, compound flows consisting of flow units 1m or more in thickness occur occasionally. The extent of lava flows depends on viscosity, slope and other variables, but perhaps the most important factor is effusion rate. Walker (1971) suggests that high effusion rates result in extensive, simple lava flows, whilst low rates produce more localized thick compound flows. If this is so, effusion rates in the present area were generally high. The lateral extent of the flows may be partly due to the retention of heat by the insulating effect of the cooled lava on their tops (Krauskopf, 1948).

The lack of perfect exposure prevents further interpretation of the relationship between lavas. The problem of interpretation of ancient andesitic lavas was foreseen by Krauskopf (1948). If the lava field at Paricutin were buried and re-exhumed, he suggested: "it would be difficult to trace the boundaries between one flow and the next, since different tongues of the same flow would overlap one another and since some flows would have moved under older ones. Massive lava and several different kinds of breccia would be complexly interlayered."

The presence of flow banding and flow jointing suggests that some

TABLE 3.4

Comparison of the lavas of the Brown Knotts - Falcon Crag area with modern andesite and basaltic andesite lavas

	Borrowdale (present account)	Paricutin, Mexico 1943-1952 eruption (Krauskopf, 1948; Segerstrom, 1950; Wilcox, 1950)	Central Mexico (8000-40,000 yr. B.P.: Bloomfield, 1975)	Summary (MacDonald, 1972 p.91-98)
Flow length	>1km	up to 7 km	1 to 13.5 km	no data
Thickness	6 to 60 m	2 to 9 m (near lower ends)	flows 10 to 70m flow units 1 to 4m	7 to 30m
Aspect ratios	>13 to >45	no data	21 to 113 (mean c. 60)	no data
Width	indeterminable	20m near source 100m away from source	up to 1.5 km (estimate from photographs)	no data
Flow velocity	-	0.02 to 0.2 m/s (on 1 to 8^{o} slopes) maximum 1 m/s (on 28^{o} slope)	-	a few feet to a few tens of feet per day
Effusion rate	-	1 to 3.5 m^3/s (large flows)	-	no data

lavas were too viscous to move as normal liquids, but none were sufficiently viscous to fold these planar fabrics. The lateral extent and uniform gentle dips of the flows indicate effusion onto gentle slopes.

Reddened flow tops in the Borrowdale Volcanic Group have been interpreted by previous authors (e.g. Mitchell, 1956) as evidence of subaerial extrusion and weathering. In the present area, they are most conspicuous in the Cat Gill Member. Other evidence from this Member, including the presence of hyaloclastites or hyalotuffs (see below), an occurrence of non-volcanic mud in the matrix of an autobreccia, and the absence of reworked tuffs suggest a quiet subaqueous, possibly submarine environment. The author questions whether subaerial weathering contemporaneous with the vulcanicity is necessarily the cause of the red colouration. A similar effect could be produced by the palagonitization of brecciated, scoriaceous tops of subaqueous flows. Also, these permeable rocks would be more susceptible to modern weathering than the massive lavas with which they are interbedded. The latter often have a purplish colouration in their outer parts, but are affected to a much lesser extent than the flow tops.

Although a detailed account of the petrogenesis of the Borrowdale Volcanic Group is beyond the scope of the present work, some conclusions may be drawn from studies of thin sections. Primary hydrous minerals are rare, indicating that the magmas were relatively dry. There is evidence in some andesites from the present area that plagioclase crystallized before pyroxene. Pyroxene phenocrysts are generally smaller and less abundant than plagioclase, and in the aggregates present in many lavas pyroxene (or its alteration products) is often interstitial to plagioclase. The mineralogy and texture of the clusters are very similar to those of the phenocryst phases present, and they are thought to have crystallized either in magma chambers, or in the magma as it rose towards the earth's surface. The rate of ascent of the magma must have exceeded the rate of sinking of phenocrysts and aggregates. Differences in conditions under which the crystals nucleated, and in composition of the magma, resulted in aggregates with different mineralogies: plagioclase, pyroxene, plagioclase-pyroxene, plagioclase-pyroxene-ore, plagioclase-pyroxene-garnet.

This last observation, and others on lavas from the Thirlmere Andesites confirm the contention of Oliver (1956) and Fitton (1971, 1972) that garnet is a primary phenocryst phase. Its composition varies with that of the rock in which it is contained (Fitton, 1972). In at least one case pyroxene crystallized before garnet, and is completely enclosed by it. Fitton and Hughes (1977) suggest a cotectic relationship between garnet, plagioclase, quartz and pyroxene at approximately 10kb, with equilibriation of the magma at this pressure (which corresponds to a depth of some 35 km).

The large inclusions in the garnetiferous lava of Bleaberry Fell are apparently more basic than the host rock, and this indicates that they were not formed by flow brecciation. A second possibility is that the lava represents a mix-magma of basic inclusions in a more acid host (as described, for example, by Blake et al, 1965, and demonstrated in the field on Lipari (Dr. G. P. L. Walker, personal communication) and Mull (Dr. R. R. Skelhorn, personal communication)). This is unlikely, however, as the inclusions appear to have behaved as rigid blocks (Plate 6A) and show none of the characteristics of mix-magmas such as chilling, plastic deformation, crenulate margins or shearing out along the flow lines of the lava. The blocks are interpreted as xenoliths, and may be cognate inclusions formed during fractional crystallization of the magma.

The causes of alteration are discussed in Chapter 7. It is, however, worth noting here the very variable degree, and apparently arbitrary distribution of alteration in the lavas. One may contain fresh plagioclase and pyroxene phenocrysts in virtually unaltered devitrified volcanic glass, whilst its neighbour may show complete replacement of phenocryst phases and overgrowth of the groundmass by chlorite and calcite. Autobrecciated and vesicular lavas tend to be more altered than massive ones, probably because of their greater permeability.

B. Intrusions

(i) Field Relations

A 20m thick andesite unit at the base of the Ashness Gill Member is interpreted as a shallow sill rather than a lava flow, due to the nature of its contact with the overlying bedded tuffs. Laterally, it can be traced for over 1 km (Plate 1) with no appreciable change in thickness; it thus has an aspect ratio greater than 50. Relationships with the adjacent strata are best seen in the steep crags of Brown Knotts (locality 27, Figure 3.1b). The base of the sill is more or less planar, and the upper part of the underlying bedded tuffs of BT3 is disturbed. The upper contact is more complex, with extensive disruption of both the andesite and the overlying tuff (Plate 8). It can be traced over a horizontal distance of some 500m before being obscured by poor exposure.

(ii) Primary Structures

The basal 2m of the andesite is auto brecciated, with a matrix of fragmental glassy andesite. The upper 6m is also brecciated. The lower part of the upper breccia is very similar to that at the base of the sill. It has a matrix partly of fine-grained, chilled lava and partly of fragmented andesite. Higher up, blocks of andesite are contained in disrupted silt grade tuffs in which traces of bedding are common (Plate 8A), often at high angles to the original dip. The disrupted tuff is some 2m thick, and is overlain rather sharply by very similar, but undisturbed parallel-bedded tuffs. The central, massive part of the sill has a characteristic blocky fracture. At locality 13, (Figure 3.1b), crude columnar jointing is apparent.

(iii) Petrography

The massive, compact, flinty, aphyric andesite of the sill is dark green in colour, with slight reddening in places. Sparse plagioclase phenocrysts up to 1mm long are partially sericitized and some are zoned. The composition of several unaltered crystals is An_{47}. The groundmass consists of feldspar microlites, with sparse interstitial pyroxene and Fe-Ti oxides, set in very fine-grained irresolvable material interpreted as devitrified glass. This is partly replaced by segregations of carbonate and quartz. The plagioclase microlites define a sub-trachytic texture, and some are sufficiently large and fresh for their composition to be determined as albite (An_4). Small, irregularly shaped amygdales are common, particularly towards the top of the unit: some are filled with chlorite, and others with calcite and quartz.

The intermixed andesite breccia/bedded tuff is poorly sorted, having a bimodal grain size distribution with modes in the 0 to -1 ϕ class and in the silt grade matrix (Table 3.5). The green and red andesite fragments are up to 3 cm long, and contain abundant small, irregular, elongate amygdales. The outlines of the clasts are highly angular and ragged,

TABLE 3.5: Grain size analysis (thin section) of peperite above andesite sill (specimen BK 13)
465 points counted

	-2	-1	0	1	2	3 >3	ø units
% andesite fragments ..	2.2	13.3	10.3	9.7	3.2	49.0	
% plagioclase crystals ..	-	-	-	-	0.6	11.6	
% sub-total	2.2	13.3	10.3	9.7	3.8	60.6	
						TOTAL	99.9%

defined partly by vesicle walls and partly by fracture surfaces (Figure 3.9a, Plate 8A). Pieces can be seen spalling off the edges of the larger fragments. Many of the clasts are of very fine-grained, irresolvable brown material, believed to represent devitrified glass, whilst felted plagioclase microlites are the predominant constituent of other fragments. A few small plagioclase phenocrysts are present. A thin rim of fine grained granular quartz of constant thickness coats many of the fragments and lines their vesicles. Whole vesicles within clasts are filled with chlorite, whilst incomplete vesicles forming the edges of fragments are infilled by the fine-grained tuff of the matrix.

In one specimen (Figure 3.9a, Plate 8A) some 60% of the matrix is silt grade tuff with traces of bedding, and 40% is of very fine to very coarse sand grade andesite and plagioclase crystal fragments. Other specimens contain little fine-grained matrix, their interstices being filled with chlorite and quartz crystals.

(iv) Composition

Ward (1876: p.16, Plate VI) presents an analysis of "Trap No. 6" from Brown Knotts. It seems certain from his description and illustration that he is referring to the sill under discussion, although he interprets it as a lava flow. The rock contains 60.718% silica, thus falling into Fitton's andesite field (Figure 2.1). It also contains 14.894% alumina, rather less than is present in lavas at a similar level in other areas (see II.A.(iv) above).

(v) Interpretation

The mixed andesitic breccia and disrupted bedded tuff are interpreted as a peperite, produced by the intrusion of andesitic magma into volcanogenic sediments. Similar relationships have been described from andesite and dacite sills intruded into partially consolidated siltstones and mudstones in the Elkhorn Mountains, Montana (Smedes, 1956) and in the Aleutian Islands (Snyder and Fraser, 1963). In the latter, the peperites, consisting of mixed igneous and sedimentary material, sometimes grade into breccias composed entirely of igneous debris, as is seen at the top of the Brown Knotts intrusion.

The chilled glassy fragments contrast with the more crystalline andesite in the centre of the sill, and their shapes are strongly reminiscent of those of hyaloclastites. They are believed to have formed by thermal shock, when the magma came into contact with the cold, wet sediment. The highly irregular shape and fragile nature of many of the fragments indicates that no reworking has taken place. Their thin quartz coats are similar in form to the palagonite rims commonly seen on hyaloclastite grains (e.g. Furnes, 1974), and may be replacing altered rinds resulting from interaction of the volcanic glass with water. The difference in composition of the groundmass and phenocryst plagioclase may reflect the greater susceptibility of the smaller crystals to albitization.

Although the bedded tuffs are highly disturbed, bedding and sedimentary structures are not obliterated. This indicates that the tuffs were partially consolidated beforeintrusion,and that the intrusion itself was a relatively tranquil event,with little or no explosive activity. The overlying undisturbed tuffs suggest either that disruption was limited to a layer about 2m thick, or that their rather sharp base is a disconformity. There is, however, no evidence of erosion here, and the former interpretation is preferred.

It is important to note that it is the upper contact of the andesite which is diagnostic of a sill. None of its other features distinguish it from lava flows. Other such intrusions may be present in the area, but have gone unrecognized because their top contact is not exposed.

III. THE VOLCANICLASTIC ROCKS

A. Hyaloclastites/Hyalotuffs

(i) General

For reasons outlined below, some of the vitric tuffs interbedded with the lavas of the Cat Gill Member are interpreted as hyaloclastites or hyalotuffs. These tuffs are rather poorly exposed, often lying under grassy or scree-covered slacks between the bold crags formed by the lavas. They are massive and mostly unbedded. Thicknesses are difficult to determine, but are not thought to exceed 2 or 3m. These rocks are best seen in the Falcon Crag area (Figure 3.3b), particularly at the base of the lower main face where faint parallel bedding occurs, and in the Barrow Beck below Ashness Bridge (Plate 1). Some are weathered red.

(ii) Petrography

The tuffs are composed almost entirely of highly angular dark green vitric fragments, whose grain size ranges from fine sand to lapilli. The grains are more or less equant, highly irregular in shape, and show varying degrees of vesicularity. They are bound partly by the walls of spherical or ovoid vesicles and partly by fracture surfaces. Thus the most vesicular ones have very irregular outlines, whilst those with few or no vesicles have more regular, blocky shapes. Most grains are aphyric, although some contain small plagioclase laths. Sparse plagioclase crystal fragments may also be present. Sorting varies from moderate to poor: in some specimens the sand size fragments are close-packed, whilst in others fine-grained matrix material is abundant, and some matrix-supported rocks occur. Some of the larger clasts show signs of in situ fragmentation, with smaller pieces spalling off their edges.

Many of these rocks are highly altered in thin section, but a specimen from the base of Falcon Crag shows almost perfect preservation of the original textures. All the clasts are of very fine-grained devitrified material with fibrous, radiating structure, consisting partly of chlorite. All are vesicular, and most of the larger ones include complete amygdales. Both the vesicle walls and the perimeters of the fragments have a thin, uniform coating of fine-grained, granular quartz. The amygdales are filled with chlorite, occasionally with small crystals of epidote or centres of radiating fibrous quartz (after chalcedony?). There are marked grain size changes between different parts of the slide, and pockets of small straight and Y-shaped shards, evidently derived from bubble walls, occur. There is little or no fine-grained matrix material, and the intergranular spaces are filled with crystalline chlorite and quartz.

(iii) Interpretation

The shapes of the vitric particles in these rocks are very similar to those described and illustrated from "hyaloclastites" (sensu lato) (e.g. Denaeyer, 1963; Fisher, 1968; Solomon, 1969; Furnes, 1972). In the terminology of Honnorez and Kirst (1975) some of the tuffs described above resemble hyaloclastites, and others are similar to hyalotuffs (see Chapter 2). In the Ibleian Hills of Sicily, two types of basaltic vitric tuff occur in the Pleistocene volcanics. Unbedded tuffs and breccias with non-vesiculated fragments are intimately associated with pillow lavas and pillow breccias. These are thought to have formed by non-explosive granulation of lava caused by thermal shock. Secondly, there are parallel-bedded tuffs composed of vesiculated vitric fragments, which are interpreted as the result of subaqueous (Surtseyan or Strombolian) explosions (interpretations: Cristofolini et al, 1973; G. P. L. Walker, personal communication). Thin sections of these two rock types collected by the present author are closely comparable with the non-vesiculated and vesiculated tuffs, respectively, of the Cat Gill Member. The thin palagonite coatings of the grains in the Sicilian rocks are very similar in form to the quartz rims described above: possibly the quartz is replacing palagonite.

It seems likely to the author that both hyaloclastites and hyalotuffs occur in the present area. In particular, the faintly bedded tuffs at the base of Falcon Crag are thought to be the deposits of subaqueous explosions. Other vitric tuffs, composed largely of non-vesiculated fragments (e.g. Plate 9) are probably hyaloclastites. There appears to be a gradation between this rock type and flow breccias: possibly some were produced by a combination of flow brecciation and granulation due to thermal shock. It is hoped that further detailed study, and in particular, application of the methods of Honnorez and Kirst (1975) may help to clarify these problems.

B. Welded Tuffs

(i) General

A 10m thick lapilli tuff horizon towards the top of the Brown Knotts Member (Figure 3.7) has a markedly different petrography from the predominantly intermediate volcaniclastic rocks in the rest of the section. It is massive and unbedded, and commonly shows crude cleavage. Everywhere its base is concealed by scree, whilst its contact with the overlying bedded tuffs of BT3 is sharp and more or less planar. The lapilli tuff can be traced laterally for 1 km (Plate 1). Its thickness does not appear to vary significantly, although exposure is poor towards the southern end of the area.

(ii) Petrography

In outcrop, equant 1 to 2 cm blocks of lava and tuff are ubiquitous. In places, and particularly in the lower part of the unit, dark coloured, highly flattened fragments are seen (Plate 10). These fiammé are up to 5 cm long, and lie parallel to the local dip. They are always subordinate to the undeformed blocks, and both are generally supported in a very fine sand to silt grade matrix. Occasionally the tuff is clast supported, and pressure solution between lapilli has been recorded. Sorting is poor, and the clasts are angular to rounded. Occasional lenticular bands of clay grade material occur. On a broad scale, grain size is uniform throughout the unit.

In thin section, the components are predominantly lithic. Intermediate and acid lava fragments are common, and include aphyric, quartz-phyric and feldspar-phyric types. Some have a very fine-grained devitrified groundmass, whilst in others plagioclase microlites define a trachytic texture. A few fragments of altered tubular pumice are recognizable. Many clasts are highly altered, and often partly or wholly replaced by calcite: it is impossible to say whether they were originally lava or tuff. The most interesting lithic components are of non-volcanic sedimentary rocks. These include sandstones composed of subrounded quartz grains with a few altered feldspars and small amounts of muscovite and sericite, and brown, micaceous siltstone fragments.

Whole and broken crystals also occur: the most important are of quartz and potassium feldspar, and occasional opaque clastic grains are present. The first are up to 1mm long and mostly subangular, obviously detrital grains, showing strain extinction. Crystal faces are preserved in some, and a few are polycrystalline. Orthoclase is partly replaced by quartz. Plagioclase is rarer, and most grains are altered, although a few fresh, zoned crystals occur. Silt-sized grains of quartz and feldspar form much of the matrix.

(iii) Interpretation

The lateral extent of this unit, the lack of bedding and the presence of fiammé suggest that it is the deposit of a hot pyroclastic flow. The predominance of undeformed lithic fragments indicates that most of the material was solid before being entrained in the fluidized flow, either from older rocks below the surface or from loose material on the surface over which the flow passed. The fiammé and some of the crystals are believed to be derived from the magma in which the flow was initiated. Although most of the lava types present are very similar to those in the 400m of section underlying the tuff, others, particularly the quartz-phyric varieties, cannot be matched. They may be from older lavas below the base of the present section, or from hypabyssal rocks which are not represented amongst the lava flows. Similarly, the non-volcanic siltstone and sandstone clasts are unlike any lithology in the lower part of the succession, and are most likely to be derived from the sediments of the underlying Skiddaw Group. The detrital quartz grains may have a similar origin. The polycrystalline quartz, however, is more likely to have an igneous or metamorphic source (Blatt and Christie, 1963). The presence of accidental components is a common feature of ash flow deposits (MacDonald, 1972, p.158).

It seems likely that this tuff unit has a different source from the andesitic lavas and tuffs forming the bulk of the section. It is interesting to note that isolated acid ignimbrite and lava units occur low in the sequence in other areas. Welded tuffs are reported from similar levels at Ullswater (Moseley, 1960, 1964) and north of Honister Pass (I. Evans, personal communication) and higher up, in the Thirlmere Andesites (see Chapter 4). Clark (1964) and Fitton (1971) describe acid lavas in the lower, andesitic part of the Group at Buttermere and south of Threlkeld respectively. Volumetrically, these "blips" of acid volcanicity super imposed on a "background" of intermediate activity, are unimportant.

C. Breccias and Conglomerates

(i) General

Several varieties of volcanic breccia and conglomerate occur in the present area, and examples from the principle volcaniclastic sequences (BT1 to BT4) are discussed more fully in section III.F below. Besides these, the most notable occurrence is that of the "Purple Breccias" at the base of the section on the shores of Derwentwater and in the lower reaches of Cat Gill. Some breccia and conglomerate units are demonstrably lenticular, whilst others may be traced laterally for over 100m before exposure fails.

(ii) Primary Structures

Many of these rudites are apparently massive and structureless. A few are cross-bedded or flat-bedded, and with decreasing grain size pass into the bedded lapilli tuffs described in section III.E. The bedding is often ill-defined. Some of the breccias lie in steep-sided channels (Plate 16; Figure 3.10) whilst others, as far as can be seen within the limited outcrops, have a sheet-like form (Plate 25). In either case, the deposit commonly shows a concentration of large clasts at or near its base, resulting in coarse tail grading, often accompanied by a change from clast-support to matrix-support (Plates 16A, 25; Figure 3.9b). A few units have clasts concentrated at their tops. The beds of breccia and conglomerate, particularly those within the tuffs of BT1 and BT4, are commonly 1 to 2m thick. Many of the units have planar, sometimes slightly erosive bases.

Many elongate clasts are oriented parallel to the regional dip, whilst others are imbricated (Plates 14A, 16B).

(iii) The "Purple Breccias"

(a) Description

The exposed thickness of these breccias near the lakeshore (NY 269 209) exceeds 10m and includes a thin aphyric lava flow. At least two breccia units must be present here. There is a gap in exposure in Cat Gill east of the road (Figure 3.3a) and above this (NY 271 209) are green lapilli tuffs very similar in appearance to, but rather finer grained than the "Purple Breccias". In the lower outcrops, there is a marked fining upwards from a clast supported boulder conglomerate with clasts up to 50cm in diameter, to matrix supported tuff-breccias whose clasts are mostly 5 to 10cm long. The breccias are chaotic and unsorted, and the clasts, ranging from sand grade to boulders, are mostly angular, although some larger ones are subrounded. No bedding is apparent, but occasional crystal-rich layers are seen, and elongate clasts are often flat-lying. Crude cleavage is seen in places. On a weathered surface, the matrix tends to stand out.

These rocks contain a great variety of lithic fragments. The most abundant are angular blocks of green or red andesitic lava, and light green, white, pink or grey acid lava. These are commonly felsparphyric, and most of the acid fragments have a devitrified glassy matrix, whilst a trachytic texture is developed in some of the andesite clasts. Many lava fragments are flow banded, and some contain irregular calcite-chlorite amygdales. Some clasts have lighter coloured, altered rims. Pumice fragments are also abundant. Light coloured tube pumice clasts up to 10 cm long are seen in outcrop, whilst in thin section, equant pumice grains with ragged outlines are common. These are composed of dark, very fine- grained, almost isotrop ic devitrified glass, probably of intermediate composition. Their ovoid vesicles are filled with quartz, calcite and chlorite. Scattered cuspate shards, obviously derived from broken pumice, also occur.

Less common clast types include acid welded tuff and dark mudstone, and in breccias exposed in the road cutting (NY 270 210) is a 2m long block of red, fissile shale. Whole and broken plagioclase crystals are commonly seen, and some of them are embayed. Most crystals are partly replaced by sericite and calcite, and some are zoned. The silt to clay grade matrix of the breccias is invariably red, due to the presence of finely disseminated haematite. The matrix is calcareous in parts, and contains numerous small feldspar laths.

(b) Interpretation

The chaotic, unsorted, massive, unbedded nature of these breccias suggests that they are the deposits of mass flows. No reliable criteria have been established for distinguishing subaerial from subaqueous debris flows, but the closest analogues in the literature to the "Purple Breccias" are submarine mudflow deposits from turbidite successions. These are from the Tertiary of the New Hebrides (Mitchell, 1970: Facies E) and

New Zealand (Ballance, 1974: Parnell Grit). In both cases, the deposits are unbedded and unsorted, and the subangular to subrounded clasts are up to 50cm and 3m across, respectively. They are heterolithic, containing a variety of volcanic clast types and fragments of sedimentary rocks. In the New Hebridean breccias, the beds are ungraded, and their tops and bases are often difficult to distinguish. Some are more than 5m thick. Those from New Zealand have beds 2 to 20m thick, in which larger clasts are concentrated towards the bases.

Similar features have been described from rocks interpreted as submarine pyroclastic flow deposits (Shibata, 1962; Schmincke, 1974) and there seem to be no unequivocal criteria for distinguishing between the sediments of these two types of subaqueous mass flow. It cannot be stated categorically that the "Purple Breccias" were deposited subaqueously, but evidence from higher in the section (see II.A.vi and III.A.iii above) suggests that this is likely.

(iv) The Breccias and Conglomerates of BT1

(a) Description

The lowest breccia unit in BT1, at locality 8 (Figure 3.1b; Plate 1) differs considerably from the others. It is polymict and clast-supported, with blocks of lava and tuff, some of them well rounded, up to 1m across. The clasts include one of accretionary lapilli tuff, a lithology which is otherwise unknown in the present area. The breccia, some 5m thick, has a sharp, roughly planar contact with the underlying lava flow. It shows coarse tail grading, and passes gradually upward into lapilli tuff.

In the other breccias and conglomerates of BT1, most clasts are of green andesitic lava, which acquires a light coloured patina on weathering, and blocks up to 1m across are seen (Plates 15, 16). The clasts are contained in a medium to very coarse sand grade matrix, with very little silt and clay grade material. Both clast-supported and matrix-supported varieties occur (Plate 14, 25), and within the latter small concentrations of pebbles in contact are sometimes found. Many of the clasts have a rectangular outline (Plate 14A) and it is thought that they were derived from lavas with rather closely spaced rectilinear joints. Most show some degree of rounding, and some are well rounded (Plate 14; Figure 3.9b).

At localities 3 and 5, some conglomerates lie in steep sided channels, eroded into bedded tuffs (Plate 16; Figures 3.10, 3.21b). That at locality 3 has blocks up to 60cm across at its base, and grades upwards into lapilli tuff. It has a maximum thickness of 6m, although more than one unit may be present. At locality 5, more sheet-like, lenticular conglomerates also occur (Figure 3.21b). These have sharp, irregular, slightly erosive bases, and are interstratified with bedded tuffs and lapilli tuffs. Most are matrix-supported, and some units show coarse tail grading, passing upwards into lapilli tuff or coarse tuff. Similar relationships are seen in the conglomerates at locality 6 (Figure 3.9b).

Most of the clasts are of green, or sometimes red plagioclase-phyric andesite, whose petrography is very similar to that of the lavas of the Brown Knotts Member. Many have a crystalline groundmass, sometimes with a trachytic texture, and a few are amygdaloidal. One contains chlorite-epidote pseudomorphs after euhedral amphibole phenocrysts. The clasts may be epidotized or chloritized, and some have lighter coloured, altered rims. Acid lava fragments occur occasionally. They are pink, grey or light green in colour and may be aphyric or feldspar-phyric. Some contain chlorite-calcite pseudomorphs after pyroxene and, rarely, small, rounded garnets. Most acid clasts have a vitric groundmass, sometimes with perlitic fractures.

The petrography of the sand grade matrix is very similar to that of the associated bedded tuffs, which are described later in this chapter. Subangular to subrounded plagioclase crystal fragments and vitric grains are the major components, and either may predominate. Pseudomorphs after pyroxene crystals are also common. Sand sized pumice grains occur occasionally, and detrital garnets rarely. There is sometimes a small amount of very fine-grained material between the grains, consisting of quartz, feldspar, chlorite, epidote and opaques. This may be, at least in part, of secondary origin. In other case, voids may be filled with coarsely crystalline calcite and chlorite.

(b) Grain Size Distribution

Grain size analyses have been made on vertical surfaces in the conglomerate outcrops at locality 5 (Figure 3.11). Thin sections from this locality were too altered to analyse, so all grains finer than -2ø are plotted together. A grain size count on a thin section of the matrix of the conglomerate at locality 3 is presented, however. The conglomerates are rather poorly sorted, with modal clast sizes in the pebble to cobble range (Table 2.1). The mode of the matrix is coarse sand. There appears to be a hiatus in the small pebble to granule grades (-3 to -1ø), suggesting a broadly bimodal grain size distribution, but this needs to be confirmed by combined macroscopic and microscopic analysis of single, unaltered conglomerate units.

Most of the clasts at locality 5 are less than 5cm long, and they are predominantly equant, with length: width ratios generally less than 3 (Figure 3.11f).

(c) Palaeocurrents

There are few measurable cross-bedding directions in the conglomerates of BT1, but it is often possible to see the three-dimensional orientations of the clasts, and the directions of dip of many of these have been measured (Figures 3.12 to 3.14a). In some beds or groups of beds there is a strong preferred orientation of the clasts, generally towards the south or south-southwest, whilst others show a broad scatter. In some cases, adjacent and apparently very similar beds have completely different clast orientation patterns (Figure 3.13). When all the measurements are plotted together, dips to the south-southwest predominate (Figure 3.14a). Since pebbles deposited by aqueous currents commonly dip upstream, transport towards the north is inferred.

(d) Interpretation

The breccia at locality 8 shows many of the features of the "Purple Breccias", and is probably the product of a single, rather large debris flow. The other conglomerates and breccias of BT1, however, are rather better sorted, in terms of both grain size and clast composition. It is thought most likely that the steep sided channels are the result of subaerial erosion, and that the conglomerates were deposited in a subaerial environment. The tuffs must have been at least partly consolidated before the channels were cut, but this does not imply any great time gap between lithification and erosion, since a hard crust may form on tuff deposits very shortly after deposition (Segerstrom, 1950; Waldron, 1967). Certainly the ashfall material deposited during the 1888-1890 eruption of Vulcano is sufficiently consolidated to bear the weight of a man. Channels similar to those in BT1, with stepped cross-sections partly following the bedding of the eroded tuffs, have been observed by the author on the modern cone of Vulcano (Plate 32B), in Recent tuffs on Lipari (Plate 31B) and in photographs taken shortly after the 1902 eruption of Soufrière, St. Vincent (collection of photographs by Tempest Anderson, Yorkshire Museum, York). Brenchley (1972) describes channels of similar form and size from Ordovician tuffs in North Wales, and interprets them as gullies eroded on a subaerial volcanic cone.

The conglomerates of BT1 bear little resemblance to pyroclastic fall deposits. Rather, they are thought to have been deposited from flows sufficiently competent to carry large boulders. Sporadic cross bedding and flat bedding indicate reworking by aqueous currents, and in many ways the conglomerates resemble the deposits of migrating longitudinal or diagonal bars in pebbly or gravelly braided streams (Walker, 1975). Common features of these are massive or roughly horizontal bedding, pebble imbrication (usually of the intermediate rather than the long axes of the pebbles), normal grading and occasional cross bedding.

On the other hand, the deposits of fluid subaerial debris flows may be graded and show horizontal orientation or imbrication of elongate clasts. These features tend to be absent from the deposits of more viscous debris flows (Walker, 1975; Reineck and Singh, 1975, p.256). Although very little clay and silt grade material is present in the conglomerates of BT1, a debris flow origin cannot be ruled out. Mudflows with as little as 1.1% clay grade material have been observed to carry boulders 75cm across, and dispersive pressure between grains, as well as matrix strength, may be important in determining the mobility of debris flows (Middleton and Hampton, 1973).

Thus, it may be difficult or impossible to distinguish between the products of fluid subaerial debris flows and pebbly streamflow deposits. It is tentatively suggested that the conglomerate units with well developed imbrication may have been deposited by rather powerful streams or fluid debris flows, whilst those with more random clast orientations may represent more viscous debris flows.

(v) The Breccias of BT2

(a) Description

Only one breccia unit is exposed in BT2, and is best seen at locality A (Figures 3.1b, 3.24b). It is lenticular, with sharp, irregular upper and lower contacts. The breccia is clast supported, and is composed entirely of blocks of parallel-bedded very fine sand to clay grade tuff, derived from the immediately underlying beds (Plate 19; Figure 3.21a). The clasts are angular, and range from 0.5 to 30cm long. Most lie roughly parallel to the bedding, although some are at high angles to it. A few have been gently buckled by soft sediment deformation. The matrix of the breccia is very coarse sand to granule grade lithic tuff.

(b) Interpretation

The clasts were evidently torn up from the partially consolidated underlying beds by a powerful erosive agent, but were not carried far. The intraformational breccia lies at the base of a coarse tuff sequence which is discussed more fully in section III.F below.

(vi) The Breccias of BT4

(a) Description

Near the base of the outcrop at locality 15 is a laterally continuous, sheet-like breccia unit 1m thick, with a sharp, planar base and top (Plate 25). There is a slight angular disordance with the underlying tuffs. The breccia is matrix-supported throughout, sorting is poor, and all the clasts are angular. The lowest 15 to 25cm is almost devoid of clasts and has reverse distribution grading, passing from coarse sand grade up into coarse/very coarse sand with lapilli. Above this, clasts appear abruptly, and the upper two thirds of the unit shows normal coarse tail grading, with little upward change in the grain size of the matrix. Clasts are rare in the upper third. Within the top 2 cm the sandy matrix grades up into clay. Narrow, elongate, slightly sinuous sheetlike structures containing finer material than the surrounding sediment extend vertically downwards for 20 cm from the top of the bed.

The majority of the clasts are of andesitic lava, with plagioclase and chlorite (after pyroxene) phenocrysts in a groundmass which may be entirely of devitrified glass, or contain abundant feldspar microlites. Tuff clasts also occur, and one block of sand grade lithic tuff appears to have broken in situ: there is a jigsaw fit between the fragments (Plate 25B). The matrix of the breccia consists largely of altered crystal fragments of plagioclase and possibly also potassium feldspar crystals. Glomeroporphyritic aggregates of plagioclase-chlorite (after pyroxene), identical to those described from the andesitic lavas, are also present. The interstices between crystal fragments are filled with altered silt to clay grade material.

Thinner lenses and sheets of breccia also occur in BT4, and these are discussed later in the chapter, together with the tuffs with which they are interbedded.

(b) Interpretation

Many of the features of this breccia correspond with those of mass flow deposits. Planar contacts, coarse tail grading and fine-grained basal layers are common in the products of both debris flows and pyroclastic flows (Schmincke, 1967; Sparks et al, 1973; Bond and Sparks, 1976). The last mentioned feature is interpreted as a result of shearing at the base of the flow. Other features suggest a mudflow origin for the breccia of BT4. There is evidence of gentle transport of fragile tuff clasts, which disintegrated in situ after the flow came to rest. Fragile objects are reported from modern mudflow deposits, and their preservation is attributed to a combination of "plug" flow and laminar flow (Johnson, 1970).

The sheetlike structures at the top of the breccia may be sheet dewatering structures, as described from Namurian sandstones of the central Pennines (J. G. Baines, personal communication). These are produced by the upward movement of water during settling and compaction of the sediment. The structures have a similar orientation to the crude cleavage seen in parts of the section, but if they are of tectonic origin, it is difficult to explain their sinuousity and why they are confined to the top 20 cm of the unit (they do not occur in the rather finer basal layer). The thin clay grade layer at the top of the flow may represent material carried upward by the escaping water, as described from modern volcanic mudflows (MacDonald, 1972, p.170).

D. Parallel-bedded Tuffs

(i) Occurrence and Field Relations

Parallel-bedded tuffs are exposed at several levels in the succession east of Derwentwater. The lowest ones are interbedded with lavas in the Cat Gill Member at Falcon Crag and in Barrow Beck (NY 270 198), but better examples are seen in BT1, BT2 and BT4 (Plate 1), where they are intimately associated with reworked tuffs and volcanic conglomerates and breccias. The greatest observed thickness of a single parallel-bedded tuff sequence is 7m (in BT1).

(ii) Primary Structures

(a) Parallel bedding and lamination

The even, parallel bedding (Reineck and Singh, 1975, p.82) is mostly thin to medium, but bed thicknesses range from 1 mm to more than 50 cm. Laterally they are very continuous, and beds only a few mm thick may be traced for several tens of metres. Occasionally, slight angular discordances are seen (e.g. in lower part of Plate 12A). Most beds have sharp planar bases and tops. Very commonly, thicker sand grade beds alternate with thinner silt-clay grade beds (Plate 11, 24A), and in some sequences the latter increase in frequency upwards. These fine-grained beds are indurated, and stand out on weathered surfaces (Plate 11). They weather white, and often appear vesicular, due to the presence of weathered-out pumice grains (Plates 27B, 28A). Parallel lamination is well developed and finely spaced in the finer tuffs, but less well developed in the sandstone beds (Plates 11, 27B; Tables 3.6, 3.7). The thickest sand grade tuffs contain lapilli, and thin lapilli tuff beds are also common. Typical sequences in parallel-bedded tuffs are described in Tables 3.6 and 3.7 .

(b) Graded bedding

After parallel lamination, graded bedding is the commonest sedimentary structure. Most graded beds are sharp-based. Normal distribution grading predominates, although reverse grading (Plates 22A, 28B) and coarse tail grading also occur. Normal graded beds become lighter in colour upwards (Plates 17, 27A), in contrast with most non-volcanic graded beds. Within silt-clay grade beds, graded laminae less than 1 mm thick are common.

The graded beds in BT1 and BT4 are simply massive or parallel-laminated. Those in BT2, however, mostly of very fine sand to clay grade, show sequences of sedimentary structures comparable with partial and complete Bouma sequences. (Middleton & Hampton, 1973) (Plates 17, 27A; Figure 24A).

TABLE 3.6

Detailed description of a varnished slice from parallel-bedded tuffs of BT1, examined under the binocular microscope. The beds are described in descending order.

SPECIMEN 1.

	Top not seen
27 mm	Medium sand grade tuff with pink and green lava fragments. Contains several pumice grains, with vesicles infilled with quartz, chlorite and calcite. Near the base is a 3 mm long clast of the underlying unit.
	Sharp base, with microloads 2 to 3 mm wide and ½ to 1mm deep.
3 mm	Clay to very fine sand grade tuff with occasional coarser fragments. Components include small feldspar grains and small green chloritized vitric particles. A thin horizon of hematite-chlorite fragments towards the top of the unit probably represents a pumice layer. The base of the unit is finer grained than the centre, and the top shows normal distribution grading.
	Sharp base. Fine grained material fills the interstices of the medium sand grade tuff at the top of the underlying unit.
35 mm	Fine to medium sand grade tuff, with angular to subrounded grains. Components include pink and green lava fragments, some of them with a vitric appearance. There is also a fine-grained matrix. Parallel bedding is shown up by grain size changes, from fine to medium sand, with rather sharp contacts between beds.
	Base not seen

The most common are cde and de, but the following also occur: abcde, abce, abc, ab, a, e, and occasional reverse coarse tail grading due to the concentration of pumice grains at the tops of beds. A few ungraded massive and parallel-laminated beds are present.

(c) Other Structures

Fine-grained parallel-bedded tuffs of uniform thickness sometimes mantle irregularities on the underlying surface, particularly small scours (Plate 18B) and protruding blocks. This is common in BT4 and is also seen at locality 3 in BT1, where the tuffs overlie breccias. Impact structures below blocks occur rarely (Figure 3.20b). Soft sediment faulting is a frequent feature (Plate 11): the faults are usually normal, with downthrows of a few mm or a few cm, and individual ones may affect a thickness of up to 1m of tuff. Where a bed is coarser than the underlying one, load structures are often developed (Plates 22A, 28B). Sparse occurrences of contorted bedding and slumping have been noted in BT1 and BT2.

(iii) Petrography

(a) General

Most of the tuffs are green in colour. Lithic grains and whole or broken plagioclase crystals are the main components, and either may predominate. Alternating beds may be rich in crystals and lithics respectively, and vitric grains are also common. In many thin sections, alteration has rendered the grain boundaries indistinct, and in some the grains are indistinguishable from the matrix. Both may be indiscriminately overgrown by chlorite and calcite.

(b) Crystal Components

Most of the feldspar grains are plagioclase, but some are too altered to recognize. Orthoclase occurs in some tuffs. The plagioclases are often

TABLE 3.7 A second example of parallel-bedded tuffs from BT1.

SPECIMEN 2.

	Top not seen
20 mm	Very fine to medium sand grade lithic tuff, showing reverse distribution grading. Fragments are very similar to those of the lowest unit.
	Sharp, slightly irregular base
2mm	Silt to clay grade tuff, filling in small irregularities in the top of the underlying bed. This unit contains at least 4 thin graded beds.
	Sharp, slightly irregular base
2 mm	Fine sand grade tuff
	Sharp base with microloads up to 1 mm deep
3 mm	Fine to very fine sand grade grains supported in a silt grade matrix
	Sharp, planar base
3-5 mm	Very fine sand grade vitric tuff, consisting of small devitrified glass shards in a clay grade matrix. Most shards are irregular, but some have shapes characteristic of broken bubble walls
	Sharp, planar base. Slight angular discordance with the underlying unit
60 mm	Fine to medium sand grade tuff, with angular to subrounded fragments of green vitric lava with small feldspars. Vague parallel bedding is defined by grain size changes, and one or two poorly laminated very fine sand to silt grade horizons occur. Overall, the unit coarsens upwards, becoming medium to coarse sand grade at the top.
	Base not seen

zoned, and are altered in the same way as those of the lavas (see II.A.iii above). Feldspar grains are commonly smaller than lithic fragments in the same tuff. Pyroxene crystals, almost always replaced by chlorite, are quite common, and rare clastic grains of quartz and garnet also occur.

(c) Lithic Components

Intermediate medium to dark green or grey lava fragments are the predominant type, showing a wide variety of textures, most of which can be matched with lava flows in the area. They may be aphyric, plagioclase-phyric, plagioclase-pyroxene-phyric, amygdaloidal, flow banded or show a trachytic or perlitic texture, and the groundmass may be vitric or micro-crystalline. Partial or total replacement by calcite or haematite is common.

Acid lava fragments occur frequently, and may be pink, white, light grey or light green in colour. Both aphyric and feldspar-phyric varieties occur, and very rarely they contain garnet. The groundmass is quartzo-feldspathic devitrified glass in most cases. Tuff fragments are not common.

(d) Vitric Components

Small pumice clasts are quite frequent, particularly in silt and clay grade beds. They are replaced by chlorite, with calcite amygdales, and are sometimes altered almost beyond recognition. Pumice, because of its porosity, is very susceptible to alteration and may originally have been a much more abundant component than it now appears. Some highly altered chloritic tuffs may originally have been rich in pumice.

Many tuffs contain angular brown or green chloritic fragments interpreted as devitrified glass. Some have thin rims of chlorite, calcite or opaque oxides, and small feldspar phenocrysts may be present. A few of these grains have the characteristic arcuate and cuspate shapes of glass shards.

(e) Matrix Material

Some of the tuffs contain a considerable amount of fine-grained matrix material. Often this is irresolvable, but where the minerals can be distinguished they include calcite, chlorite, quartz, sericite, opaque oxides (especially haematite and leucoxene), epidote and, rarely, green amphibole. Silt grade detrital quartz and feldspar may also be important matrix constituents. Within the matrix, coarser blebs of calcite, chlorite, epidote and opaques are often developed, and in the more altered tuffs both groundmass and fragments become overgrown by calcite and bright green, slightly pleochroic chlorite. The presence of calcite is sometimes indicated by surfaces showing solution weathering; much of it is thought to originate from the decomposition of plagioclase. It is difficult to determine how much of the matrix represents volcanic dust, and how much is of secondary origin. Certainly both origins are represented: the section includes massive clay grade tuffs with a conchoidal fracture whose fine-grained texture is undoubtedly primary, if somewhat altered and recrystallized, whilst in some altered tuffs, the grains are replaced by fine-grained material of almost identical appearance.

Many of the coarser beds have little or no fine-grained matrix (e.g. Plate 29B) and the fragments are closely packed, sometimes with pressure solution between them. Voids in these rocks may be filled with crystalline chlorite, calcite and quartz.

(f) Grain Size and Shape

The grain size of the parallel-bedded tuffs varies from clay to lapilli, but most fall into the silt to coarse sand grades. Sorting ranges between good and poor, although most samples appear moderately sorted. The majority of the grains are subangular to subrounded. Many thin sections are too altered to allow grain size measurements, but determinations have been made on several from the parallel-bedded tuffs of BT1 (Figures 3.15, 3.16). The usefulness of these diagrams is limited by the presence of a substantial amount of fine-grained matrix, whose grain size distribution and origin are impossible to determine. If material finer than 4ø is disregarded, most of the histograms demonstrate moderate sorting. None of the distributions shown is normal. Different beds in the same thin section (e.g. BT1.8a, c and d, Figure 3.15) may show quite different grain size distributions. Direct comparison with sieve analyses of modern volcaniclastic rocks is not possible, as no correlation factors have been established for sediments with such highly variable grain shape.

(iv) Palaeoslope Indicators

Several soft sediment faults in BT1 and BT4 have downthrows to the west and north, and directional load casts (Figure 3.20a) and overturned contorted bedding indicate movement towards the north and northwest. These observations are insufficient to draw any firm conclusions, but there is a suggestion of a palaeoslope down towards the northwest.

(v) Interpretation

The parallel-bedded tuffs of BT1 and BT4, and some of those of BT2, show many features characteristic of pyroclastic fall deposits, including laterally continuous parallel bedding, parallel lamination, draping of irregularities, normal and reverse grading and occasional impact structures. They are closely comparable with modern ashfall deposits seen by the author on Lipari and Vulcano (Plates 30-32) and with modern and ancient examples described by Segerstrom (1950), Brenchley (1972), Bloomfield (1973), Pettijohn et al. (1973), and Schmincke (1974). Non-vesiculated fragments are commonly the product of Vulcanian or violent Strombolian eruptions (Bloomfield, 1973; Francis 1976). The abundance of crystal-rich tuffs indicates that many of the magmas which erupted explosively were porpyritic, and probably very similar to those which produced the intermediate lava flows of the area. The remainder of the fragments were formed primarily by the explosive disruption of solidified intermediate and acid lava, either congealed in the vent or from earlier volcanic or hypabyssal rocks. Acid magma was at this time only reaching the surface as pyroclastic material.

Bedding in pyroclastic fall deposits results from discontinuity in the activity (Bond and Sparks, 1976). It is thought that each bed fell from a single ash cloud resulting from a single explosion, although the explosions may have been closely spaced in time (e.g. 1973 eruption of Heimaey, Iceland: Dr. C. J. Stillman, personal communication). The formation of bedding is also assisted by changes in wind velocity and direction and, on the ground, by raindrop impact and wind-winnowing (Segerstrom, 1950). Thin, fine-grained beds may be deposited from rain flushing, and commonly contain pumice lapilli which were falling at the same time (Booth, 1973).

Graded bedding results from the differing fall velocities of the various particles: the finer grained material from any one explosion falls more slowly through air or water than the coarser particles (Segerstrom, 1950). This is not true of pumice falling through water, which, because it sinks more slowly, is commonly concentrated at the tops of beds. Further evidence of sorting in the eruption column is provided by the alternation of lithic and crystal rich beds. Declining eruption intensity may also produce graded beds (Brenchley, 1972) and may account for the upward increase in fine-grained beds in some of the BT1 sequences.

It may be difficult to distinguish subaerial airfall deposits from those which fell into quiet, shallow water, and no firm environmental conclusions can be drawn from the parallel-bedded tuffs of BT1 and BT4. The sedimentary sequences described from some of the beds of BT2, however, indicate that they are turbidites. Interbeds which do not show these sequences are probably of ashfall origin.

E. Reworked Tuffs

(i) Occurrence and Field Relations

The lowest tuffs in the succession showing evidence of reworking are those of BT1, and more are seen in the upper part of BT2, and in BT3 and BT4. In all except BT3, they are closely associated with parallel-bedded tuffs, and coarse tuff units are frequently separated by thin, fine-grained airfall horizons. Some tuffs appear massive, with sporadic, rather vague cross-bedding and flat-bedding. They may be bedded throughout, but this does not show because of lack of grain size contrast between beds, or because the bedding has not been picked out by weathering.

(ii) Primary Structures

(a) Cross Bedding

Trough cross bedding (Plate 21A) is the most common type, and the 5 to 15 cm high sets are often very irregular in form (Plate 12B; Figure 3.17). Most have erosive bases, but non-erosive, planar bases are also seen (Plate 12A). Tabular cross bedding has been recorded from BT2 and BT3. Cross bedding is present, although less well defined, in lapilli tuffs (Plate 13A), and lenses of apparently massive lapilli tuff and breccia are common (Plate 23A). Individual cross strata are often sharply bounded, and coarser and finer beds alternate. Thin, rippled silt grade units occur on some foresets.

(b) Flat Bedding

Discontinuous, often poorly defined flat bedding (Plate 13B) alternates with cross bedding in some of these tuffs. It is very different from the

TABLE 3.8 Detailed description of a varnished slice from the contact of cross-bedded tuffs with the underlying parallel-bedded tuffs, BT1 (from the outcrop shown in plate 12A). The section was measured under a binocular microscope. Beds are described in descending order.

SPECIMEN 5

	Top not seen
70 mm	This part of the specimen shows cross-bedding on the weathered surface in outcrop, but it is not easy to see here. A crude stratification can be seen, corresponding to slight grain size variations. The grain size is fine to medium sand, and grains are subangular to rounded. Green, grey and red lava fragments predominate, and there are occasional pumice grains. There is quite a high proportion of fine-grained matrix material. The unit is rather finer at the base.
	Sharp irregular base
7 mm	Very fine sand to silt grade tuff with small feldspathic and chloritic fragments whose shapes suggest devitrified shards, and larger ragged fragments of chloritized pumice. A 12 mm long pumice fragment has partly embedded itself into the unit, causing some disturbance in the top surface.
	Sharp, planar base
33 mm	Fine sand grade tuff, with many fragments subrounded to rounded. Green and grey lava fragments predominate; quartz and haematite grains also occur. The unit is finer at the top. Parallel lamination in the lower 8 mm is shown up by thin fine-grained bands.
	Gradational, planar base
9 mm	Fine to medium sand grade crystal/lithic tuff, with mostly angular to subangular fragments.
	Sharp, planar base, affected by faulting in the underlying unit.
7 mm	Silt to clay grade tuffs, containing at least 7 thin graded beds. Affected by normal soft sediment faults with throws up to 1 mm.
	Sharp, planar base affected by faulting in the overlying unit.
8 mm	Fine to medium sand grade lithic tuff.

even, parallel bedding described from the ashfall deposits.

(c) Ripple Cross-Lamination

Many finer grained beds, including some within parallel-bedded ashfall sequences, contain current ripple cross-lamination (Plates 27B, 28A). Irregular surfaces are often draped, and irregularities filled, by rippled tuff (Plates 22B, 23, 24B; Figure 3.20B). Wave ripple cross-lamination has been recorded from BT2 (Plate 20).

(d) Erosion Surfaces and Channels

Besides the local erosion at the bases of cross sets, more extensive erosion surfaces occur. Some are planar, but most are irregular (Plate 21B; Figures 3.18, 3.19). Steep sided channels, often only 10 to 20 cm deep, with forms very similar to those described from the conglomerates (III.C.iv above) are common (Plate 26; Figures 3.18, 3.19). One outcrop shows evidence of a meandering channel (Figure 3.18b) whilst in others several phases of channelling have taken place at the same site (Plate 26A). Channels may be filled with cross-bedded or parallel-bedded tuff, and some were draped by ashfall material (Plate 26B) prior to filling. A thin basal lag of lava pebbles is present in some channels, whilst others have fills of graded lapilli tuff.

Within the fine, parallel-bedded tuffs of BT2, small scours, and lenses of intraformational conglomerate occur occasionally (Plate 18).

(e) Soft Sediment Deformation

Soft sediment deformation is not common in these tuffs, but small scale faults (Plate 12B) and slumping are seen. In BT4, some tuff beds are stepped down into channels and scours by a series of small faults, and collapse of channel banks appears to have occurred in places (Plate 26A).

(iii) Petrography

The components of the reworked tuffs, and their abundances, are very similar to those of the parallel-bedded tuffs, and need not be described futher here, However, it has been possible to determine plagioclase compositions in several tuffs from BT1 and BT2. They are all low in the andesine range: those from two lava blocks are An_{31} and An_{35}, whilst fresh detrital plagioclases from three tuffs have compositions of An_{31}, An_{32} and An_{34}. These are very similar to those from the blocks, and from many lavas in the area.

Rounding of the grains is marginally better than in the parallel-bedded tuffs. The sorting of the reworked tuffs is mostly moderate to good, and many of the sand grade tuffs have little fine-grained matrix. Scattered lapilli are common.

(iv) Palaeocurrents

Although cross bedding is abundant, it is often exposed only in two dimensions, and palaeocurrents are difficult to measure. Those which can be determined have a wide scatter, and box the compass (Figures 3.14b, 3.25b). Wide divergences may be observed within a single outcrop (e.g. 090°, 270° and 340° at locality 17, BT2).

(v) Interpretation

The compositional and textural similarity to, and close association with the parallel-bedded tuffs indicate that the reworked tuffs described here are locally derived from unconsolidated ashfall deposits. Some of the fine-grained material was removed, but reworking was insufficient to increase the rounding of the grains significantly. Much of the evidence suggests reworking by running water, some of which was confined to channels. For reasons outlinedabove (III.C.iv) these are thought to have been subaerially eroded, and most features of the reworked tuffs can be interpreted in terms of subaerial erosion and deposition. The rippled silty layers, slight angular discordances within ashfall sequences and irregular erosion surfaces may represent deposition and erosion by sheet flow, an important process in some volcanic areas (e.g. Segerstrom, 1950).

Most streams on volcanoes in low latitudes (as this area was in the Ordovician: see Chapter 1) are ephemeral or intermittent (e.g. Segerstrom, 1950; Baker, 1963). They run after heavy rain, which may be seasonal, or may be induced by large eruptions (an eruption column may carry upwards steam from the volcano and entrained moist air, until it reaches a height where precipitation occurs). These streams may vary from a trickle to torrential floods carrying boulders, and this could account for the variety of reworked deposits in the present area.

The cross-bedding was deposited by dunes which often filled irregular erosional hollows, similar to those described in ephemeral desert streams from Utah. In such streams cross bedding is an unreliable indicator of flow direction (Picard and High, 1973). Discontinuous flat bedding may result from deposition by upper flow regime currents, and lenticular bedding may indicate fluctuating flow regimes and migrating channels (Picard and High, 1973). Antidunes frequently developed during torrential floods at Paricutin (Segerstrom, 1950), and may be represented in the massive tuffs of the present section. Graded units may form during receding floods.

The presence of base surge deposits cannot be ruled out, and some of the thin, fine-grained rippled tuffs draping irregular surfaces may have been deposited by this process.

F. The Principle Volcaniclastic Sequences

(i) BT1

(a) Description

Imperfect exposure of this horizon makes correlation between sections difficult, but it is evident that major lateral facies changes occur over a north - south distance of some 200m (Figure 3.22). The ashfall tuffs in the north (more than 10m thick at locality 1) are apparently cut out to the south by the overlying coarse tuffs and conglomerates, which descend as far as the top of the underlying lava flow. Within the reworked sequence, coarser tuffs and conglomerates become more abundant to the south.

At locality 2, ashfall interbeds within the reworked tuffs become thinner and less frequent upwards. BT1 is overlain by a vesicular andesite flow which has disturbed and indurated the uppermost tuffs.

(b) Interpretation

It is suggested that the sections show a large channel or small valley eroded into the ashfall tuffs, and later filled with the deposits of ephemeral streams and debris flows. As in the major channel fill deposits at Paricutin (Segerstrom, 1950) bedding is often poorly defined. All the material is thought to have been derived locally, largely from unconsolidated ashfall material. Rounding of larger clasts does not necessarily imply long distances of transport, as stream transported angular volcanic clasts may become subrounded to rounded only two miles from their source (Pearce, 1970).

(ii) BT2

(a) Description

No major lateral facies changes have been recorded in BT2, but the vertical sequence has been examined in detail (Figure 3.24). Several m of thinly bedded fine-grained tuffs in the lower part of the section at locality A are interrupted by a 50 cm thick sand grade tuff, consisting of a single, erosive-based tabular cross-bedded set directed towards the south. At all localities the parallel-bedded tuffs are succeeded abruptly by coarser reworked sediments (Figure 3.24b), sometimes with an intraformational breccia at the base (see III.C.iv above). This sequence is particularly well seen at locality A (Figure 3.24b) where the breccia is succeeded by trough cross-bedded tuffs which fine upwards over 2m. The cross sets decrease in size upwards, and the sequence is overlain by more parallel-bedded tuffs with a wave ripple-laminated bed.

Above this, the remainder of the sequence is mostly of cross-bedded tuffs but, at locality 25 fine-grained, parallel-bedded tuffs are seen below the overlying welded tuff.

(b) Interpretation.

In the lowest part of the sequence. coarse interbeds and other evidence of reworking (e.g. Plate 18) indicate that the fine-grained turbidites were deposited in shallow, but for the most part, tranquil water. Such an association is difficult to envisage in a shallow marine environment. It is suggested that this may have been a lake, perhaps a few m deep, and that accumulations of fine ashfall material became unstable, sloughing away as turbidity currents. Some was deposited into the lake as primary ash shower beds. At one stage, an ephemeral stream entered the lake, depositing a thick cross-bedded unit.

Later, after the partial lithification of thinly bedded tuffs, the uppermost ones were disrupted by a violent event, probably a torrential flood entering the lake. As it waned, the flood deposited first the tuff clasts and then cross-bedded sand whose grain size and set thickness decrease upwards. After this event, more ash showers were deposited into the lake, and were gently reworked by wave action. The less well exposed upper parts of the section are dominated by reworked ashfall material, but ash shower deposits occur again near the top of the sequence.

(iii)BT3

This tuff unit is reworked throughout. Its petrography and primary structures are very similar to those seen in other volcaniclastic horizons, and it is thought to consist of local stream-reworked ashfall material.

(iv)BT4

(a) Description.

BT4 is a laterally continuous horizon showing no ordered sequence; there is random interbedding of parallel-bedded and reworked tuffs and lenticular and sheetlike breccias. A complex series of erosion surfaces and channels is exposed. Part of the sequence is shown in Figure 3.25a.

(b) Interpretation.

The sediments represented include ashfall deposits, mudflow units and ashfall material reworked by streams. The lateral continuity of BT4 suggests that they are not confined to a valley. The facies association is similar to that described from alluvial fans in both volcanic and non-volcanic areas(Segerstrom, 1950 ; Cooke and Warren, 1973;Reineck and Singh,1975)

IV.ENVIRONMENTAL SYNTHESIS.

A. The Overall Sequence.

Generally the lava flows in this succession give little indication of environment:it is the volcaniclastic horizons which provide the key. In the Cat Gill Member, the presence of subaqueous tuffs (Honnorez and Kirst, 1975:see Chapter 2), a single occurrence of non-volcanic mudstone and the absence of reworking indicate a subaqueous environment. The first evidence of subaerial reworking is seen in BT1, at the base of the Brown Knotts Member, and continues intermittently up into the Thirlmere Andesites(BT4). In BT2, lacustrine turbidites are believed to be represented, whilst higher in the sequence a partially welded ignimbrite and a shallow andesitic intrusion with peperite are exposed.

B. The Volcanic Environment.

Although slopes must have existed in order for streams to flow and to incise steep sided channels, nowhere in the succession is there any suggestion of steep slopes: the lava flows are often laterally extensive; there is a wide scatter of palaeocurrent directions; all the parallel-bedded tuffs have similar dips. Since the turbidites of BT2 must originally have been horizontal, it follows that the other parallel-bedded tuffs were also deposited on near-horizontal surfaces. Thus, local steep sided tuff cones such as that of Vulcano (plate 32) are not represented here.

Possibly the section forms part of a large andesitic strato-volcano, and this is discussed further in Chapter 7. In many respects, the subaerial part of the sequence resembles that of the andesitic, plateau like, monogenetic volcano fields of Mexico (Krauskopf, 1948; Segerstrom, 1950; Bloomfield, 1975). These have extensive lava flows and gently dipping ashflow deposits which blanket the surrounding topography. They originate from cones composed of scoriaceous or blocky andesite fragments. A single cone is formed rapidly and erupts for only a few months or years before becoming extinct. Several tens of years later, another cone may be erupted, with its associated lava flows and ashfall deposits. The ashfall deposits rapidly become deeply dissected and reworked by ephemeral streams and sheet and gully erosion.

Admittedly there is no evidence for these cones in the present section, but they are eften spaced several km apart and may be destroyed by erosion and by rafting away of parts of the cones by lavas emerging from beneath them.

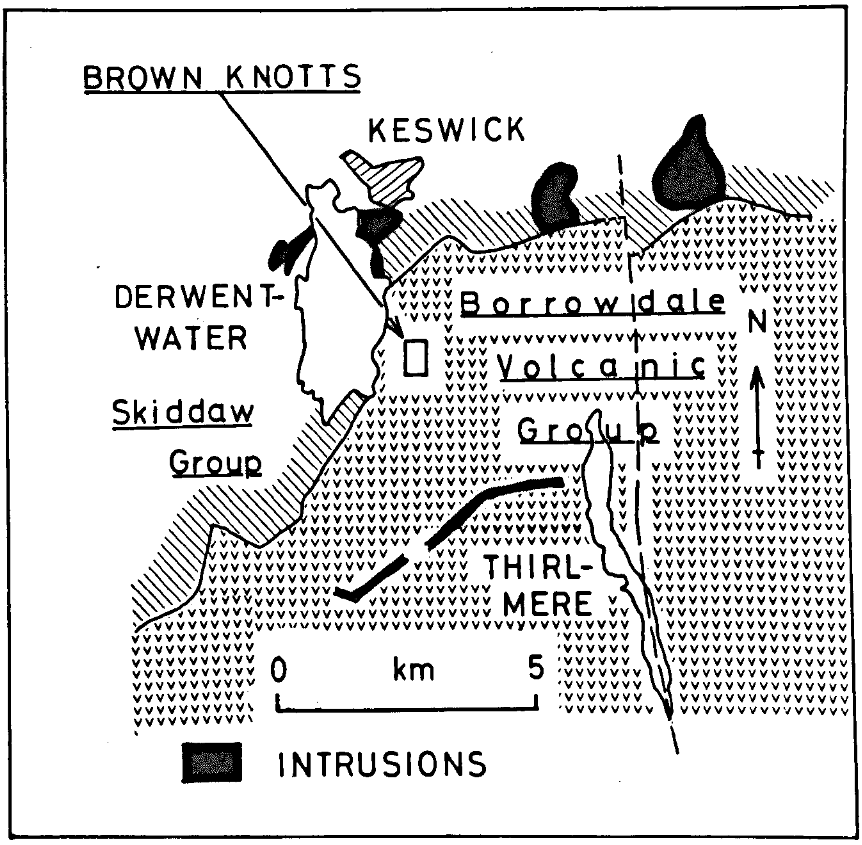
C. Sources.

Sources are very difficult to determine, as no significant thickness variations have been observed in any of the lavas or volcaniclastic units. Certainly some of the conglomerates in BT1 were derived from the south, suggesting that one source lay in this direction. Earlier authors (e.g. Ward, 1876) have suggested that the Castle Head dolerite intrusion near Keswick, north of the present area (Figure3.1a) is a volcanic neck. This intrusion is more basic than the lavas in the area (48% SiO_2 :Fitton, 1971), but this does not preclude its being a source. If the environment was of the monogenetic volcano field type, a number of sources should be expected, and earlier vents might be covered by later lavas and volcaniclastic rocks.

FIGURE 3.1

(a) Map indicating the position of the Brown Knotts section, relative to the regional geology. (After Geological Survey quarter-inch sheet 3).

(b) Locality map of the Brown Knotts area. Numbers refer to localities mentioned in the text.


BROWN KNOTTS
KESWICK
DERWENT-
WATER
Borrowdale
Volcanic
Group
Skiddaw
Group
N
THIRL-
MERE
0 km 5
INTRUSIONS

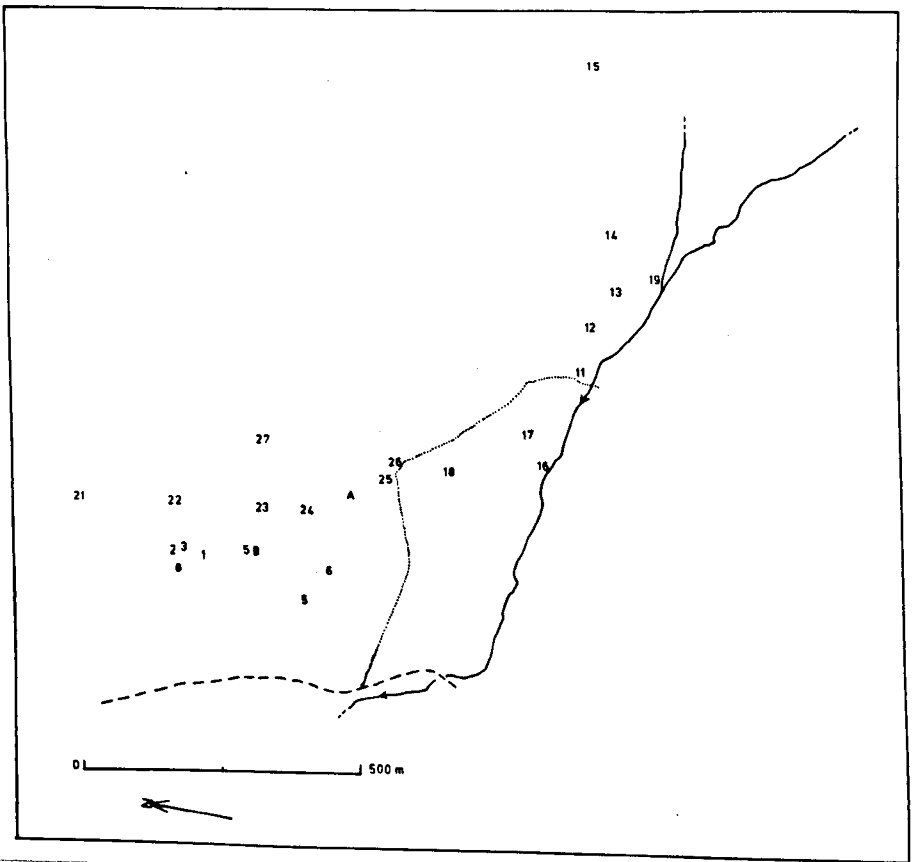

15
14
19
13
12
11
27
17
26
25
18
16
21
22
23
24
A
2 3
1
5
6
0 500 m

FIGURE 3.2

Geological map of the area east of Derwentwater.

Within the thick andesite sequences, only a few of the many flow boundaries are shown. Shallow intrusions are not differentiated from lavas. Shading indicates the predominant lithology: thin tuff bands between lavas, and thin lavas within tuff sequences, are not shown.

Topographic detail from 1:10,560 Ordnance Survey map.

GEOLOGICAL MAP OF THE AREA EAST OF DERWENTWATER

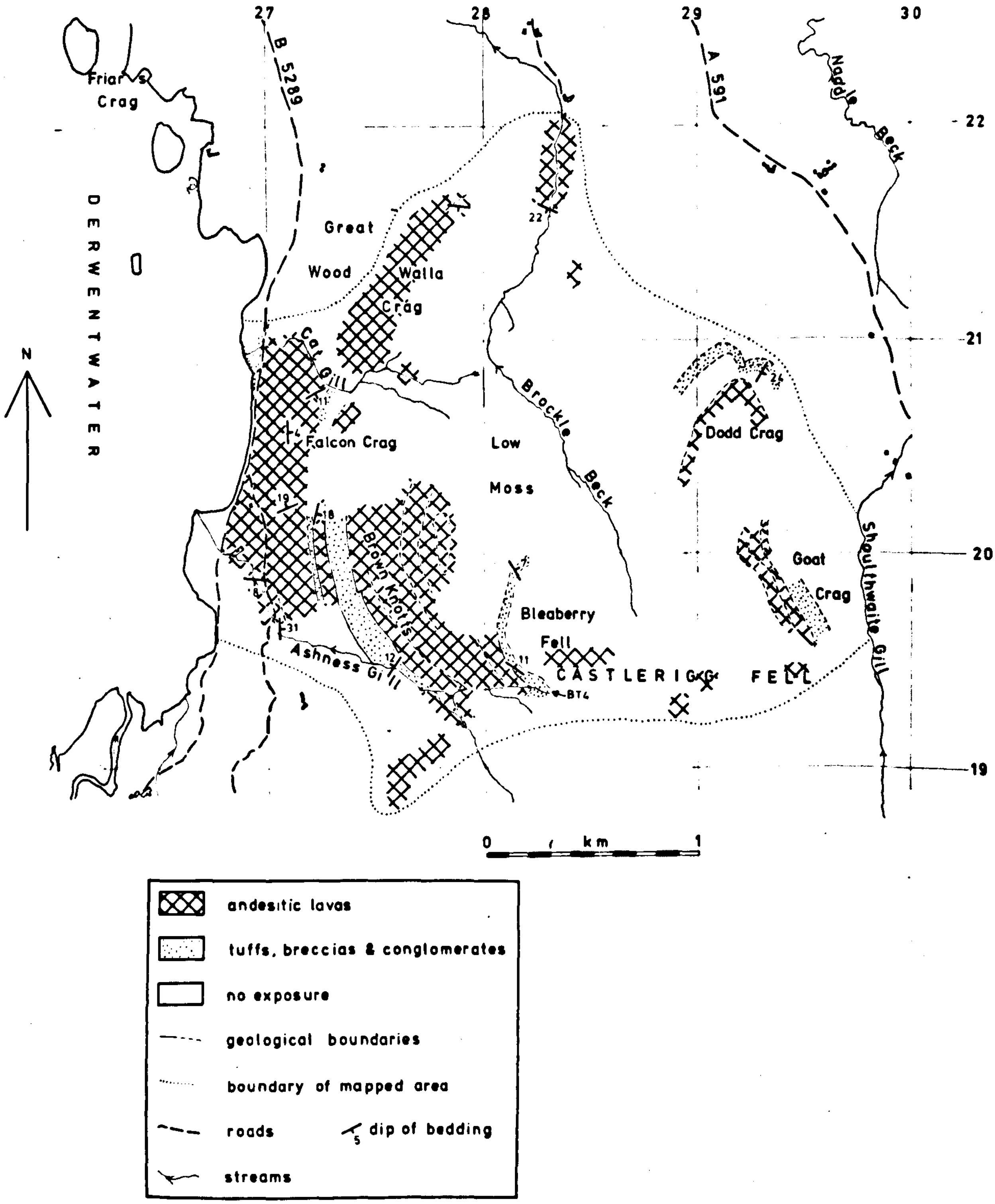
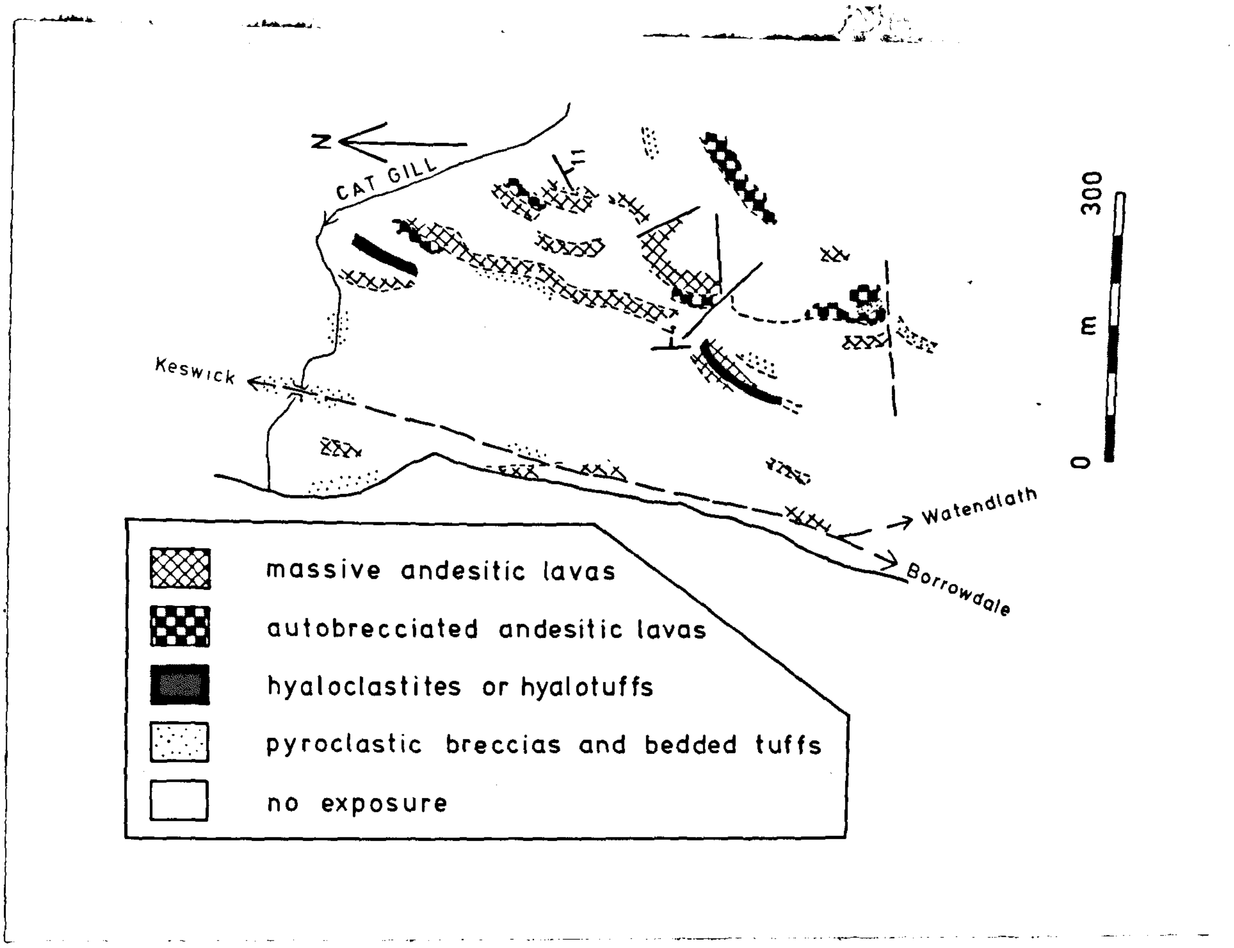


FIGURE 3.3

(a) Outcrop map of the Falcon Crag area. Based on enlarged aerial photographs.

(b) Geological cross-section of the Brown Knotts area along the line A-B of plate 1.


N
CAT GILL
Keswick
Watendlath
Borrowdale
0
m
300
massive andesitic lavas
autobrecciated andesitic lavas
hyaloclastites or hyalotuffs
pyroclastic breccias and bedded tuffs
no exposure

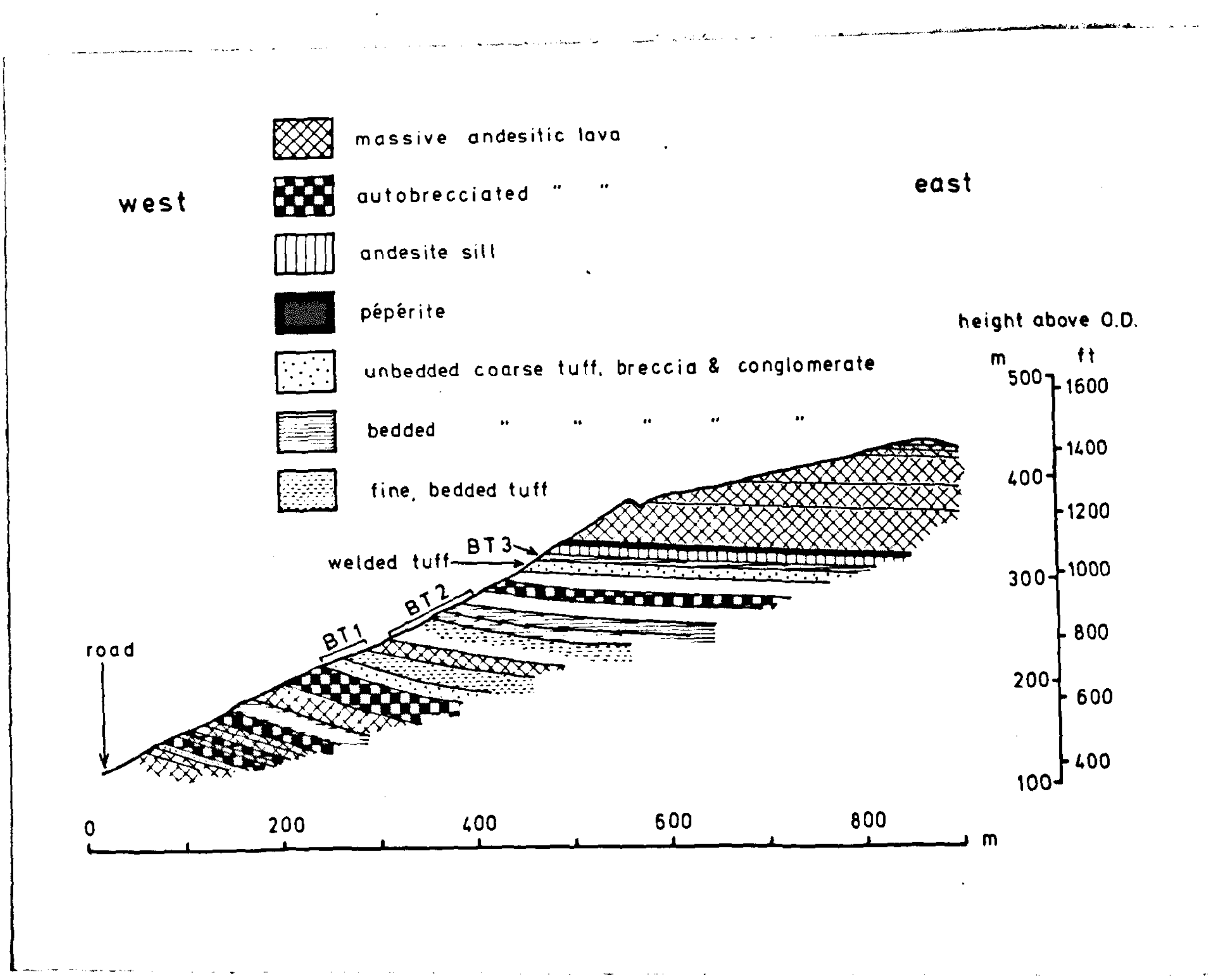
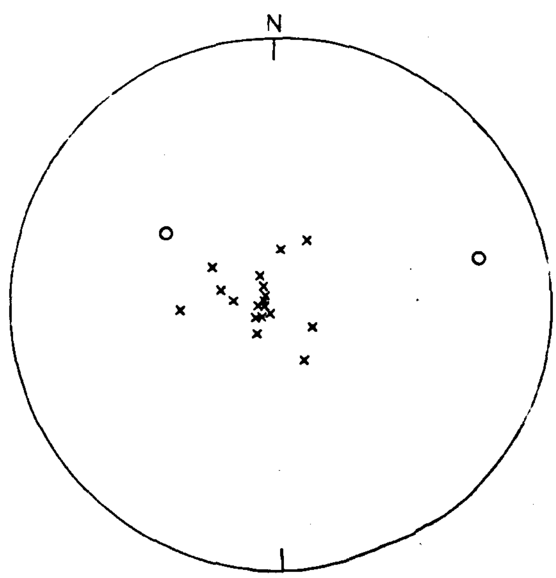

west
east
massive andesitic lava
autobrecciated " "
andesite sill
pépérite
unbedded coarse tuff, breccia & conglomerate
bedded " " " " "
fine, bedded tuff
height above O.D.
m
ft
500
400
300
200
100
1600
1400
1200
1000
800
600
400
welded tuff
BT3
BT2
BT1
road
0
200
400
600
800
m

FIGURE 3.4

Lower hemisphere stereographic projection of structural data from the Brown Knotts area, Borrowdale.

BORROWDALE - STRUCTURAL DATA



× poles to bedding

o poles to cleavage

FIGURE 3.5

The succession of the Borrowdale Volcanic Group in the Borrowdale - Thirlmere area.

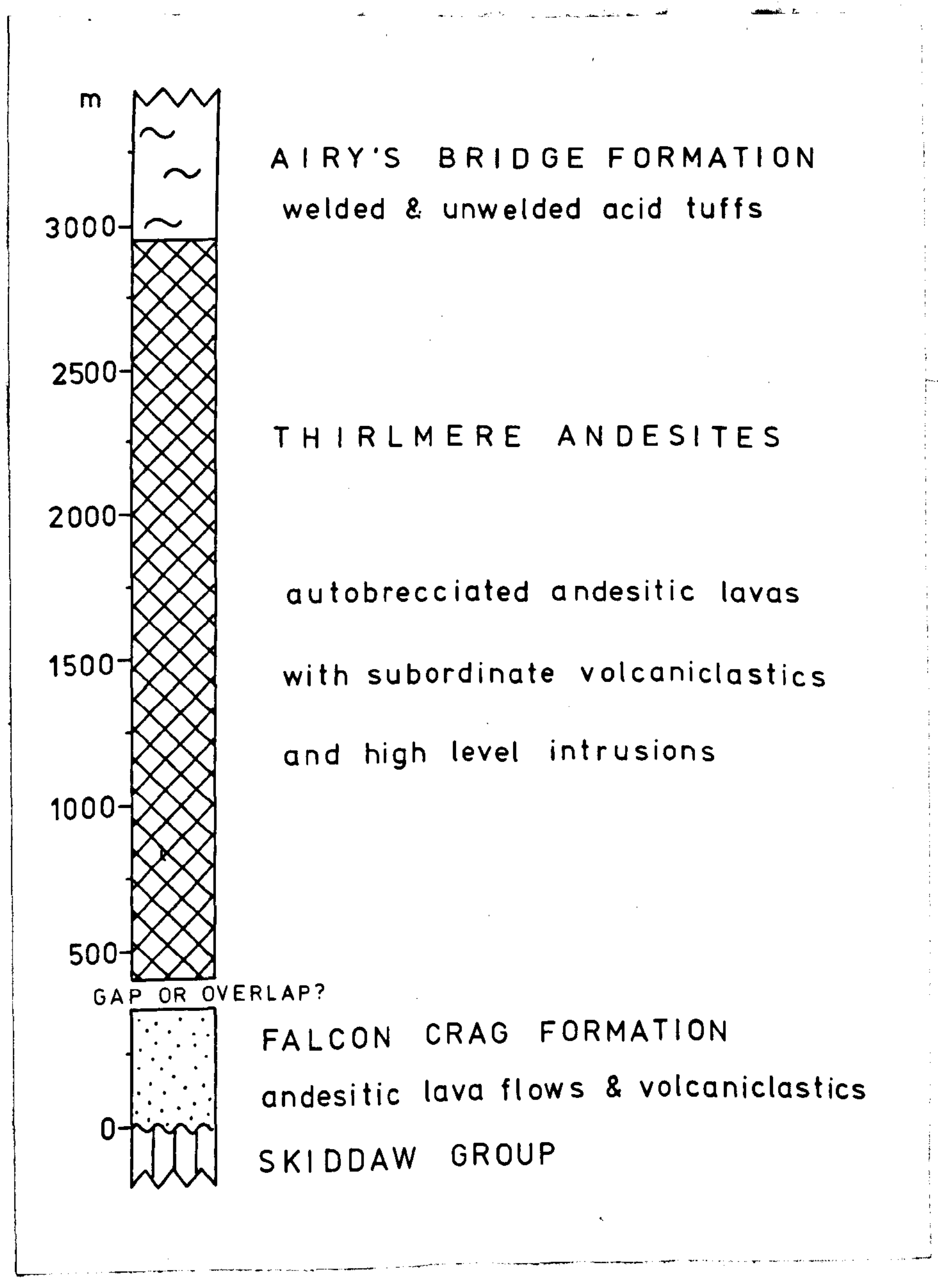
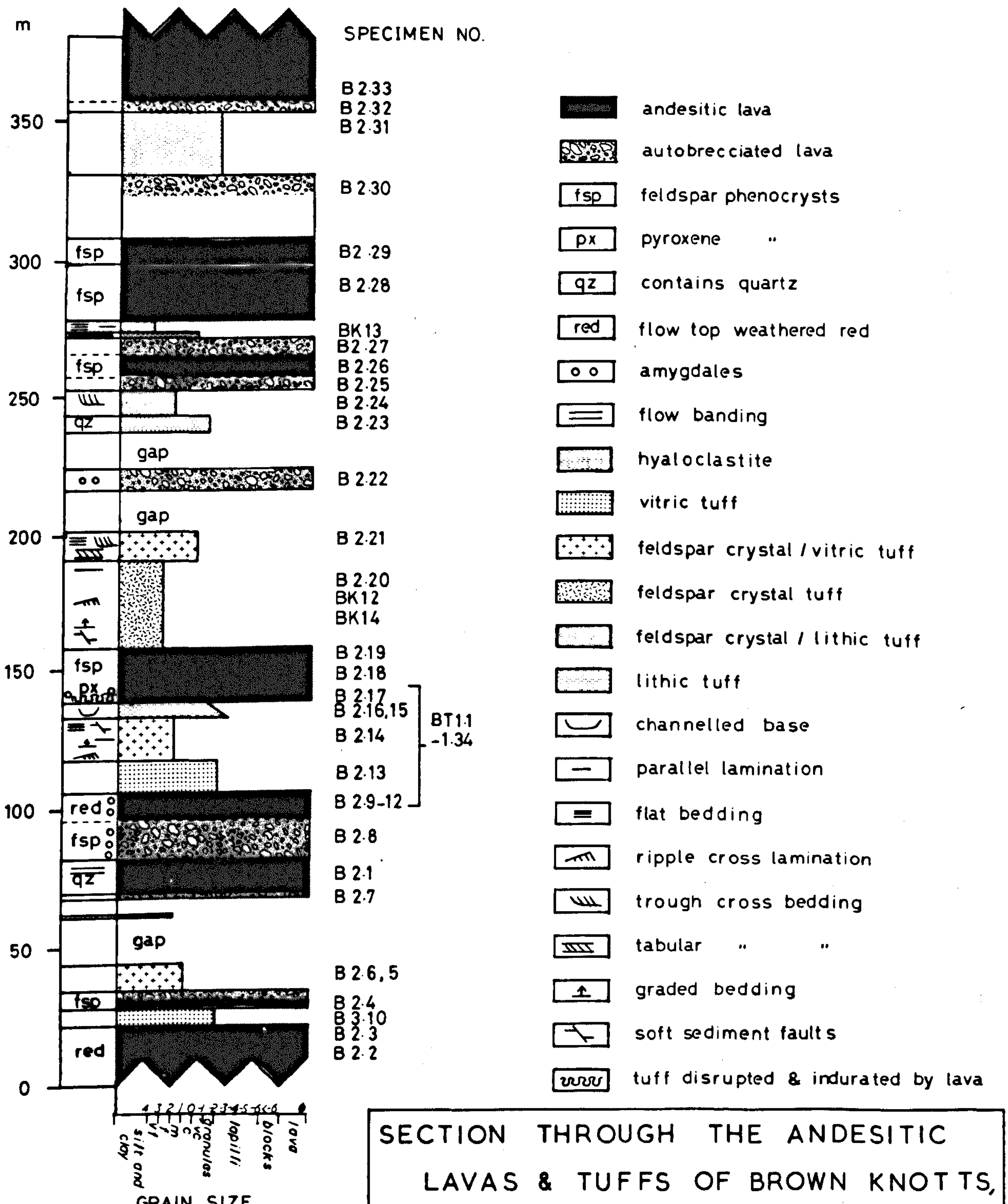

m
3000
2500
2000
1500
1000
500
0
AIRY'S BRIDGE FORMATION
welded & unwelded acid tuffs
THIRLMERE ANDESITES
autobrecciated andesitic lavas
with subordinate volcaniclastics
and high level intrusions
GAP OR OVERLAP?
FALCON CRAG FORMATION
andesitic lava flows & volcaniclastics
SKIDDAW GROUP

FIGURE 3.6

Section through part of the succession at Brown Knotts,

Borrowdale, commencing 100m below BT1.



SECTION THROUGH THE ANDESITIC LAVAS & TUFFS OF BROWN KNOTTS, BORROWDALE.

FIGURE 3.7

Stratigraphy of the Brown Knotts - Bleaberry Fell area, Borrowdale.

Key:	cross hatching	:	andesitic lavas
	unshaded	:	bedded tuffs
	wavy symbol	:	welded tuffs
	vertical lines	:	pelites

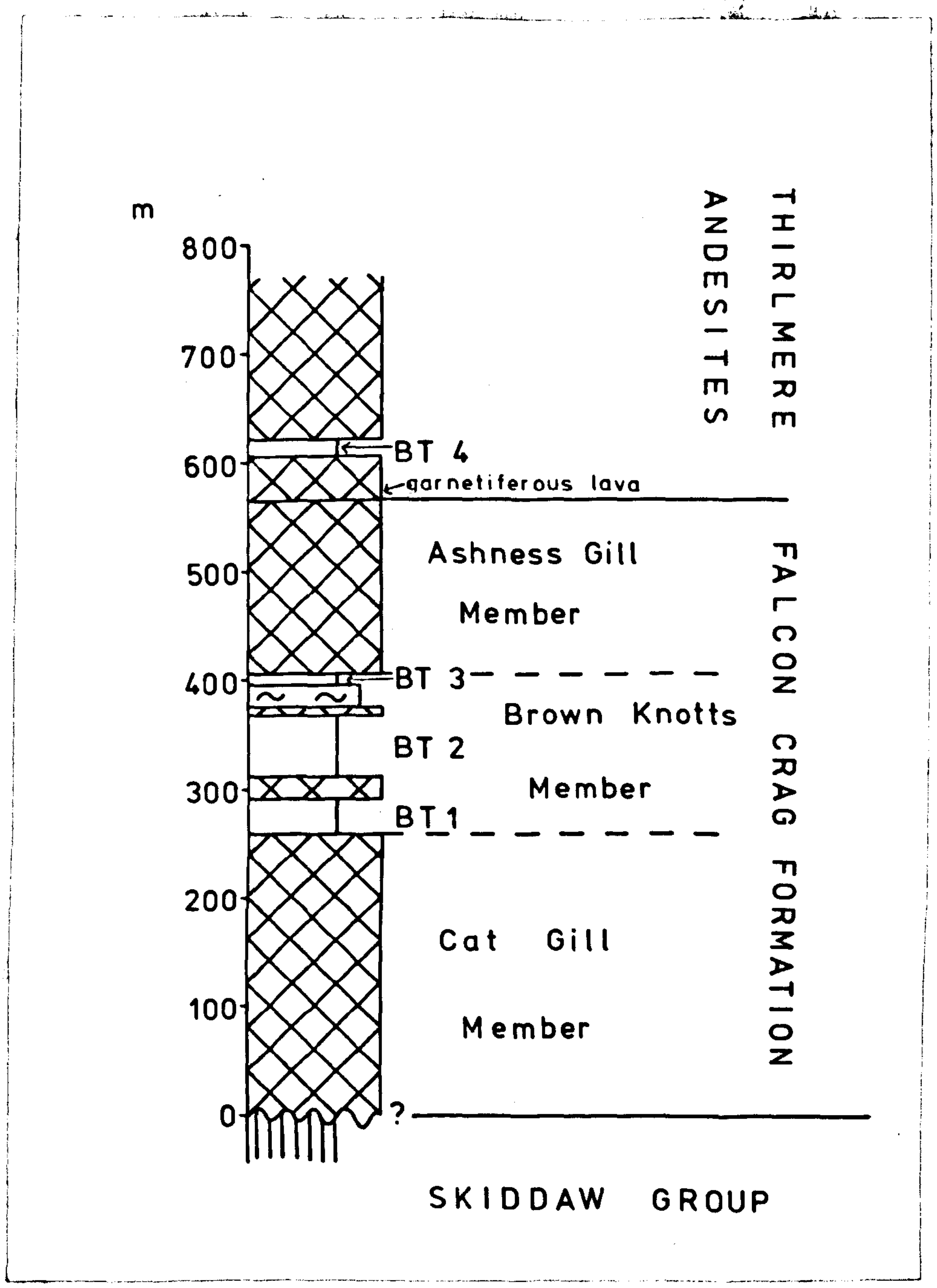
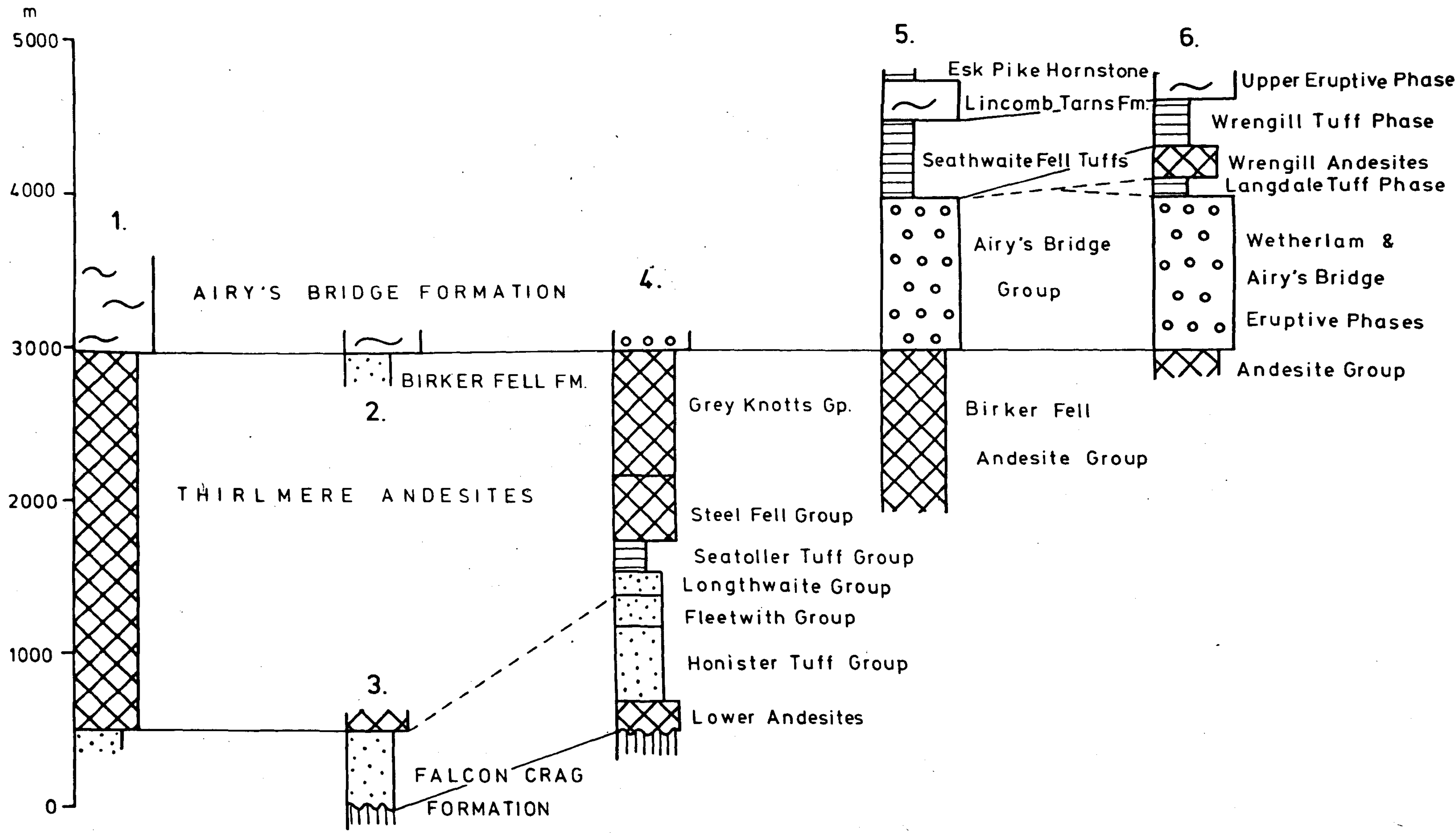

m
800
700
600
500
400
300
200
100
0
BT 4
garnetiferous lava
BT 3
BT 2
BT 1
?
THIRLMERE ANDESITES
Ashness Gill Member
Brown Knotts Member
Cat Gill Member
FALCON CRAG FORMATION
SKIDDAW GROUP

FIGURE 3.8

Lithostratigraphical correlation of the Borrowdale and Thirlmere sections of the present account with those in adjacent areas. The thicknesses of most units are variable. Key as for Figure 1.8. Broken lines indicate uncertainty.

1. Thirlmere (present account)
2. Sour Milk Gill, Borrowdale (present account)
3. Brown Knotts, Borrowdale (present account)
4. Borrowdale - Honister (Strens, 1962)
5. Borrowdale - Scafell (Oliver, 1961)
6. Langdale (S.M. Smith, unpublished)

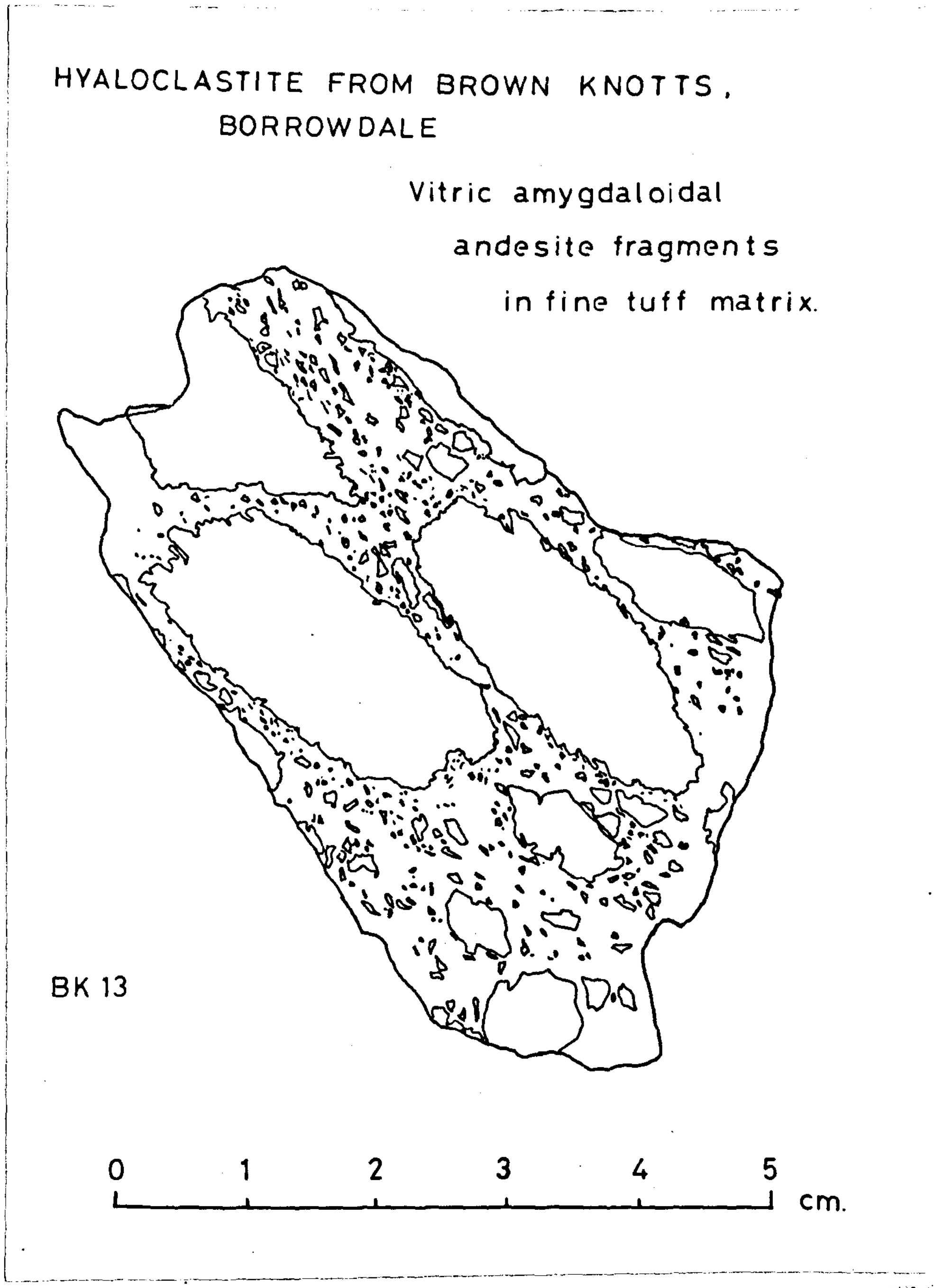


m
5000
4000
3000
2000
1000
0
1.
AIRY'S BRIDGE FORMATION
THIRLMERE ANDESITES
2.
BIRKER FELL FM.
3.
FALCON CRAG
FORMATION
4.
Grey Knotts Gp.
Steel Fell Group
Seatoller Tuff Group
Longthwaite Group
Fleetwith Group
Honister Tuff Group
Lower Andesites
5.
Esk Pike Hornstone
Lincomb Tarns Fm.
Seathwaite Fell Tuffs
Airy's Bridge
Group
Birker Fell
Andesite Group
6.
Upper Eruptive Phase
Wrengill Tuff Phase
Wrengill Andesites
Langdale Tuff Phase
Wetherlam &
Airy's Bridge
Eruptive Phases
Andesite Group

FIGURE 3.9

(a) Peperite from above andesitic intrusion, Brown Knotts. Enlarged tracing from varnished rock slice. Locality 27.

(b) Conglomerate showing concentration of large clasts towards base, in a matrix of coarse to very coarse sand grade. The conglomerate is underlain by medium to coarse sand grade tuff with traces of cross-bedding and flat-bedding. Sketch from photograph. Horizon BT1, locality 6E.


HYALOCLASTITE FROM BROWN KNOTTS, BORROWDALE
Vitric amygdaloidal andesite fragments in fine tuff matrix.
BK 13
0 1 2 3 4 5
cm.

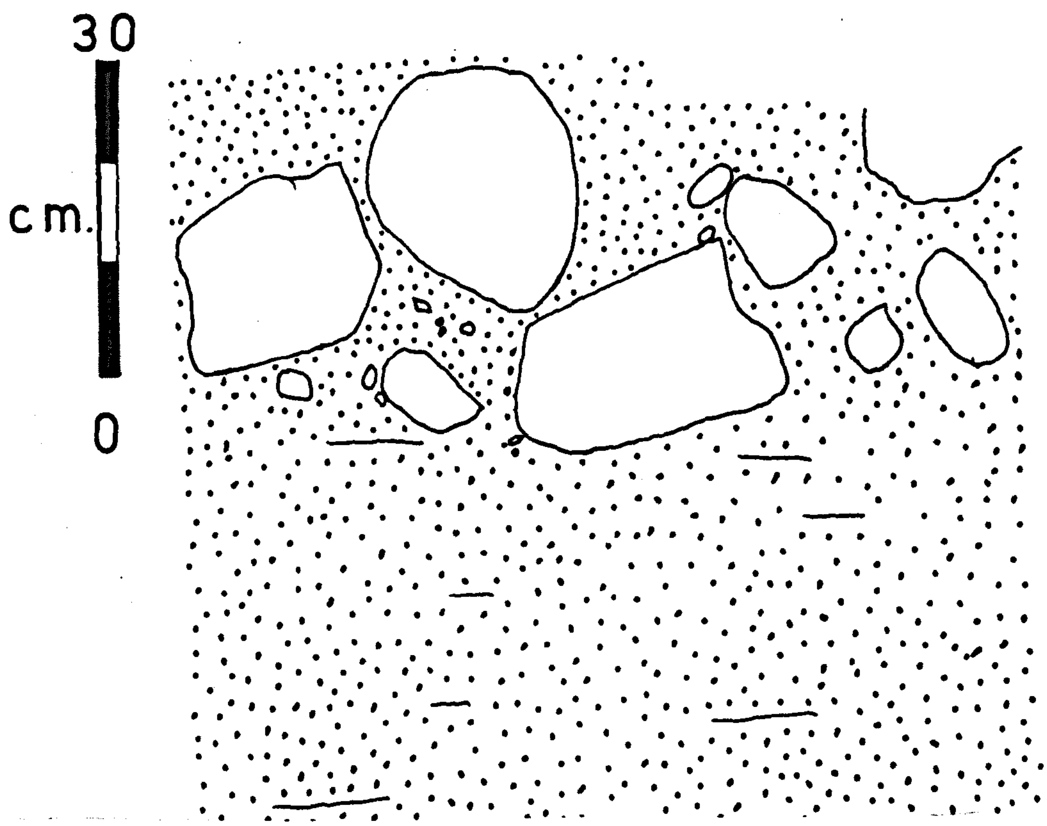
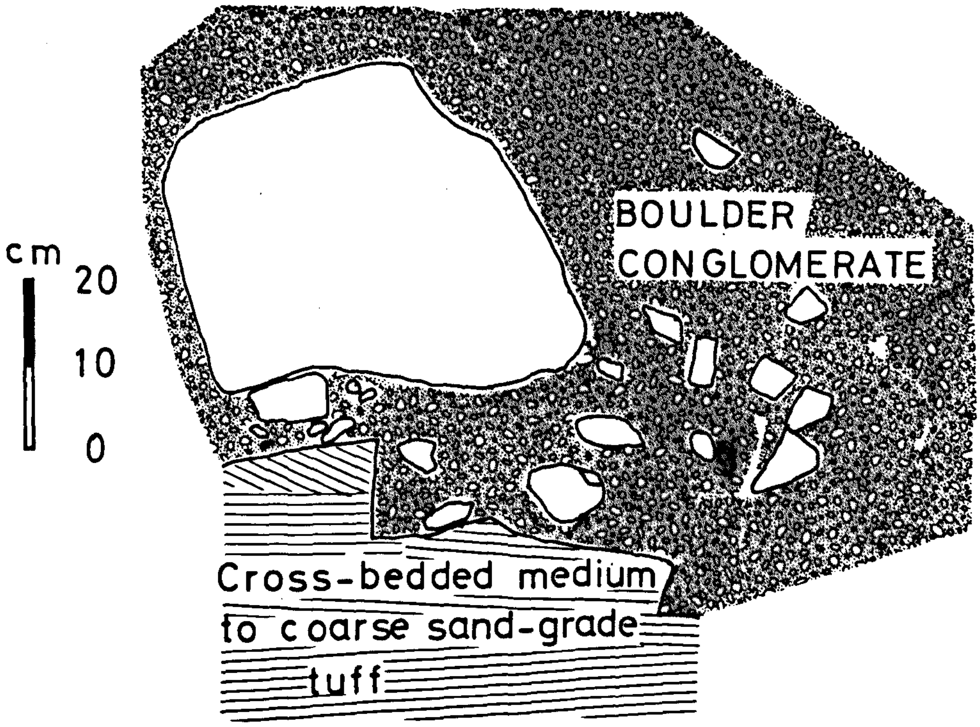

30
cm.
0

FIGURE 3.10

(a) Steep-sided, conglomerate-filled channel with stepped profile. Horizon BT1, locality 3. Drawing from photograph.

(b) Steep-sided, conglomerate-filled channel. Horizon BT1, locality 5. Drawing from photograph.

CHANNEL AT LOC. 3, BT1, BROWN KNOTTS



CHANNEL AT LOC. 5 BT1, BROWN KNOTTS

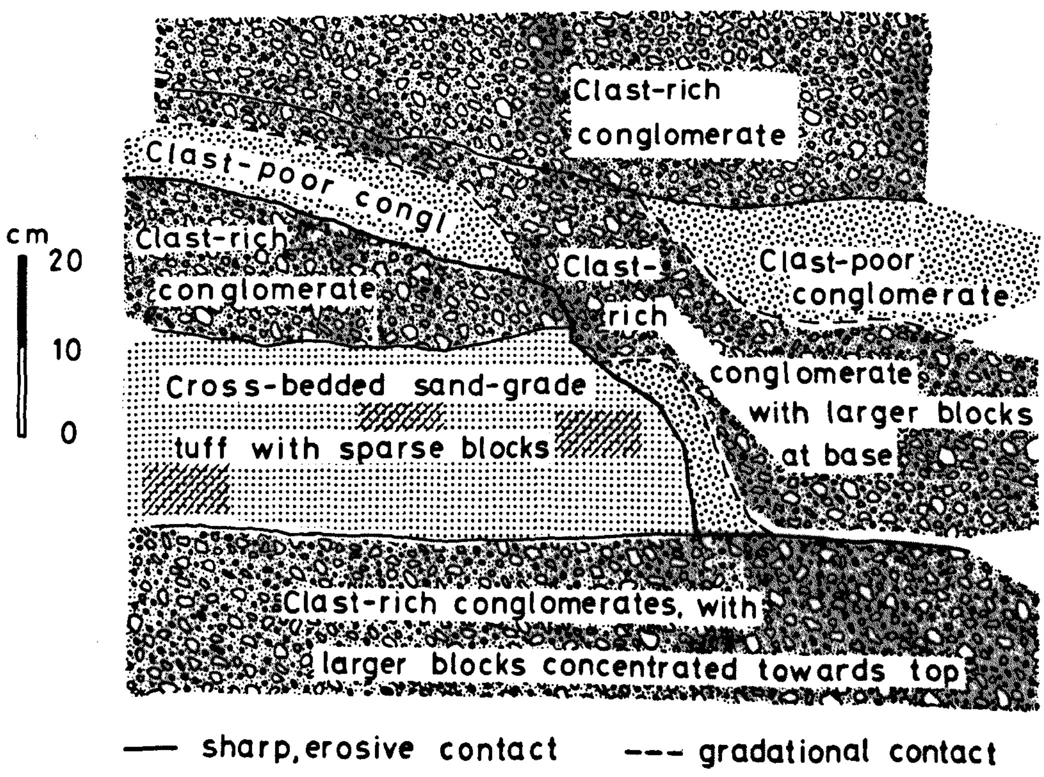


FIGURE 3.11

(a) to (e) Grain size analyses from conglomerates of horizon BT1.

(a) locality 5: lower outcrop

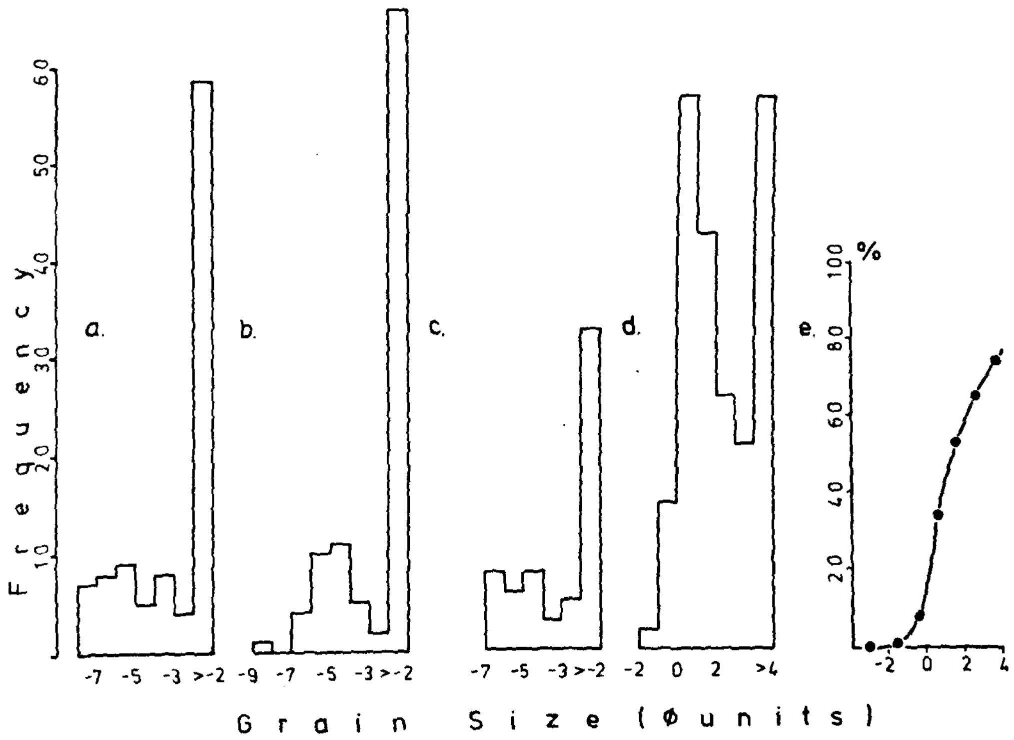
(b) locality 5: upper outcrop, sections A to E

(c) locality 5: upper outcrop, sections F and G.

(d) locality 3: matrix of conglomeratic channel-fill.

(e) cumulative curve of (d)

(f) Plot of length versus length:width ratio for clasts from the conglomerates of BT1 at locality 5.


Frequency
a.
b.
c.
d.
e.
%
Grain Size (ø units)

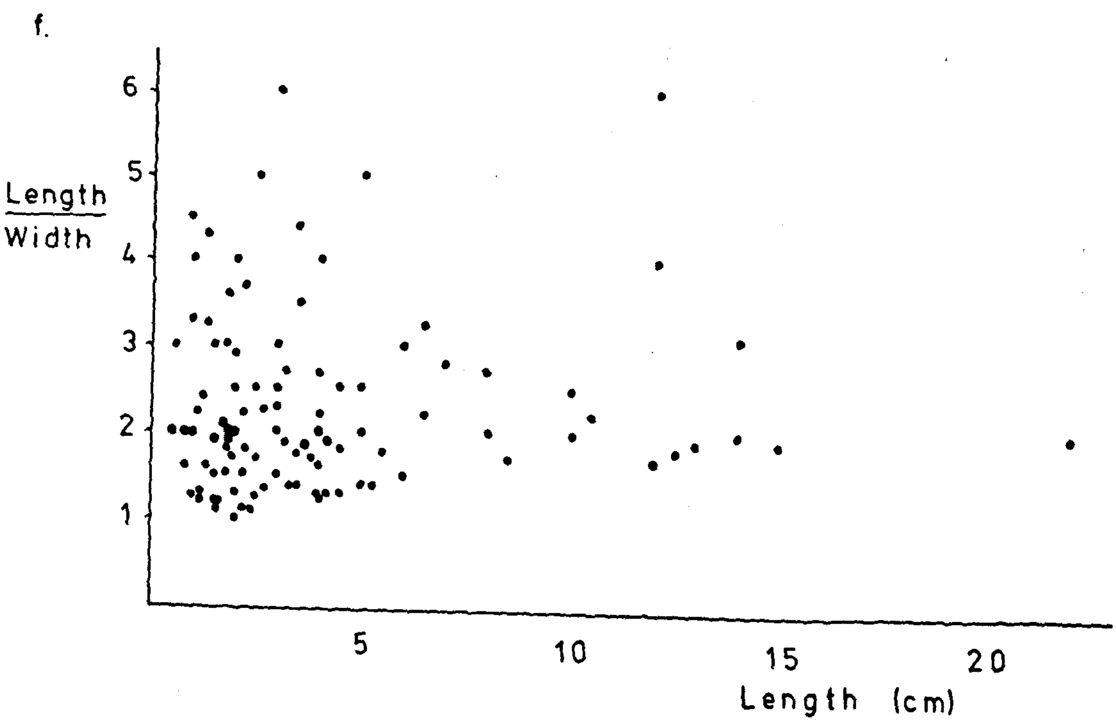

f.
Length / Width
Length (cm)

FIGURE 3.12

Directions of dip of elongate clasts in the conglomerates of BT1. The rose diagrams are divided into 10° classes.

(a) Channelling breccia, locality 3.

(b) Lower outcrop, locality 5.

(c) Upper outcrop, sections A to E, locality 5.

(d) Upper outcrop, sections F & G, locality 5.

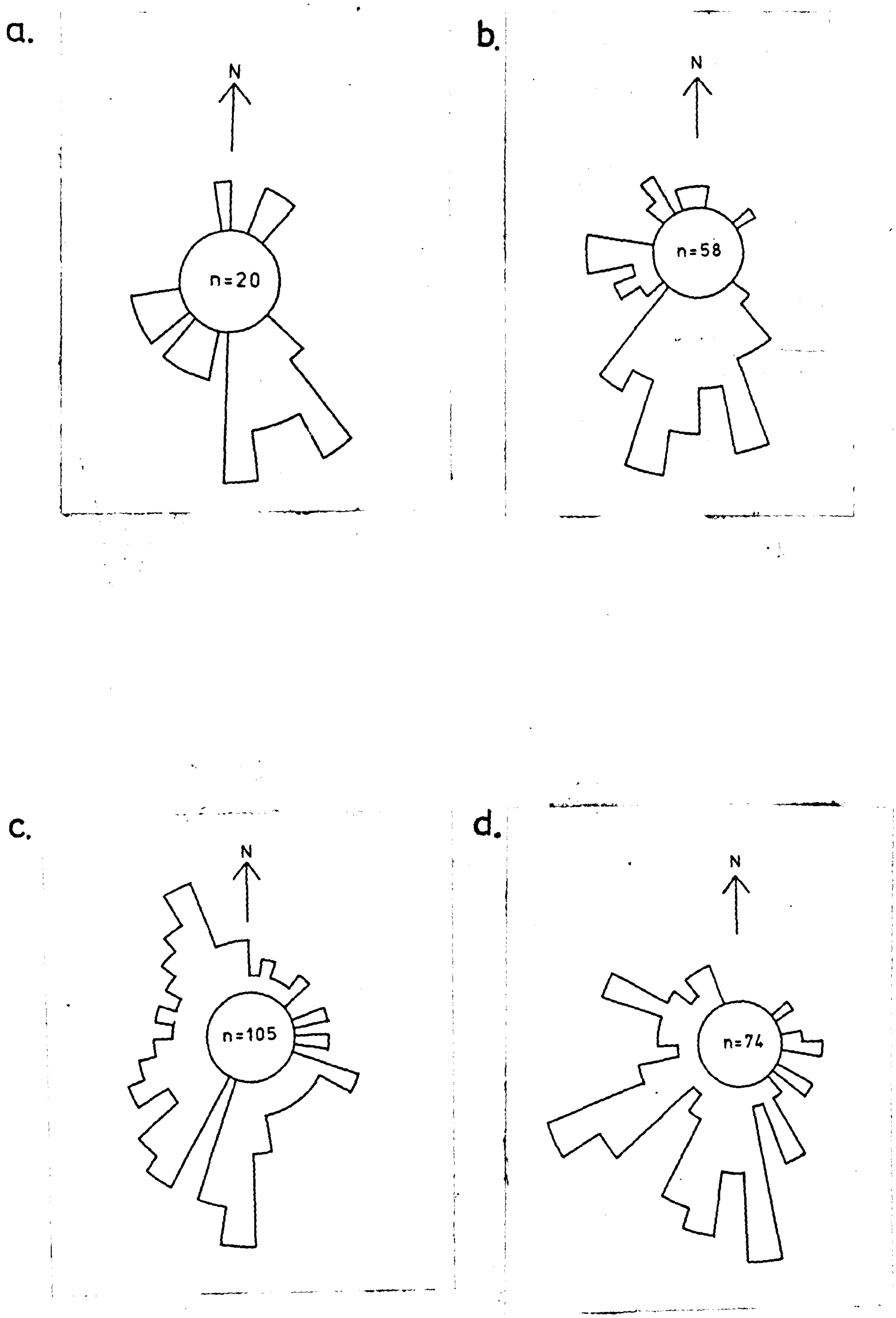
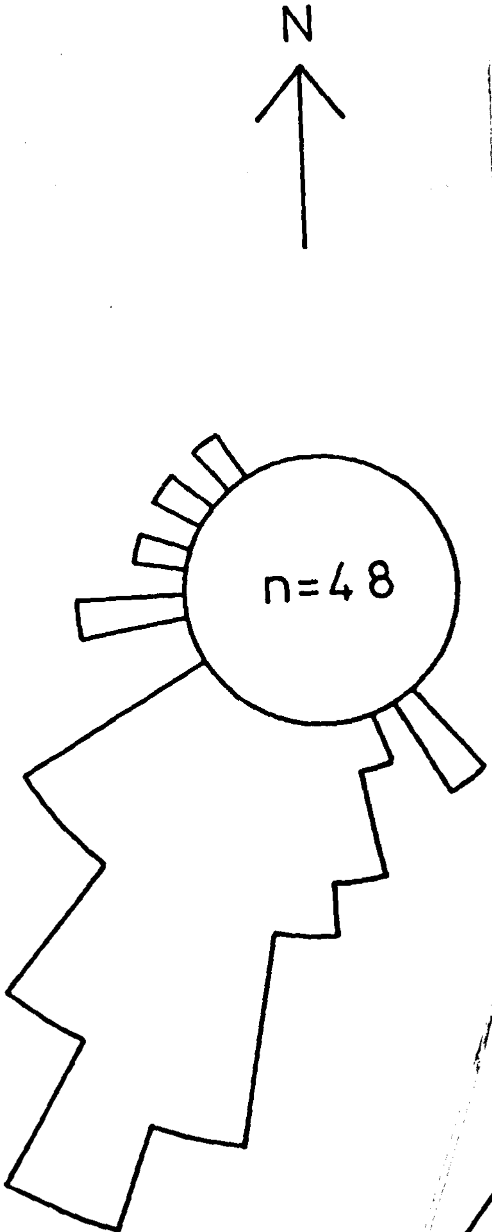

a.
N
n=20
b.
N
n=58
c.
N
n=105
d.
N
n=74

FIGURE 3.13

Directions of dip of elongate clasts in the conglomerates of BT1.

(a) Locality 6E, unit 1.

(b) Locality 6E, unit 2.


N
n=48

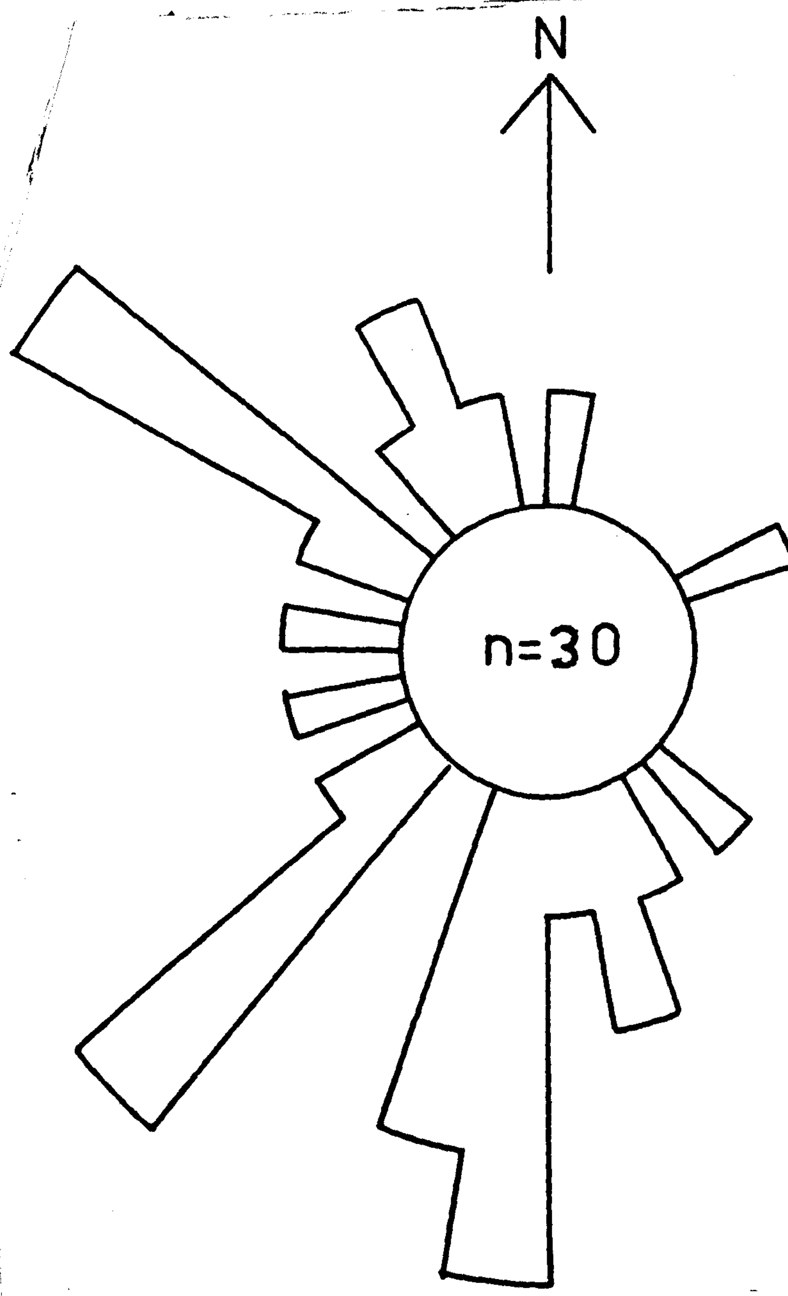

N
n=30

FIGURE 3.14

(a) Directions of dip of all clasts in the conglomerates of BT1

(b) Palaeocurrent directions in bedded tuff horizons BT1, BT2 and BT3.

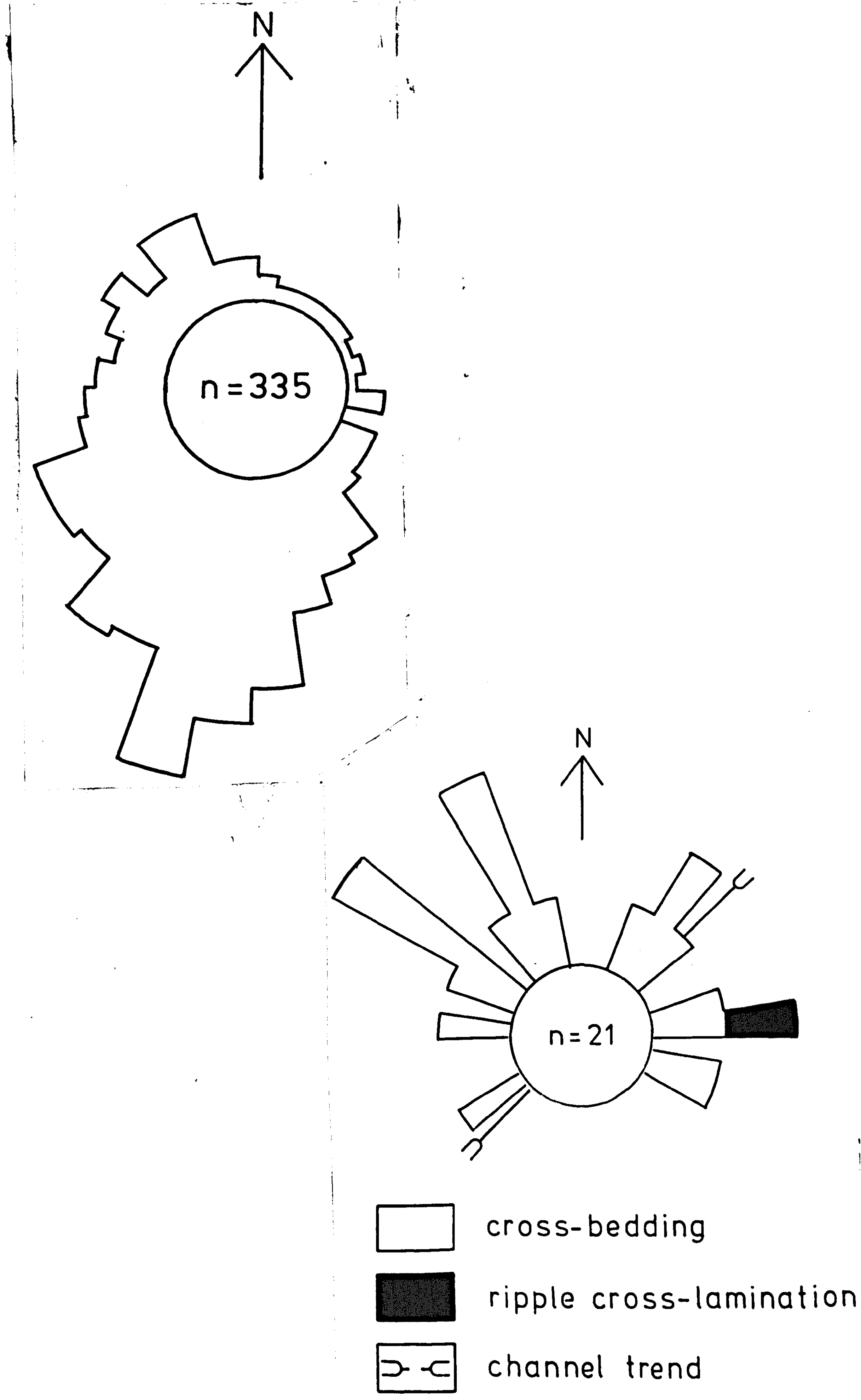
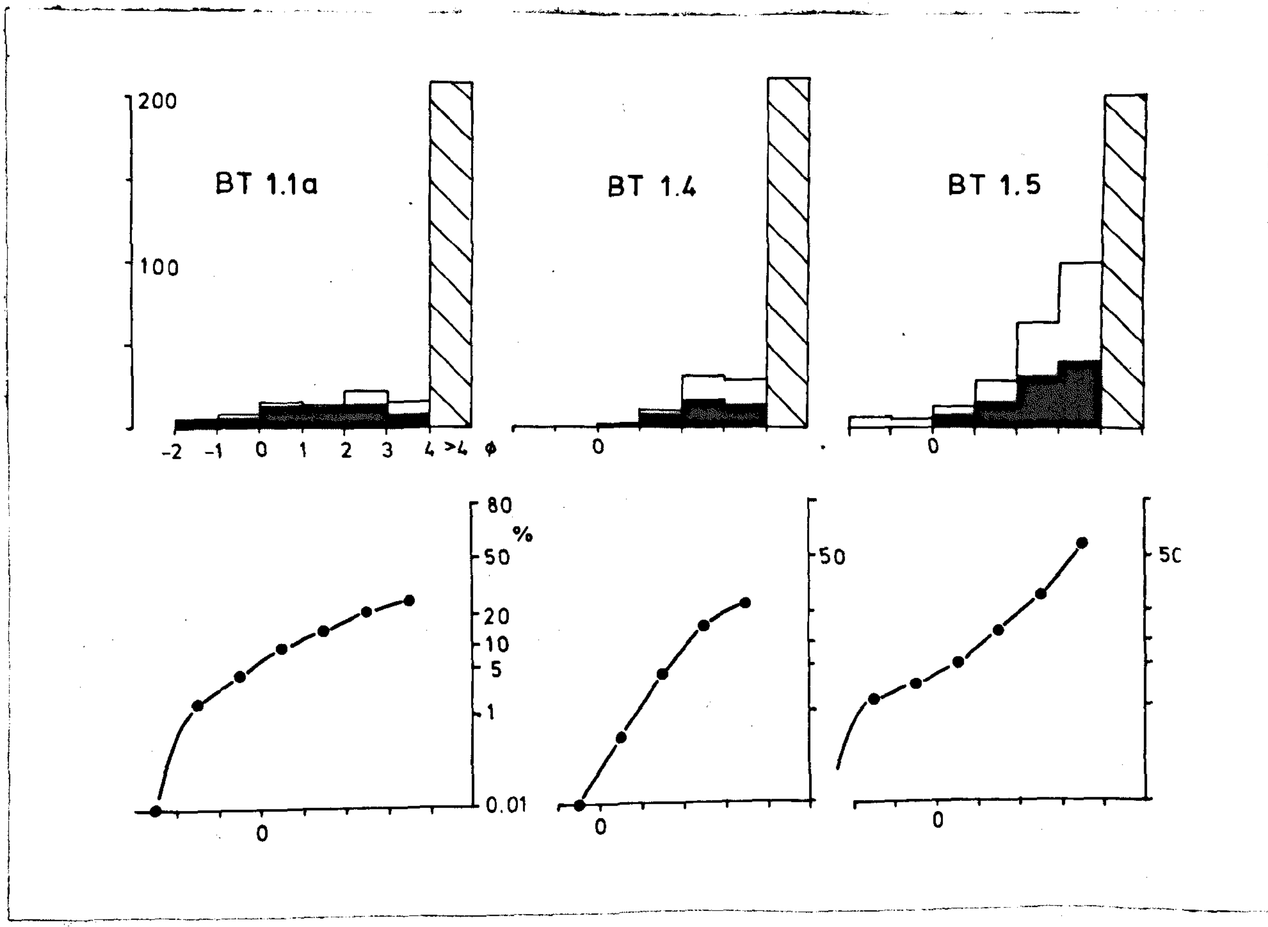

N
n = 335
N
n = 21
cross-bedding
ripple cross-lamination
channel trend

FIGURE 3.15

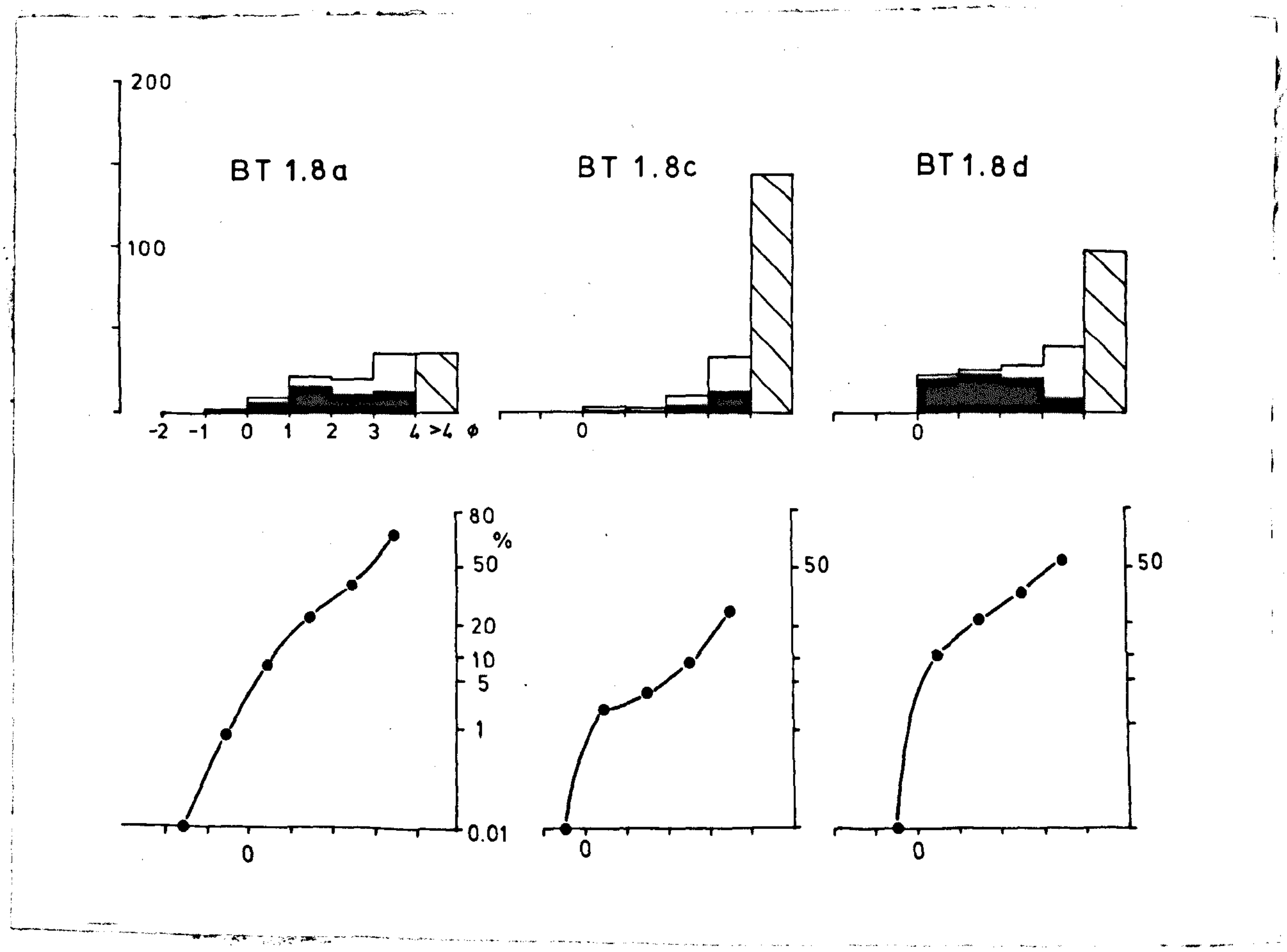
Grain size characteristics of parallel-bedded tuffs from BT1.

Histograms: black - feldspar crystals
unshaded - other components
diagonal lines - undifferentiated silt and clay grade material.

The cumulative curves are plotted on probability paper. Numbers refer to specimen numbers.



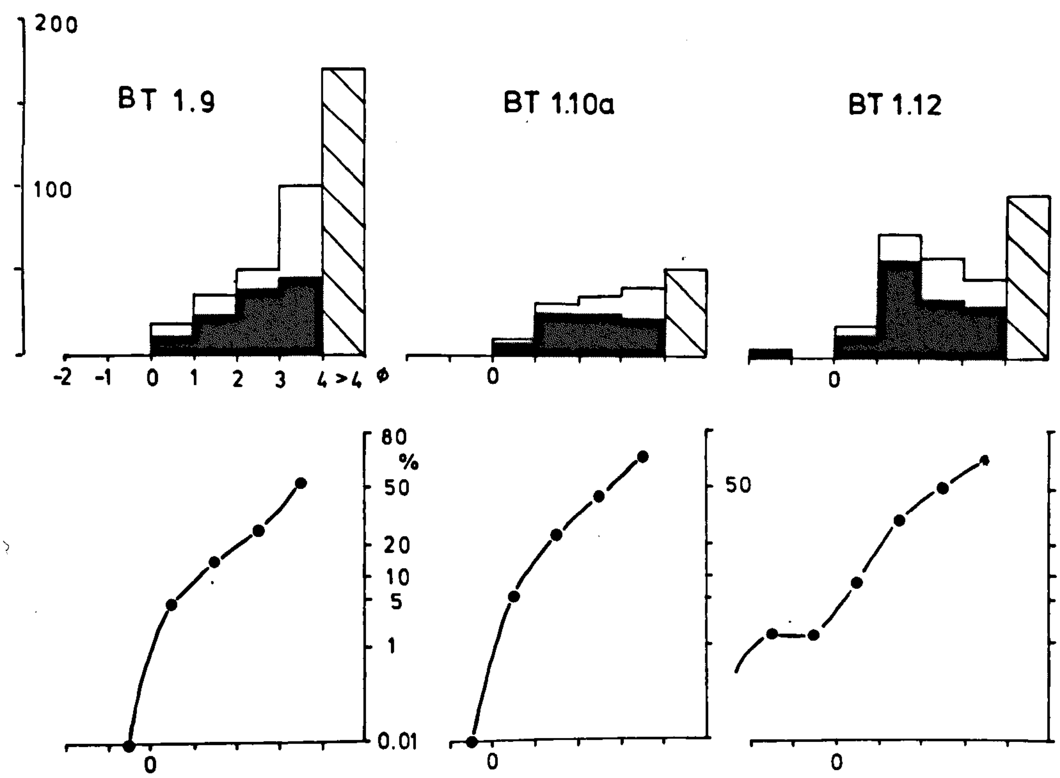
BT 1.1a
BT 1.4
BT 1.5
200
100
-2 -1 0 1 2 3 4 >4 φ
80
%
50
20
10
5
1
0.01
0



BT 1.8a
BT 1.8c
BT 1.8d
200
100
-2 -1 0 1 2 3 4 >4 φ
80
%
50
20
10
5
1
0.01
0

FIGURE 3.16

Further grain-size data. For explanation see Figure 3.15


200
100
BT 1.9
BT 1.10a
BT 1.12
-2 -1 0 1 2 3 4 >4 ϕ
0
0
80
%
50
20
10
5
1
0.01
0
0
0
50
50

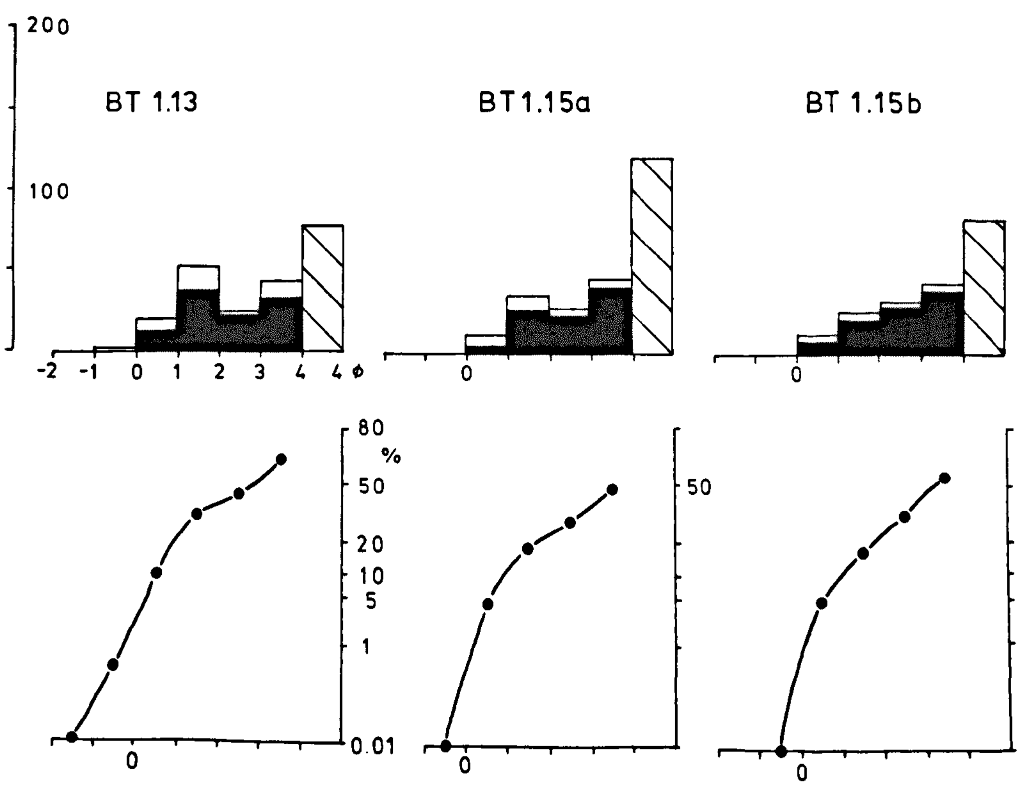
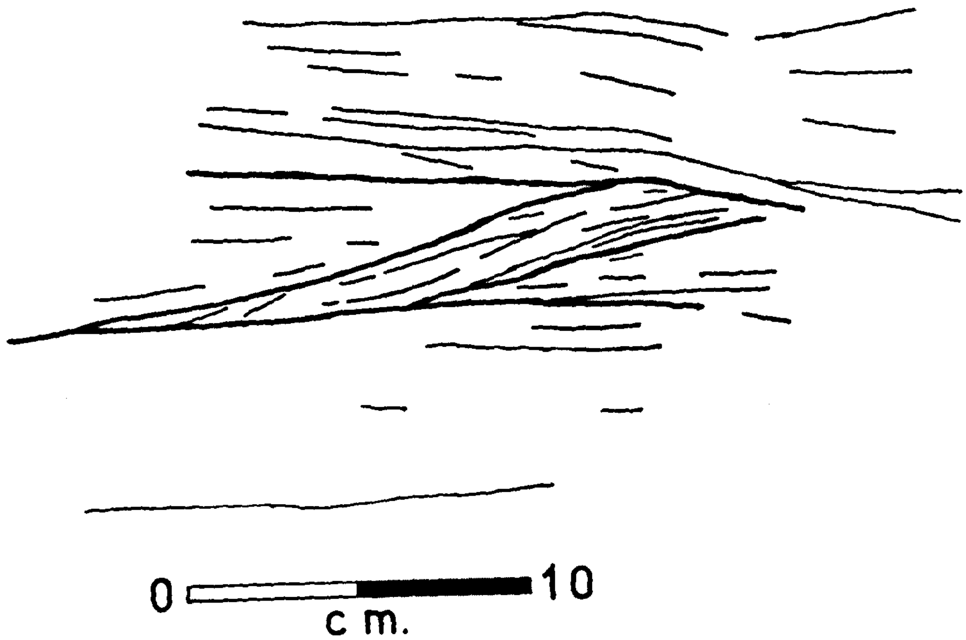

200
100
BT 1.13
BT 1.15a
BT 1.15b
-2 -1 0 1 2 3 4 4 ϕ
0
0
80
%
50
20
10
5
1
0.01
0
0
0
50
50

FIGURE 3.17

(a) Trough cross-bedding in medium to very coarse sand grade tuff. Horizon BT1, locality 1. Sketch from photograph.

(b) Cross-bedding and flat-bedding in tufts at locality 15, horizon BT4.


0
10
cm.

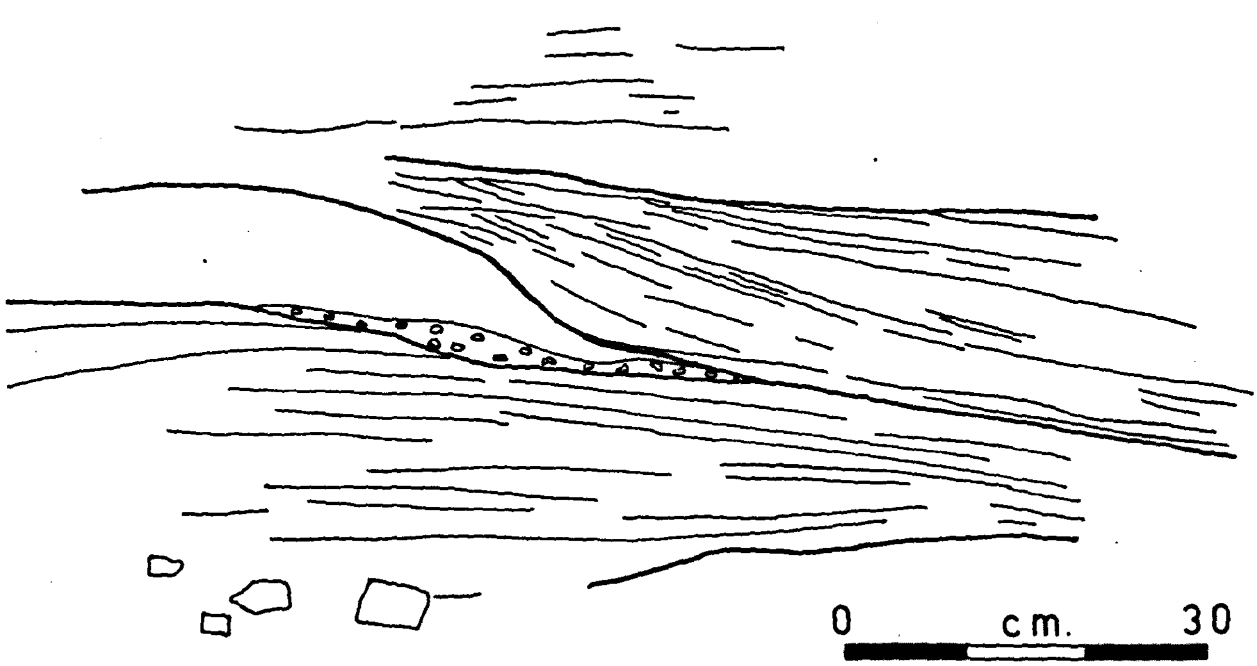
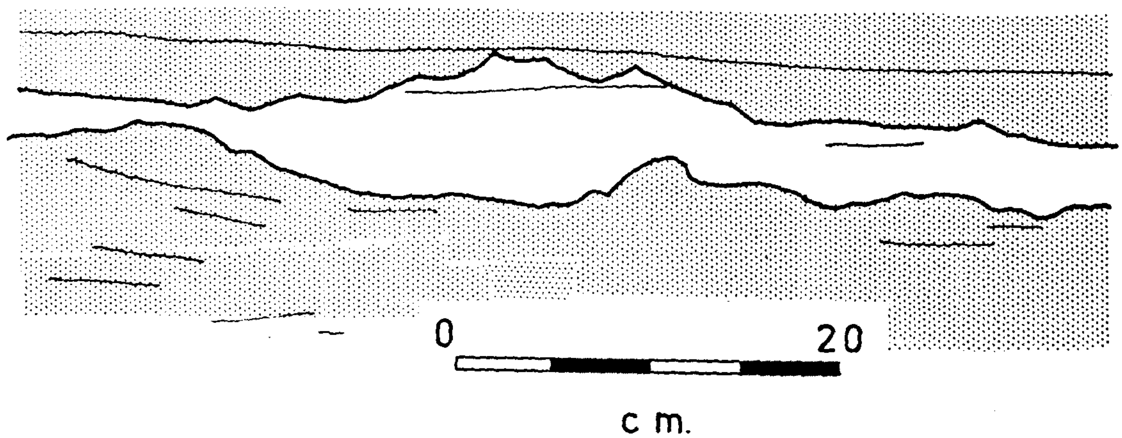

0
cm.
30

FIGURE 3.18

(a) Erosion surfaces below and above a fine-grained tuff layer. The upper surface is filled in, not mantled, by the overlying tuff. Locality 15, horizon BT4. Drawing from photograph.

(b) Channel eroded into lapilli tuff. The channel is lined with a thin layer of silt-clay grade material (unshaded) which has been partly eroded away. The main channel-fill is cross-bedded coarse tuff. The profile of the channel suggests a cross-section of a meander, and some, at least, of the cross-bedding may represent lateral accretion surfaces. Locality 15, horizon BT4. Drawing from photograph.


0
20
c m.

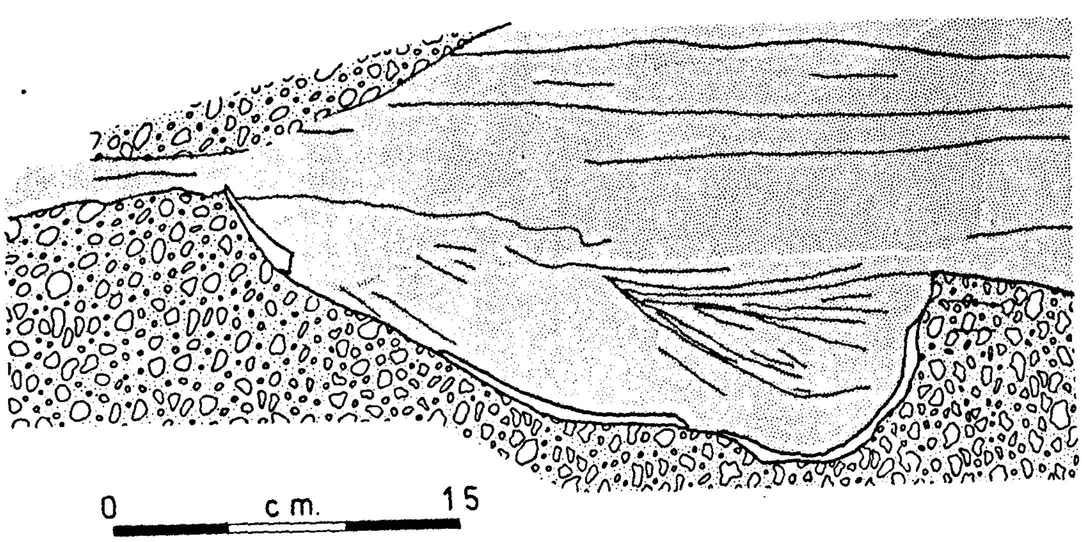
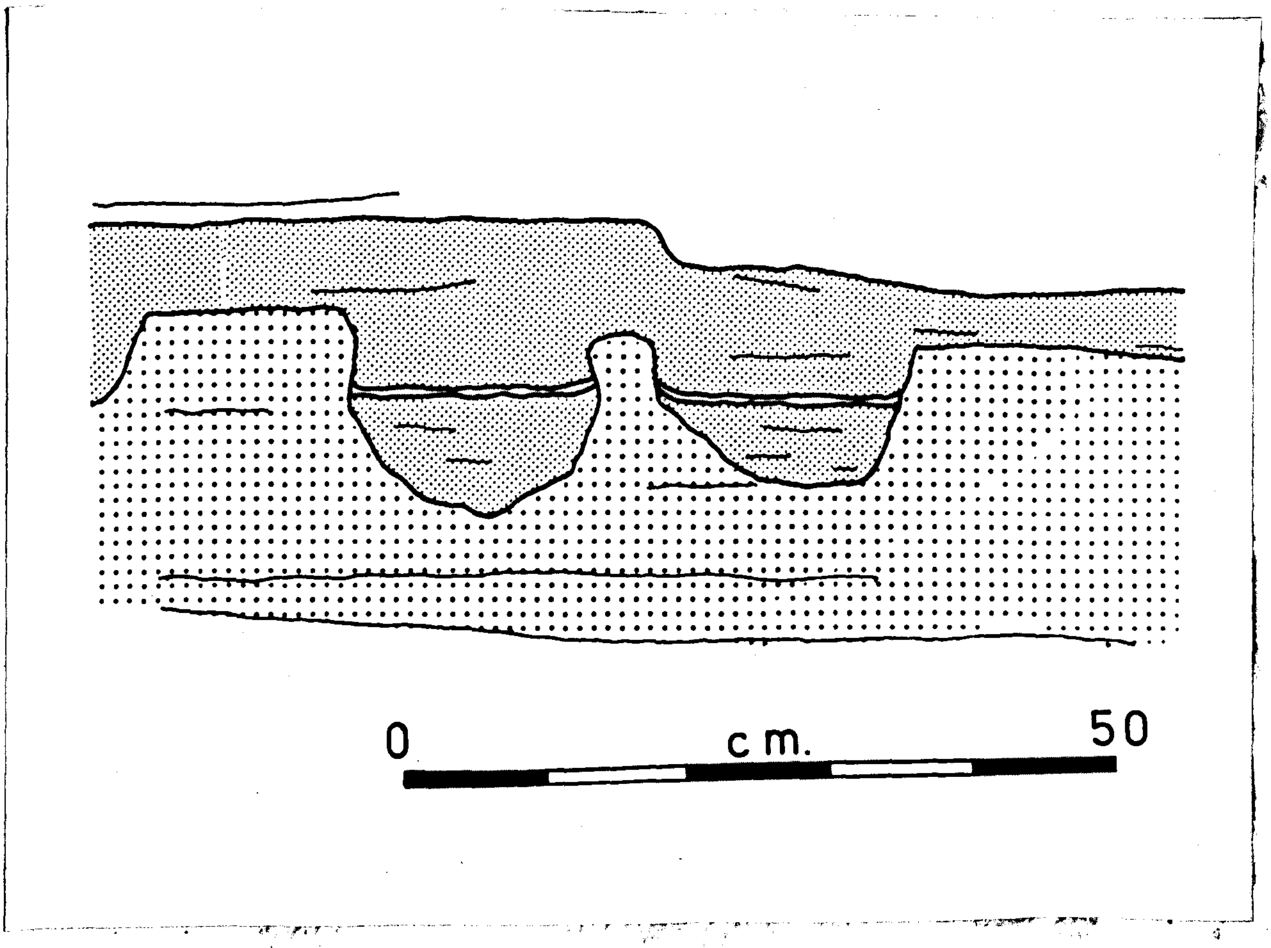

0
c m.
15

FIGURE 3.19

(a) Steep-sided to overhanging channels eroded into sand grade tuff and filled with parallel-bedded sand and silt grade tuffs. A thin silt grade layer occurs at the same level in both channels, indicating that they are connected. The parallel beds fill but do not drape the channels. BT4, locality 15. Sketch from photograph.

(b) Part of the same erosion surface seen in (a), showing overhanging channel walls. There are hints of cross-bedding in the lower part of the fill. The silt grade layer seen in the channels of (a) also occurs here, but is not found to the left of the prominent overhanging channel wall. Sketch from photograph.


0
cm.
50

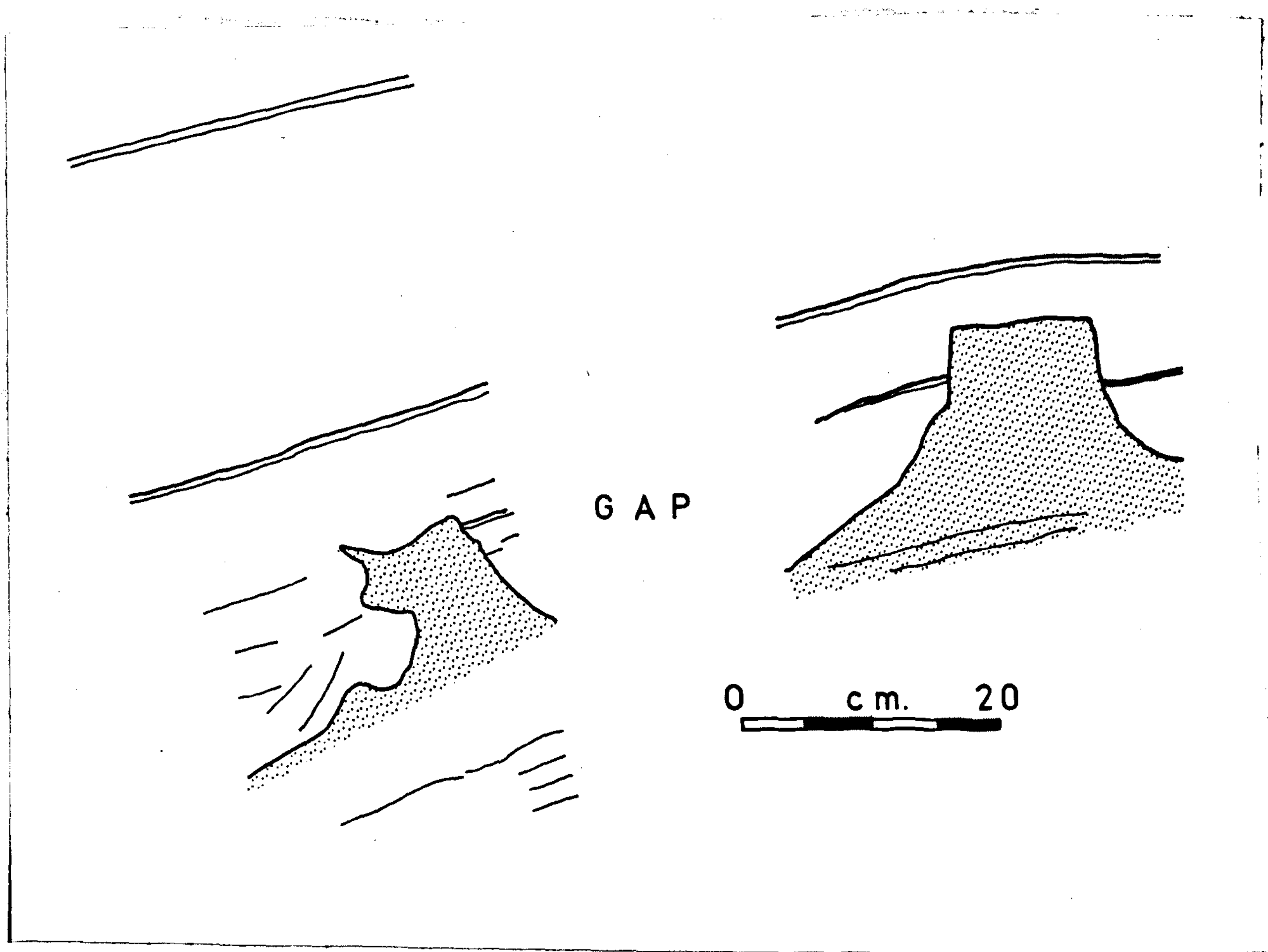
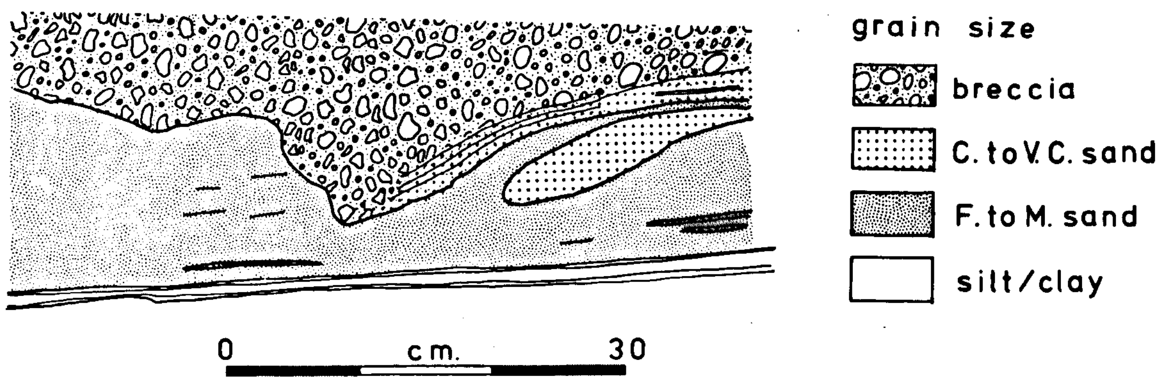

GAP
0
cm.
20

FIGURE 3.20

(a) Erosion surface cut into fine to medium sand grade tuff. An asymmetrical load cast on the base of the overlying bed indicates a palaeoslope towards the north. BT4, locality 15. Drawing from photograph.

(b) Impact structure below a lava block, which has broken through bedded silt grade tuff. More silt grade tuff, with ripple cross-lamination, drapes the top of the block. BT4, locality 15. Drawing from photograph.


grain size
breccia
C. to V.C. sand
F. to M. sand
silt/clay
0
cm.
30

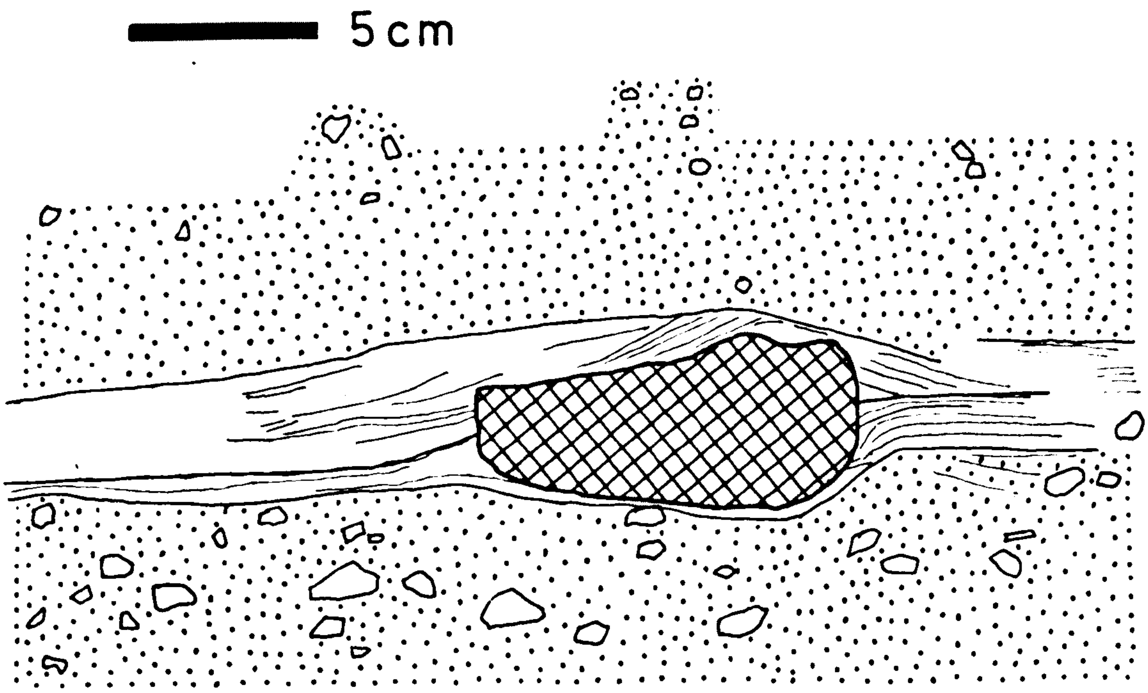

5 cm

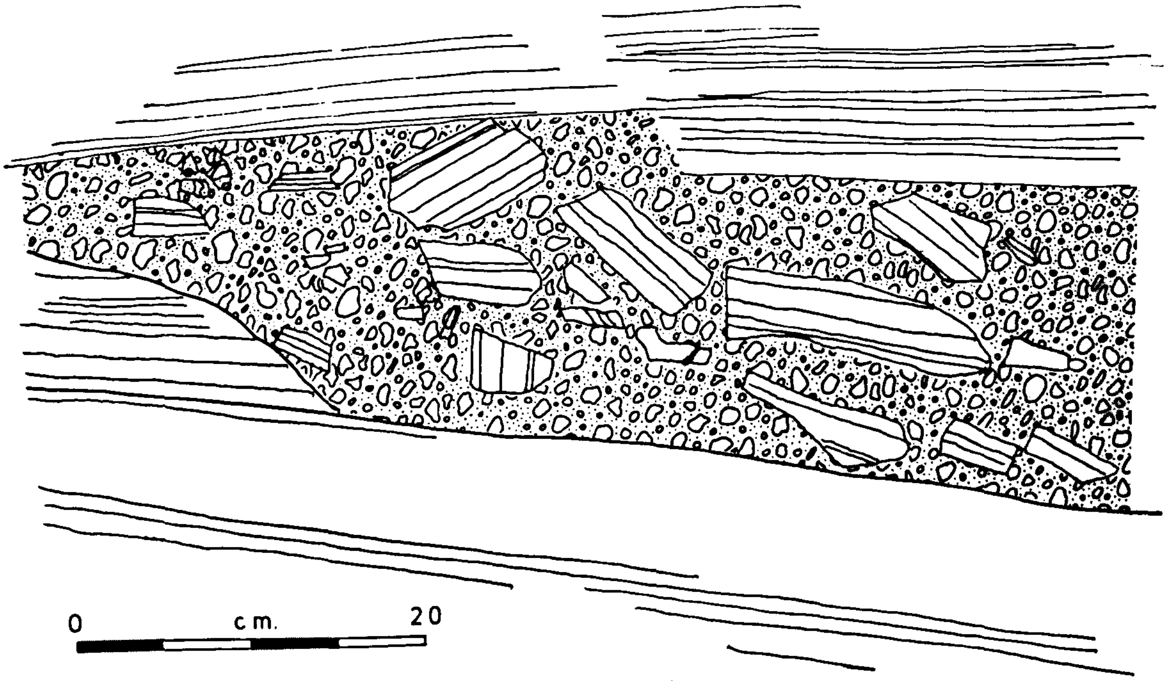
FIGURE 3.21

(a) Thin-bedded, graded, silt-clay grade tuffs, overlain by an intraformational breccia of clasts derived from the underlying beds. The breccia is overlain by further parallel-bedded tuffs. Horizon BT2, locality A. Sketch from photograph.

(b) Locality 5, horizon BT1. Lateral facies changes and channelling in reworked tuffs and conglomerates. The diagram was constructed from 9 sections measured at horizontal intervals of approximately 2m: these are indicated by vertical lines. No vertical exaggeration.

---------- gradational contact

__________ sharp contact


0
cm
20

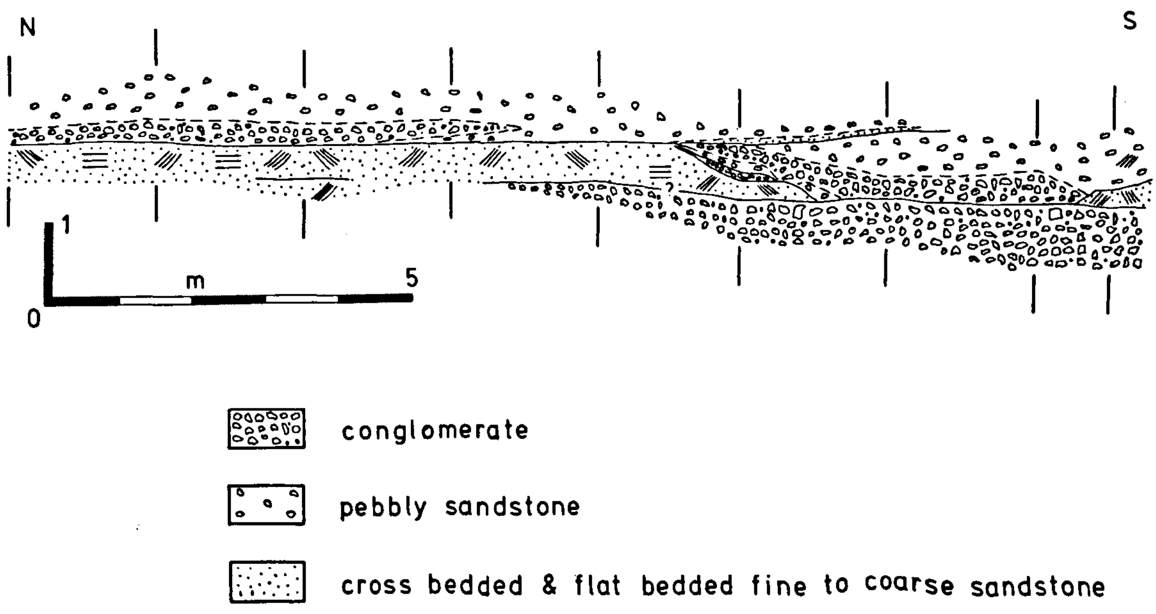
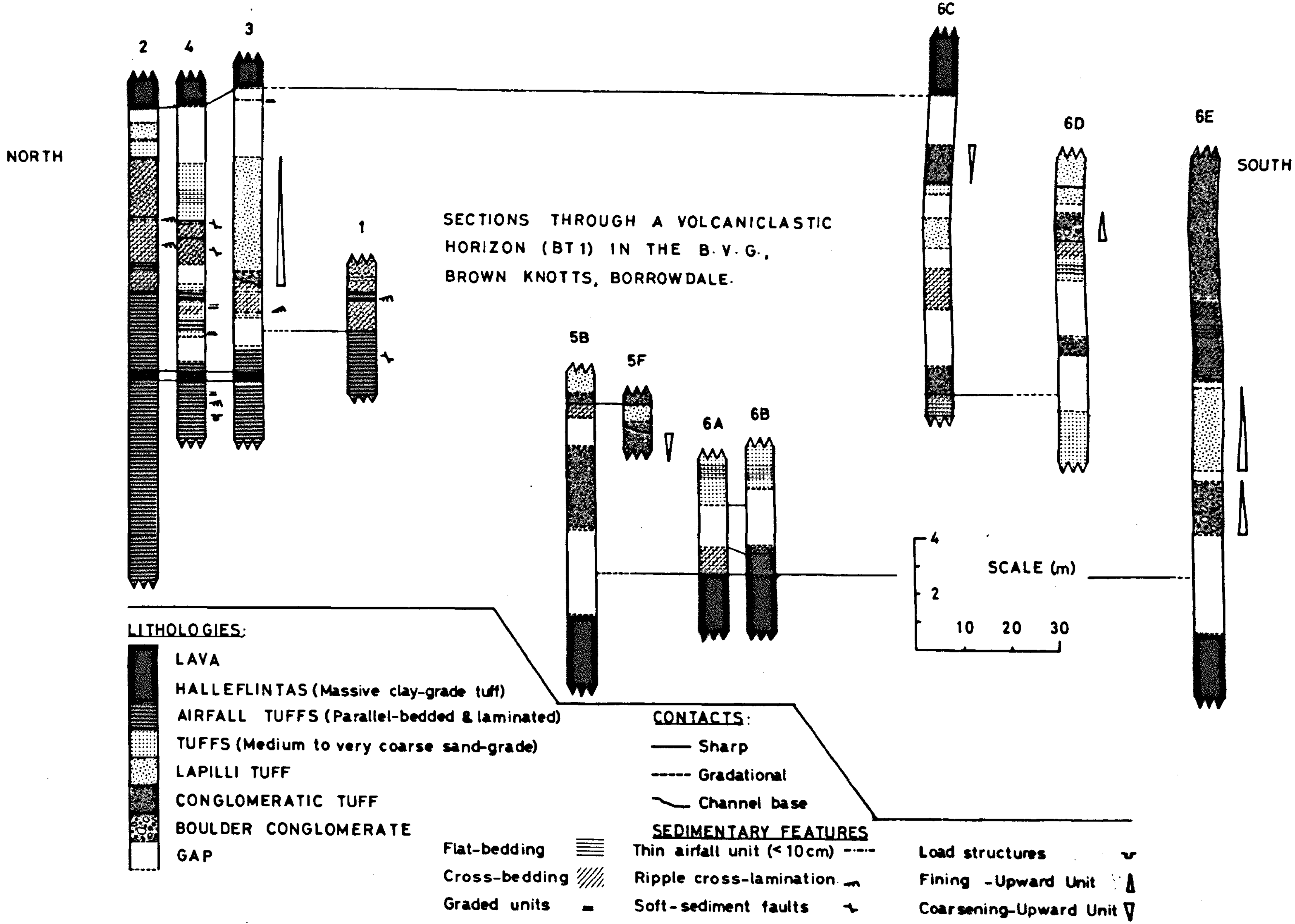

N
S
1
0
m
5
conglomerate
pebbly sandstone
cross bedded & flat bedded fine to coarse sandstone

FIGURE 3.22

Correlation of sections in bedded tuff horizon BT1, showing lateral facies changes. These changes occur within a horizontal distance of some 200m.



SECTIONS THROUGH A VOLCANICLASTIC HORIZON (BT1) IN THE B.V.G., BROWN KNOTTS, BORROWDALE.
NORTH
SOUTH
2
4
3
1
5B
5F
6A
6B
6C
6D
6E
SCALE (m)
4
2
10
20
30
LITHOLOGIES:
LAVA
HALLEFLINTAS (Massive clay-grade tuff)
AIRFALL TUFFS (Parallel-bedded & laminated)
TUFFS (Medium to very coarse sand-grade)
LAPILLI TUFF
CONGLOMERATIC TUFF
BOULDER CONGLOMERATE
GAP
CONTACTS:
Sharp
Gradational
Channel base
SEDIMENTARY FEATURES
Flat-bedding
Cross-bedding
Graded units
Thin airfall unit (< 10cm)
Ripple cross-lamination
Soft-sediment faults
Load structures
Fining -Upward Unit
Coarsening-Upward Unit

FIGURE 3.23

Key to detailed sections of chapters 3 to 6.

CONTACTS

- sharp, erosive
- sharp, planar
- gradational
- gap in exposure
- thin silt-clay grade bed
- thin sand grade bed

- intermediate lavas
- acid lavas
- autobrecciated lava
- peperite
- pillows
- flow banding
- flow folding
- amygdales or vesicles
- columnar jointing
- welded tuff

- pl plagioclase phenocrysts
- px pyroxene "
- q contains quartz
- red reddened flow top
- lithic blocks
- pumice blocks
- pumice granules & shreds
- bedded tuff blocks
- accretionary lapilli
- calcareous concretions
- even, parallel bedding
- discontinuous, even, parallel bdg.
- trough cross bedding
- tabular " "
- parallel lamination
- current ripples & c.r. lamination
- wave ripples & w.r. lamination
- climbing ripple lamination

- steep sided channel
- fining upward sequence / bed
- coarsening upward sequence / bed
- graded bedding
- reverse graded bedding
- mudcracks
- curled mudflakes
- soft sediment faults
- contorted or disturbed bedding
- load casts
- flame structures
- sand diapirs
- bedding draped over blocks
- impact structure
- x crystal tuff
- l lithic tuff
- v vitric tuff
- h hyaloclastite / hyalotuff

FIGURE 3.24

(a) Sections in the lower, fine-grained part of BT2.

In this and subsequent diagrams, grain size changes within graded beds are indicated by the slant of the right hand margin of a bed.

(1) Locality 21

(2) Locality 26

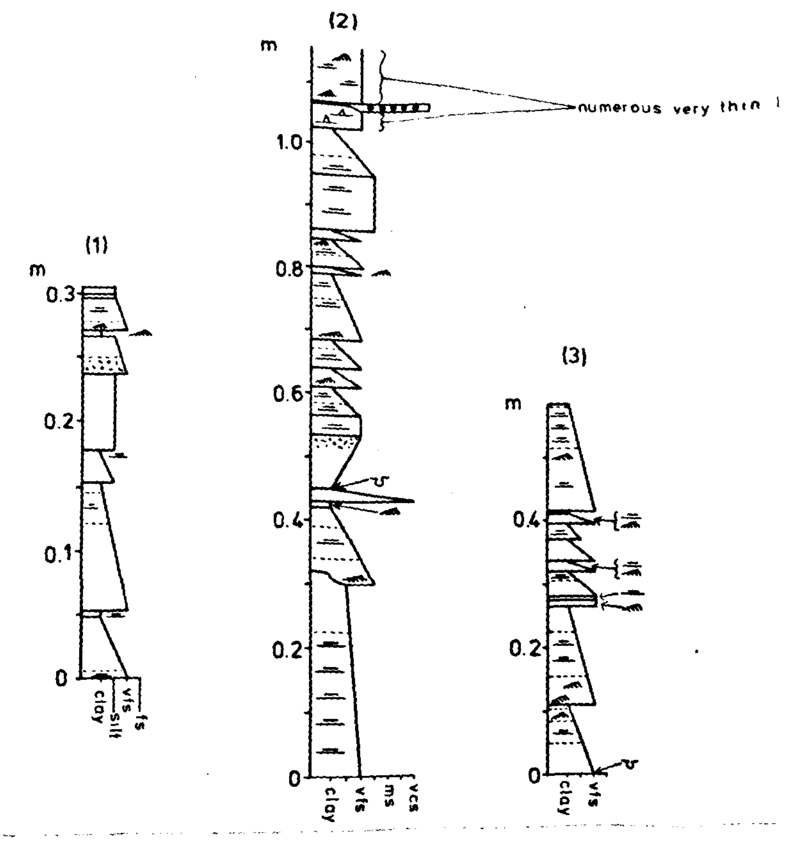
(3) Locality A

(b) Sections in the upper, coarse-grained part of BT2.

(1) Locality 17

(2) Locality A

See figure 3.23 for key.


(1)
m
0.3
0.2
0.1
0
clay
silt
vfs
fs
(2)
m
1.0
0.8
0.6
0.4
0.2
0
numerous very thin
clay
vfs
ms
vcs
(3)
m
0.4
0.2
0
clay
vfs

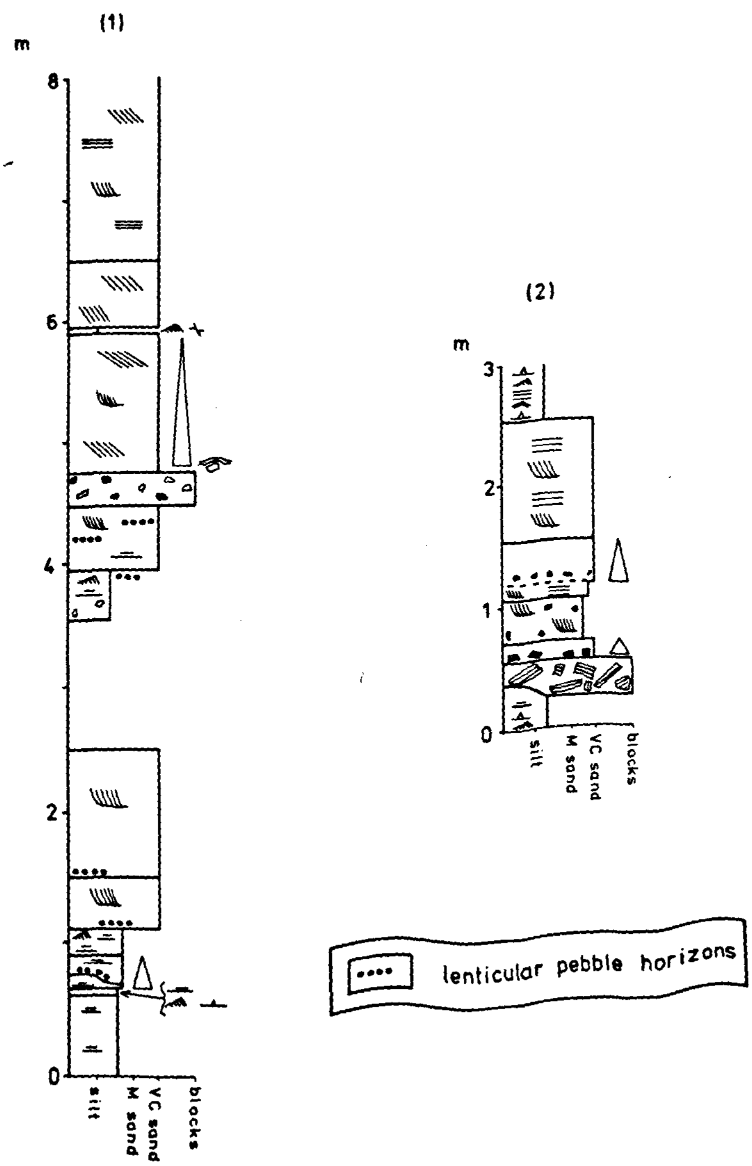
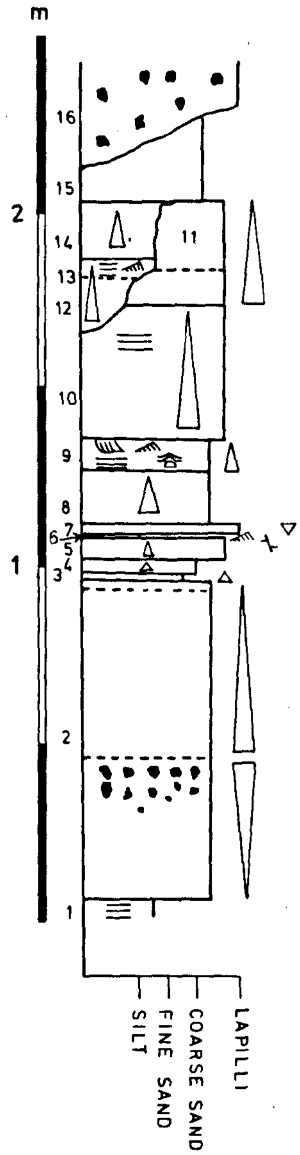
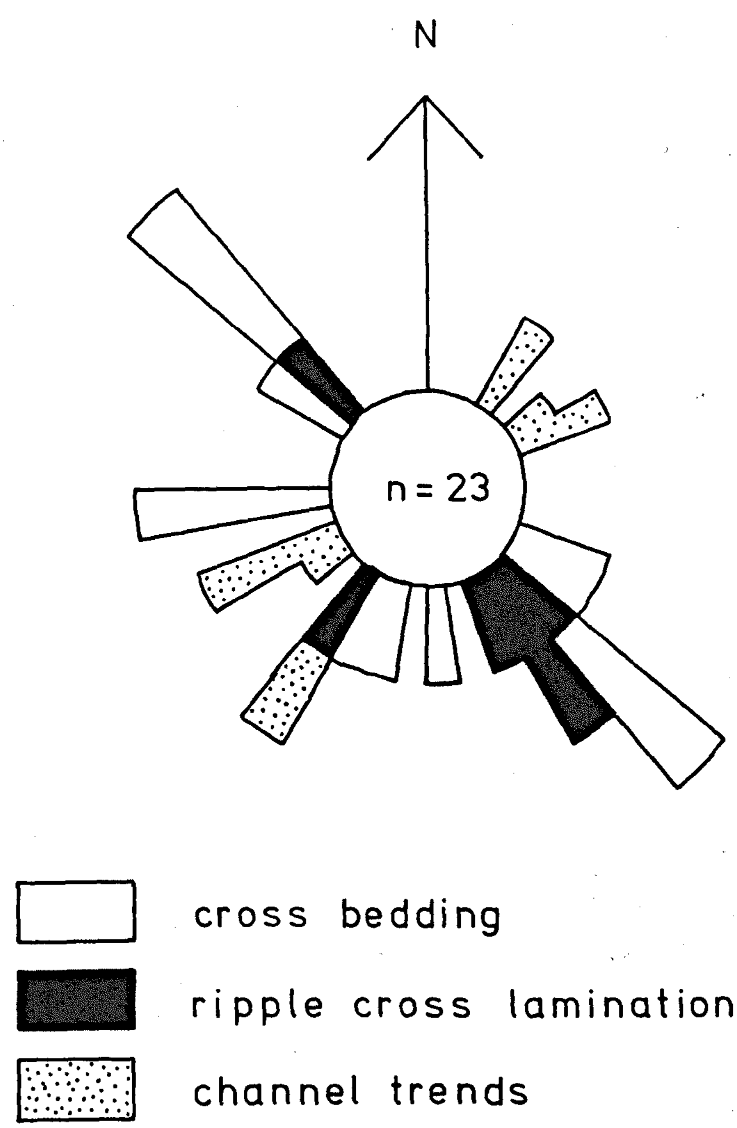

(1)
m
8
6
4
2
0
silt
M sand
VC sand
blocks
(2)
m
3
2
1
0
silt
M sand
VC sand
blocks
lenticular pebble horizons

FIGURE 3.25

(a) Section through part of BT4 at locality 15, showing graded and reverse graded beds, and a probable mudflow deposit (unit 2). In graded beds, the width of the column indicates the grain size of the coarsest part of the unit. For key see figure 3.23.

(b) Palaeocurrent directions in BT4, locality 15. Channel trends give direction but not sense of movement, and both possible directions are plotted, with a value of ½ unit each. 10° classes.


m
2
1
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
SILT
FINE SAND
COARSE SAND
LAPILLI


N
n = 23
cross bedding
ripple cross lamination
channel trends

CHAPTER 4. THE THIRLMERE SECTION.

I. INTRODUCTION.

A. General.

On the shores of Thirlmere Reservoir, a variety of lavas and volcaniclastic rocks are exposed. Individual outcrops are often glacially smoothed and clean, and yield a large amount of detail, but exposure is not continuous (Figure4.1a). The outcrops were particularly well seen during low water stage in the dry summers of 1973, 1975 and 1976. Road cuttings are abundant around and north of Thirlmere, but most are too weathered to show much detail. To the west of the lake, continuity of outcrop is lost, for the most part, in the extensive coniferous plantations.

B. Structure.

In the area between Shoulthwaite and Smaithwaite(Figure 3.1), more or less horizontal dips are encountered in the Shoulthwaite Syncline (see Chapter3). To the south, a few northwesterly dips are seen, and a small anticline is present at the north end of the lake. South of this, southeasterly dips from 28° to 72° prevail over a distance of 4 km, before they swing eastwards and become much more gentle (figure4. 1a) This represents, respectively, the steep northern limb and the gently eastward plunging core of the broad Scafell Syncline.

A major fault (Figure 4 .1a) runs through the southern part ofthe lake (Hartley, 1941), and its shatter zone is exposed at locality 5. This fault extends south over Dunmail Raise, and eventually to Coniston (Moseley, 1972). Minor faults are common, and some of the lavas are strongly jointed. The faults and joints commonly have NW- SE and NE- SW orientations (Figure 4. 2a,b). Some of the tuffs and amygdaloidal lavas are cleaved (Figure 4.2c)

C. General Sequence.

The lower 2500m of the section (Figure 4.2b) consists predominantly of andesitic lavas, and also contains andesite sills, and subaqueous tuffs , bedded tuffs, breccias, and rare acid welded tuffs. At Hause Point, this sequence is sharply overlaid by bedded, unbedded and welded tuffs of acid composition, which persist beyond the southern end of Thirlmere. Their top is not seen in this section.

D. Stratigraphy.

Garnetiferous lavas outcrop near Thirlmere Dam, and are thought to correlate with similar rocks on Bleaberry Fell (see Chapter 3), where the base of the Thirlmere Andesites is defined. Thus, the rocks to the north of Thirlmere belong to the upper part of the Falcon Crag Formation (Figure 3.8, 4.3). Because of the discontinuous exposure and lack of suitable markers, the Thirlmere Andesites have not been subdivided. Further mapping to the west of Thirlmere, to join up with that of Strens (1962) is required before this can be attempted. The top part of the Thirlmere Andesites coincides with the Birker Fell Formation (Figure 3.8) and the acid sequence above belongs to the Airy's Bridge Formation (this correlation is discussed more fully in Chapter 5). The Stratigraphy of Hartley (1941) is difficult to apply, because of misinterpretations of lithology and structure.

Most of the rocks east of the major fault have not been studied, but andesitic rocks at locality 6 are thought to belong to the Thirlmere Andesites.

II. THE LAVA FLOWS.

A. Field Relations.

The extent of most of the lava flows cannot be assessed, due to the lack of exposure, and in many cases the contacts are not exposed. Where they are, the bases are often very irregular, and underlying tuffs are commonly disturbed. The lavas may contain deformed blocks derived from these tuffs. In one case, pillows below the base of a lava flow, thought to be formed by loading of the lava into wet sediment, are completely surrounded by disrupted tuff (Plate 41B). A hollow in the top of another flow is filled by the overlying heterolithic breccia (Plate 38A).

Lava flows are typically on the order of 5 to 20 m thick

B. Primary Structures.

(i) Breccias.

Autobreccias of the same types as those in the Borrowdale section (Chapter 3) are exposed at many places in the Thirlmere Andesites particularly at flow tops and bases, and they are interpreted in a similar way. They may have a matrix either of chilled lava or of comminuted lava debris (Figures 4.6d, e; Plates 35, 36, 37, 38). In some cases flow banded lavas are brecciated (Plate 37B). Grain size analyses have been carried out on some of the autobreccias (Figure 4.9): they tend to be poorly sorted, with a fine tail and a mode in the cobble to boulder grades. When mapped in detail, the upper parts of lava flows are exceedingly complex, with several facies of breccia and other lava types (Figure 4.8)

One type of autobreccia not previously described has a matrix of parallel-bedded silt to clay grade tuff. It is seen in Smaithwaite Road Cutting and at locality 37 (Plates 39,40). In the latter outcrop, the tuff occur s towards the tops of autobrecciated lava flows, and is identical to tuffs overlying the lava sequence. Its bedding is parallel to the regional dip, and it is thought to be the result of fine grained ash settling out, possibly through water, into the interstices of the breccias. The bedding is sometimes slightly buckled or faulted (Plate 40) possibly due to subsequent movements of the lava blocks.

In Smaithwaite Road Cutting (Figure 4.7), the tuff is confined to a rather narrow vertical zone of 'jigsaw fit' autobreccia, which extends through the whole thickness of the outcrop. Although the bedding is sometimes parallel to the gentle dip of the lava flow, it is often parallel to the side of the fissures between the blocks. The tuff also forms veins in the otherwise massive andesite. It is proposed that the lava may have passed over wet, fine-grained ash which was fluidized by the heat of the flow or a steam explosion. The fluidized tuff was then injected upwards through the lava, which itself was probably brecciated by steam explosions. Streaming through the fissures produced a parallel lineation. After the pressure had been released some of the tuff in suspension may have settled into the cavities, producing the gently dipping beds now seen.

(ii) Flow Banding and Flow Folding.

Flow banding is common in the Thirlmere Andesites (Plate 34A) and, like that in the Falcon Crag Group, is due primarily to differences in vesicularity and crystallinity. Flow jointing is present at some localities (Plate 34B). In many outcrops, the flow banding is folded, often into tight, complex overfolds and recumbent folds (Figures 4.6a-c); (Plate 33A). Disharmonic folding, boudinage and breakage of folded layers have also been recorded. Many of these features are similar to those illustrated by Wachendorf (1973) and MacDonald (1972, p95). The wavelengths of the folds vary from a few cm to more than 1m. The presence of flow folding indicates that many of the lavas were more viscous than those of the Borrowdale section in which flow banding and jointing are always planar. The abundance of flow folding at Thirlmere means that dip measurements on flow banding or flow jointing are unreliable indicators of tectonic structure. At some localities the dip, although uniform within the outcrop, differs widely from the regional dip, suggesting the presence of large scale flow folds (examples of discordant dip are seen in Figure 4.1a)

(iii) Other Structures.

Many of the lavas are amygdaloidal, sometimes with gas cavities up to 30cm long (Plate 33B). These lavas are often cleaved, with the amygdales flattened in the plane of the cleavage (Plate 33). Very occasionally local developments of pillows are seen (Plate 41B), and are interpreted as the result of interaction between rather fluid lava and water or wet sediment. Columnar jointing is a feature of some of the andesites at Hause Point (Locality 37: Plate 42B).

In Smaithwaite Road Cutting, a variety of lava types is exposed, and these are apparently separated by steep, generally gradational contacts, although the flow is near horizontal. It is tentatively suggested that this is an example of ramp structure, a feature commonly developed by shearing near the fronts of rather viscous lavas (MacDonald, 1972, p93-94).

C. Petrography.

(i) General.

The petrography and alteration of the lavas of the Thirlmere Andesites are in many respects very similar to those of the upper part of the Falcon Crag Formation and the Thirlmere Andesites in Borrowdale (Chapter3), and need not be fully described here. Plagioclase-phyric lavas predominate, commonly with subordinate pyroxene, but pyroxene-phyric and aphyric types are also represented. Typical modes are shown in Table 4.1. Glomeroporphyritic clusters are abundant, mostly 2 to 4 mm, but up to 15 mm long. Some have a doleritic texture.

(ii) Plagioclase

Out of more than 50 thin sections, only four yielded sufficient fresh, unzoned crystals for determination of composition, and these are all from locality 2. One specimen has phenocrysts of An_{34} and groundmass plagioclase of An_{30} , whilst phenocrysts from two other lavas have compositions of An_{32} and An_{33}. These fresh crystals exhibit albite, Carlsbad and Carlsbad-albite twinning. At other localities the plagioclase is mostly replaced by fine-grained alteration products. Sometimes, fresh rims and altered cores testify to the presence of zoning, with more calcic cores. In a few cases alteration has proceeded so far that the feldspars are barely discernible 'ghosts', often with ragged outlines.

TABLE 4.1: Point counts on andesitic lavas from the Thirlmere section. Pseudomorphs are counted as the primary phases which they replace.

SPECIMEN NO.	Th1.1	Th2.2	Th2.12	Th6.2	Th37.13	RT13	RT15
plagioclase phenocrysts ..	13.8	17.3	22.1	24.4	29.7	18.5	10.7
pyroxene phenocrysts ..	7.3	8.1	4.8	3.0	2.5	1.0	17.3
groundmass plagioclase ..	3.1	35.6	25.8	1.2	-	2.4	18.1
groundmass pyroxene	-	0.2	-	-	-	-	-
opaques	1.2	-	-	0.4	1.4	-	1.1
quartz	-	0.3	-	-	-	-	-
apatite	-	-	-	-	-	0.2	-
garnet	-	-	-	-	-	0.3	-
biotite	-	-	-	-	-	3.2	-
amygdales/vesicles	-	0.8	15.2	2.5	-	-	-
groundmass	74.5	37.7	32.1	68.6	66.3	74.4	52.8
TOTAL:	99.9%	100.0%	100.0%	100.1%	99.9%	100.0%	100.0%
Number of points counted ..	573	665	850	566	710	594	619

The first part of each specimen number indicates its locality number, except for RT13 and RT15, which are from localities 71 and 73 respectively. See Figure 4.1b for localities.

(iii) Pyroxene

Fresh twinned and zoned brown clinopyroxene is a phenocryst phase in lavas from several localities near Thirlmere Dam. In the same thin sections, chlorite pseudomorphs after pyroxene occur, but no partially replaced pyroxene is seen. It is suggested that these are two-pyroxene andesites, and that the chlorite is replacing orthopyroxene. At other localities, pyroxene is commonly replaced by chlorite of penninite type and, more rarely, by fine-grained green or brown amphibole, or by biotite.

(iv) Other Minerals

Rounded quartz phenocrysts are present in a few lavas, particularly at locality 6. Euhedral and subhedral phenocrysts of opaque oxides occur, and may be an important constituent of glomeroporphyritic aggregates. Small clots of leucoxene are locally abundant. An acid lava at locality 74 contains fresh euhedral red garnets up to 1mm across, with small chlorite inclusions. Garnets are also present in an andesite at locality 74.

(v) Groundmass

Most lavas in the Thirlmere Andesites have a groundmass of devitrified glass, and in some (e.g. from Shoulthwaite Road Cutting and locality 2) the devitrification products are so fine-grained as to be almost isotropic. In many cases, a perlitic texture is developed in the vitric groundmass. This is generally seen only in thin section, but in Shoulthwaite Road Cutting a good example can be seen in outcrop and hand specimen (plate 42B). Where the groundmass minerals can be identified, they differ little from those in the Borrowdale lavas (Chapter 3). Epidote is brown and highly birefringent, suggesting an iron-rich composition. Cleavage may show in thin section as discontinuous sericite strings in the groundmass. Some lavas contain small white spherulites, consisting almost entirely of leucoxene (Plate 42B).

(vi) Amygdales

Amygdales, a common feature of many flows, are often highly irregular in shape, and may form up to 60% of the rock, in exceptional cases. They are often filled by complex sequences of minerals (Table 4.2).

(vii) Acid lavas

Lavas of acid composition occur rarely in the Thirlmere Andesites sequence. Some lavas in the Hause Point section (Figure 4.5) have an acid appearance, but they are too altered for this to be confirmed. At locality 71, a pink and green vitric acid lava outcrops. It contains abundant altered feldspar phenocrysts (probably plagioclase), chlorite pseudomorphs after pyroxene and (?) amphibole, and sparse euhedral garnets, in an altered vitric groundmass.

(viii) Distribution of alteration

The freshest lavas are found at Thirlmere Dam (locality 2) and contain fresh plagioclase and zoned clinopyroxene phenocrysts in a very fine-grained, almost isotropic devitrified groundmass. The most altered lavas are those from localities 6 and 37. Some of these are very light coloured, although an andesite mineralogy is sometimes recognizable. Plagioclase is completely replaced by sericite and calcite, and the groundmass is also highly altered. Both these localities are close to the Coniston Fault (Figure 4.1a), whilst locality 1 is well away from it. The alteration may have been caused by hydrothermal solutions rising along the permeable fault zone, and possibly originating from ground water heated by an intrusion at depth.

D. Composition.

Two of Fitton's (1971) analyses are from the Thirlmere Andesites of the present area: one from locality 91 is a basalt (52.97% silica) and the other, from near locality 87, is a basaltic andesite (56.56% silica).

TABLE 4.2

Amygdale fill sequences from lavas of the Thirlmere Andesites.

	rim		core
1.	chlorite with sparse quartz grains		
2.	radiating quartz and chlorite (partly as rosettes)		
3.	radiating fibrous quartz and chlorite		granular calcite
4.	chlorite		calcite
5.	radiating fibrous quartz	chlorite	calcite
6.	radiating fibrous quartz	fibrous chlorite with platy calcite	
7.	radiating prismatic quartz	chlorite	anhedral quartz mosaic
8.	radiating fibrous quartz		anhedral quartz mosaic
9.	radiating fibrous quartz		chlorite
10.	granular quartz		chlorite
11.	quartz	chlorite	anhedral quartz mosaic
12.	quartz	calcite	chlorite
13.	quartz		calcite
14.	granular quartz	chlorite	granular calcite
15.	banded chalcedony	anhedral quartz mosaic	calcite plates
16.	calcite	radiating fibrous chlorite	

Some amygdales also contain scattered crystals of epidote and muscovite.

Of three lavas at a horizon equivalent to the lower part of the Thirlmere Andesites at Dowthwaite Head, 6km ENE of Thirlmere Dam, two are basaltic andesites and one is andesite (53.25% 56.97% and 62.11% silica) (Fitton, 1971).

E. Interpretation.

In many respects, the lavas of the Thirlmere Andesites and the upper part of the Falcon Crag Formation at Thirlmere are very similar to the andesites and basaltic andesites of the Borrowdale succession, and most of the remarks of section II.A.vi (Chapter3) also apply here. Rather thick simple lavas with flow brecciated tops and bases predominate. These are interpreted as blocky lava flows resulting from high effusion rates. In detail, the breccias are often very complex.

There is considerable evidence of interaction between lavas and wet, unconsolidated volcaniclastic sediments, including the local development of pillows and the abundance of deformed tuff clasts in some flows, (especially at locality 6: Figure 4.4a). The common occurrence of a glassy groundmass and perlitic texture suggests that many lavas cooled rapidly. Perlitic cracks are thought by some authors, (e.g. Marshall, 1961) to result from strain produced in the glass during rapid cooling, whilst others (e.g. Friedman et al, 1966) suggest that hydration of shattered glass is responsible. The present author prefers the former view, and it is tentatively suggested that the rapid cooling may have been the result of extrusion of the lavas into water.

Many lavas had a high gas content, indicated by the abundance of amygdales. However most of the magmas were relatively dry, as hydrous phenocryst phases are rare. Although more complex in detail, a broad view of the succession of the Thirlmere Andesites shows a tendency for the lavas to become more acidic upwards. Pyroxene-phyric lavas occur near the base of the section, whilst quartz appears as a phenocryst phase in some of the higher members.

III THE INTRUSIONS

A. High Level Sills and Peperites.

(i) General

For reasons given below, several andesite units within the Thirlmere Andesites are thought to be high level intrusive sheets rather than lava flows. Other sills may have gone unrecognized because their contacts are not exposed. Peperites with unclear field relations are exposed at several localities.

(ii) The Swirls Intrusion

(a) Field Relations and Structures

On the lake shore west of The Swirls (locality 9) a complex of massive andesite and andesitic breccia outcrops. In the northern part of the exposure a dyke-like body of andesite has steep intrusive contacts with the coarse breccias. A few metres to the south, and across an unexposed gap, the relationship is more complex. Here, irregular-shaped masses of breccia are contained within the andesite (Plate 43A). They range from 1cm to several m long, and some of the larger 'rafts' are imbricated (figure 4.10b). The breccia bodies have sharply defined margins.

(b) Petrography

The petrography of the andesite does not differ significantly from that of the lavas of the Thirlmere Andesites. Plagioclase may constitute 40% or more of the rock: in some specimens it occurs mainly as phenocrysts, whilst in others it is mostly in the groundmass. Most crystals are zoned, and although a few are fresh, most are highly altered. Small chlorite pseudomorphs after pyroxene are common, both singly and in glomeroporphyritic aggregates with plagioclase and opaque oxides. Fresh clinopyroxene occurs occasionally.

The fine-grained groundmass forms 50% of some thin sections, but is much less important in others. It appears to have been vitric, but is now rather altered. Within the fine-grained base of feldspar, chlorite calcite, epidote, quartz etc. are clots and veins of carbonate and dendritic patches of secondary opaque oxides. Occasional thin amygdaloidal layers are seen.

(c) Interpretation

The outcrops appear to show an andesite intrusion into breccia. It is tentatively suggested that the lower part of a sill and its feeder dyke are exposed here. The breccias were apparently lithified, and were broken into rigid blocks by the intruded magma, which carried large 'rafts' of breccia for short distances.

(iii) The Yewhow Wood Intrusion

(a) Field Relations and Structures

At locality 25, on the west shore of Thirlmere, the section shown in Figure 4.10a is exposed. The lowest part consists of some 9m of brecciated andesite, whose base is not exposed. It contains rather equant blocks , mostly between 1 and 20cm long, in a matrix of angular comminuted andesite debris. The breccias are poorly sorted, with a fine tail, and a mode in the boulder to cobble range (Figure 4.9c). There is a rough 'jigsaw fit' between the fragments in places. In the upper part of the breccia, most of the clasts have a thin light coloured chilled margin (Plate 44A). Here the breccia contains andesite pillows, still in a fragmental matrix (Plate 44B). It passes up into a horizon containing closely packed pillows and angular blocks with chilled edges, in a matrix of red tuff (Plates 45, 46A). Some of the blocks have a combination of convex and straight edges. Vesicles are sometimes concentrated towards the margins of these bodies, which are often more than 1m across. Traces of disrupted bedding can occasionally be seen in the red tuff, and a thin zone of baked tuff occurs around each pillow or block.

Above the pillows, tongues of vesicular andesite 5 to 20cm thick interfinger with the red tuffs (Plate 46B). In detail, the contacts are very irregular (Plate 47A); isolated (in two dimensions) blebs of andesite are found in the tuff, and small tuff inclusions occur in the andesites. Thin chilled margins and baked zones are again present. One tongue has an altered perlitic texture within its 1cm thick chilled margin. Within the thickest tongue is a 50cm long pocket of autobreccia with a perfect 'jigsaw fit' between the fragments, whose interstices are filled with quartz (Plate 47B).

At the top of the section, the red tuffs and andesites are overlain by parallel-bedded green tuffs of silt to very coarse sand grade. The thin beds are individually well sorted, and the tuffs show much evidence of plastic deformation. In plan, a series of soft sediment faults is seen (Plate 48).

(b) Petrography

The petrography of the andesite blocks and pillows is very similar to that of the tongues, apart from the obvious differences in vesicularity. They contain abundant altered ½ to 1mm long plagioclase phenocrysts (Table 4.3) which are commonly in clusters with chlorite (after pyroxene) and Fe-Ti oxides. The highly altered matrix includes feldspar, chlorite, quartz, sericite and opaque oxides, and is pervaded by anastomosing veins of very fine-grained white mica, defining the crude cleavage. Along the pillow-tuff contacts, a thin layer of opaque oxide occurs.

The pillows contain small chlorite filled amygdales. In the andesite tongues amygdales may form more than 30% of the rock (Table 4.3) They have very irregular shapes, and are mostly elongate and sub-parallel. The smaller amygdales have fills of radiating fibrous chlorite, whilst the larger ones are filled with calcite. One large calcite amygdale shows a 'sawtooth' junction between two crystals, probably representing a crystal front which developed during re-crystallization of radial fibrous calcite (J. R. Davies, personal communication).

The matrix of the autobreccia in the lower part of the section is a poorly sorted vitric tuff of fine sand to lapilli grade, with angular to subangular grains. Many grains have an altered perlitic texture and small plagioclase phenocrysts may be present. The red tuffs are mostly highly altered.

Most are of silt to clay grade, with scattered fine to medium sand grade feldspar crystal fragments. The red colour is imparted by finely disseminated haematite. One specimen is a well sorted coarse sand grade tuff, consisting largely of close packed altered vitric fragments, with pressure solution between them.

(c) Interpretation

Schmincke (1967a) described the following features, produced when a basaltic lava flowed over, and burrowed into, unconsolidated sediments: distorted bedded tuff with thin sheets and tongues of basalt, lava particles ranging from silt size to boulders several metres across, fragment shapes varying from pillow-like forms to angular blocks, chilled edges, baked tuff zones around the basalt fragments, and a high degree of vesicularity in much of the lava. Similar features have been described in andesite and dacite sills from the Aleutian Islands (Snyder and Fraser, 1963).

All the features described by Schmincke (1967a) have been observed in the Yewhow Wood section, and the present author has little doubt that a similar type of peperite complex is represented here. It was the result of an intrusion of andesitic magma into wet, unconsolidated volcaniclastic sediment. There is insufficient evidence to state whether the intrusion originated directly from ascending magma, or from a burrowing lava flow.

Several processes are important in the formation of a peperite complex. Snyder and Fraser (1963) suggested that a 'giant emulsion' of pillows, lava fragments, disrupted sediment and water was formed as a sill, advancing close to the sediment-water interface, came into contact with unconsolidated muds. The peperite is the product of this emulsion. The autobreccias, with their chilled edges and matrix of vitric tuff, may have formed by a process of granulation due to thermal shock, similar to that responsible for hyaloclastites.

Processes of flow brecciation similar to those seen in lava flows (see Chapter 3) may also have been active. Locally, steam explosions may have been important (Schmincke 1967a) and pockets of 'jigsaw fit' autobreccia (autoclastic explosion breccia) may have formed by this process (e.g. Plate 47B).

It is suggested that the bedded tuffs overlying the peperite complex were disturbed during the intrusion of magma beneath them.

(iv) Other occurrences of Peperite and Related Lithologies

At locality 13, there is an intimate mixture of plastically deformed, thinly bedded tuffs and brecciated andesites (Plate 43B) In places, it is difficult to distinguish between flow banded andesite and bedded tuff. For example, a block of flow banded andesite is seen at lower left in Plate 43B, but the rest of the lower part of the photograph is in bedded tuffs with structureless andesite blocks. This outcrop is interpreted as a peperite. Its field relations are unknown, due to lack of exposure.

Complex relationships between thin tongues of lava and disrupted breccia and bedded tuff are seen at locality 12 (Plate 49). These gradationally overlie a massive, sheared andesite, which is in fault contact with autobrecciated andesites. It is tentatively suggested that the section exposes the upper contact of an andesite sill intruded into wet, unconsolidated volcaniclastic sediments.

B. Dykes

(i) General

Dykes with widths up to 3m, but commonly less than 50cm , have been recorded at several localities around Thirlmere (figure 3.1a). These are usually near vertical, and have sharp margins which may be planar or irregular (plate 50). A thin chilled edge is generally present, and some dykes contain inclusions of the wall rock (plate 50A). The dyke rocks weather to a brown patina.

A 10cm wide dyke intruding welded tuffs at locality 38 has finely spaced flow banding throughout, parallel to its edges (plate 50B). At one point, the dyke bifurcates. It runs at 90°to a darker coloured 2m thick dyke, but the relationship between them is obscured by a gap in exposure. However, their dissimilar petrographies suggest that they are not connected. The larger dyke has trains of small chlorite vesicles parallel to its walls.

(ii) Petrography

Large, generally unoriented plagioclase laths are an important constituent, and may form more than 40% of the dyke rock (Table 4.3: Th 7.2). They are mostly altered, and sometimes completely replaced by calcite, but at locality 7, plagioclase composition was determined as An_{37}. The interstices may be filled either with pyroxene (or its alteration products), or with a fine-grained groundmass material, or both.Pyroxene is usually replaced by chlorite, sometimes with calcite, but in the less altered rocks at locality 7, fresh,anhedral, zoned clinopyroxene occurs. Fresh orthopyroxene is also present in two thin sections from this locality: it has not been observed in any of the remaining 300 or more thin sections examined during the present study. It is brown in colour, and is distinguished from the clinopyroxene by its low birefringence, straight extinction, large 2V and negative optical sign.

The fine-grained groundmass material includes calcite, chlorite, Fe-Ti oxides, epidote and quartz. Coarser patches of calcite and chlorite are present and in one case pyrite cubes with quartz-chlorite pressure shadows are seen. In some finer grained dykes the groundmass is of devitrified glass.

(ii) Interpretation

None of these dykes is seen to intrude tuffs, where evidence of interaction with wet sediment might be seen, so their time of emplacement is not clear. If the dykes were contemporaneous with

TABLE 4.3: Point counts on intrusions of the Thirlmere area. Pseudomorphs are counted as the primary phases which they replace.

SPECIMEN NO.	Th7.2	Th9.2	Th9.3	Th25.3
plagioclase phenocrysts	42.9	40.8	7.4	14.8
groundmass plagioclase	-	0.8	37.6	-
pyroxene	53.2	4.4	4.5	-
opaques	2.9	4.0	0.5	-
quartz	-	-	0.5	-
amygdales/vesicles	1.1	-	0.5	31.1
groundmass	-	50.0	49.0	54.0
TOTAL ..	100.1%	100.0%	100.0%	99.9%
Number of points counted: ..	553	524	202	607

The first part of each specimen number indicates its locality number. See Figure 4.1b for localities.

the vulcanicity, their present vertical orientation, taking into account the regional dip, indicates that most of them must have been emplaced as inclined discordant sheets. The single plagioclase determination suggests that some, at least, of the dykes are andesitic, and may be associated with the andesitic vulcanicity. Others may be dolerites.

Alternatively, the dykes may have been emplaced vertically after the main end-Silurian folding episode. In this case, they are not directly related to the vulcanicity.

IV THE VOLCANISLASTIC ROCKS

A. Unbedded Vitric Tuffs

(i) General

At several levels in the Thirlmere Andesites (e.g. Localities 6, 12, 15, 17, 58, 62, 64, 68) massive, unbedded, sometimes cleaved vitric tuffs are exposed. These dark green sand to granule grade tuffs contain occasional lapilli, and are poorly sorted. They are generally interbedded with andesitic lavas, with which they may be confused in poor exposures.

(ii) Petrography

The predominant component of the tuffs is angular, equant green vitric fragments, which may be aphyric, plagioclase-phyric or amygdaloidal, and commonly exhibit perlitic texture (Figure 4.11). Alteration along these cracks is common, and in some cases the crescentic voids are filled with quartz and chlorite. The fragments are often completely replaced by chlorite or quartz, in which the perlitic texture is preserved. Grain boundaries are frequently obscured by alteration.

Between the larger fragments, and sometimes spalling off them, are smaller vitric grains, and plagioclase crystal fragments are also important. A few specimens have a calcite cement between the grains, but most contain a considerable proportion of fine-grained material, consisting of chlorite, calcite, quartz etc. The frequent presence of amygdales and vague perlitic cracks in this "matrix' indicates that much of it is of secondary origin.

(iii) Interpretation

The unclear field relations and high degree of alteration of these rocks make interpretation difficult. In many cases, however, the textures resemble those of hyaloclastites or hyalotuffs, as illustrated by Honnorez and Kirst (1975), and it is suggested that one or both of these rock types may be represented in the Thirlmere Andesites. Their mode of formation is discussed in Chapter 3. Some of the vitric tuffs may have been produced by other processes, but the lack of diagnostic features makes further interpretation impossible.

B. Welded Tuffs

(i) Occurrence and Field Relations

Welded tuffs comprise much of the lower 500m of the Airy's Bridge Formation examined at Thirlmere (Figure 4.2d) but thin units also occur within the Thirlmere Andesites at localities 11, 37, and 83 (Figures 4.2d, 4.5). There are often marked contrasts in lithology between adjacent outcrops, but contacts are rarely exposed, and the thicknesses of units are difficult to determine.

(ii) Petrography

(a) General

Most of the welded tuffs are poorly sorted, and of lapilli tuff grade. They tend to weather white, but on fresh surfaces are dark grey-green, with a vitric appearance. The chief components are fiamme, which tend to weather inwards, and undeformed equant blocks of acid lava which stand out on weathered surfaces (Plate 51A). Either component may predominate and the texture varies from lapilli tuffs consisting of lava blocks with a few isolated fiamme, to eutaxitic welded tuffs without blocks (Plate 53B). Perlitic texture is occasionally developed, either in individual fragments, or pervading the whole rock.

(b) Fiamme

Most fiamme are 1 to 3 cm long, but examples up to 15cm long and 1cm thick occur. Aspect ratios vary from 2 to 20, but most are less than 10; they may be very variable within a single specimen (Figure 4.12) Although flattened in cross section (Plates 51A, 53B, 54A) the fiamme tend to be equant, and sometimes disc-shaped, in plan (Plates 51B, 53A).

There are two types of fiamme. The first is composed of dark green or black chloritic material (Plates 51B, 54A), sometimes feldspar-phyric, and may occasionally be recognised as deformed tubular pumice fragments. The second type consists of light coloured acidic fiamme, often with fine contorted banding and altered feldspar phenocrysts. This type may be replaced by quartz and calcite. Some welded tuffs consist almost entirely of small agglutinated acid fiamme, which are apparent in plane polarized light, but appear as a recrystallized quartz-feldspar mosaic under crossed polars.

Fiamme are often strongly deformed around rigid fragments such as lava blocks and feldspar crystals, and may be seen to be welded together.

(c) Lithic Fragments

Angular to subangular fragments of white, grey or light green acid lava may be up to 20cm across, although most fall into the coarse sand to lapilli range. They may be aphyric, plagioclase-phyric, plagioclase-chlorite (after pyroxene) -phyric or flow banded. Sparse apatite prisms may be present. Many fragments were originally glassy, and have been devitrified to a very fine-grained quartz-feldspar mosaic.

(d) Crystals

Whole and broken plagioclase crystals are an important constituent of most of the welded tuffs. Those whose composition can be determined are andesine (An_{32}, An_{36}, An_{37}) and some occur in clusters. Orthoclase is also present.Some feldspars are embayed, and many are aligned parallel to the eutaxitic texture. Quartz crystal fragments are locally abundant, and garnet occurs occasionally, either as detrital grains, or in aggregates with plagioclase.

(e) Groundmass

Some welded tuffs contain a fine-grained matrix which may be largely the result of alteration. It often contains chlorite veins and coarse patches of replacive calcite, and both groundmass and fiamme may be haematized. Small subhedral leucoxenes (after ilmenite?) are locally abundant, and pyrite cubes with chlorite pressure shadows also occur.

(iii) Brecciation

At localities 28, 29, and 38 'jigsaw fit' breccias are patchily developed within the welded tuffs (Plate 54B). The fractures cut across the eutaxitic texture, and are filled with small angular welded tuff fragments in a chlorite matrix. At locality 29 the breccia is confined to a narrow dyke-like zone.

(iv) The Section at locality 38

This 20m thick section at the base of the Airy's Bridge Formation (Figure 4.5) is the only place in the present area where zonation may be observed within a welded tuff unit. The base of the section is not seen, but the lowest outcrops show 1m of welded lapilli tuff with well defined parallel bedding and abundant undeformed acid lava blocks (Plate 52A). This passes gradually up into a tuff-breccia containing large blocks of eutaxitic welded tuff (Plate 52B), and supported in a matrix of welded tuff. The blocks become smaller upwards, and over 3 or 4m the rock passes up into welded lapilli tuff (Plate 53A). At this point the section is interrupted by a 2m thick dyke, above which 5 to 6m of eutaxitic welded tuffs are exposed (Plate 53B). Few undeformed fragments are present and the fiamme tend to become larger upwards. Above this level the exposure fails.

(v) Composition

Analyses from equivalent horizons to the west are quoted in Chapter 5 (Section III.C.iii). A single analysis (Fitton, 1971) of a welded tuff from the eastern side of Thirlmere (NY 235 137) is rhyolitic in composition (72.01% silica). This almost certainly belongs to the Airy's Bridge Formation, but as it is east of the Coniston Fault, its exact stratigraphical position is unknown.

(vi) Interpretation

There can be no doubt that the welded tuffs in the Thirlmere section are pyroclastic flow deposits. They show many of the features reported from both ancient and modern ignimbrites (e.g. R. L. Smith, 1960; Beavon et al, 1961; Rast, 1962; MacDonald, 1972 pp153-167; Howells et al, 1973). They represent large scale pyroclastic flow sheets like those described from the western U.S.A. and New Zealand (R.L. Smith 1960; Marshall, 1935). Ignimbrites are thought to be emplaced from rapidly moving fluidized flows generated during explosive eruptions, and containing plastic magma particles, crystals, solid lava fragments, vitric dust and volcanic gases. It has recently been proposed that large scale pyroclastic flows form by the gravitational collapse of Plinian-type eruption columns (Sparks and Wilson, 1976). Normal grading of lithic clasts, as seen at locality 38, is a common feature of ignimbrites (Sparks 1976). The bedding at this locality probably formed during the later stages of the flow; as it deflated, turbulent motion was replaced by laminar flow, at least near the base (Schmincke, 1974). (The origin of bedding in welded tuffs is discussed in Chapter 5, section III.Ciii)

Because of discontinuous exposure, it is not clear whether neighbouring outcrops with contrasting lithologies are separate flow units, or parts of a single, zoned ignimbrite. Fiamme of two compositions are present, and this has been reported from other areas of the Borrowdale Volcanic Group (Konig, 1964). There are two possible causes: either the fiamme originated from two contrasting magma types, or fiamme which were originally of similar composition have been altered to different mineralogies. The present author prefers the first alternative, as the two fiamme types are quite distinct, and in some rocks there appears to be a marked size difference between them. The simultaneous eruption of acid and andesitic glass has been reported from recent eruptions (e.g. Curtis, 1968) and suggests the occurrence of mix-magmas (Blake et al, 1965)

Vesicles are rather scarce in the fiamme of the Thirlmere welded tuffs, suggesting that many originated as non-vesicular glass blebs rather than as pumice. In this respect, and in the presence of abundant undeformed acid lava blocks, they closely resemble some of the ignimbrites described by Marshall (1935) from New Zealand.

The flows originated in a porphyritic magma, which erupted explosivly. The abundance of undeformed lava blocks suggests that some of the magma was solidified before eruption, whilst the fiamme represent magma which was liquid on eruption. The breccias described above (section iv) are interpreted as autoclastic explosion breccias produced within the welded tuff body as it cooled.

C. Breccias and Conglomerates

(i) Locality 13

At this locality, a dark coloured, unsorted heterolithologic breccia fills in a hollow in the top of an autobrecciated andesitic lava (Plate 38). It appears that some of the clasts at the top of the lava were slightly reworked either before or during the emplacement of the overlying breccia which, it is tentatively suggested, may represent a debris flow.

(ii) Locality 3

(a) General

At the eastern end of Thirlmere Dam are outcrops of heterolithologic breccia with clasts up to 2m long (plate 55). These are several metres thick, and are overlain to the south by finer breccias with a sharp irregular base. Both matrix-supported and clast-supported breccias are seen, and at one point a finer breccia contains irregular veins of coarser breccia, up to 50cm wide.

(b) Petrography

The breccias are poorly sorted, with a bimodal grain size distribution: the modes are in the pebble and coarse to very coarse sand grades (Figure 4.13a,b). The clasts are rather equant (Figure 3.14c) and most are subangular to subrounded. They are predominantly of acidic composition, and include amygdaloidal, plagioclase-phyric and plagioclase-chlorite (after pyroxene)-phyric lava, often partially replaced by calcite. Clasts of welded tuff, bedded tuff, unbedded tuff and andesite are also present.

The sand to granule grade matrix material consists largely of pink and white acid lava fragments. Other components include plagioclase-phyric andesite, tubular pumice (replaced by green amphibole), plagioclase, and chlorite (after pyroxene) crystal fragments, and sparse detrital garnet and quartz. The plagioclase is often fresh and much of it is in clusters: its composition is An_{36}. The garnets are partly replaced by chlorite, calcite, epidote and quartz. Between the grains is very fine-grained quartzofeldspathic material showing crude cleavage, and partly overgrown by calcite.

(c) Interpretation

The features of this deposit are consistent with a mass flow origin. In many ways it resembles the 'Purple Breccias' of Borrowdale (Chapter 3), and a similar mode of emplacement, probably as one or more debris flows, is envisaged.

(iii) Locality 6

Associated with the parallel-bedded tuffs at this locality is a breccia containing large, slightly deformed bedded tuff blocks in a matrix of coarse sand grade tuff (Plate 56A). The field relationships are unclear, but this appears to be the result of foundering or slumping of partly consolidated silt to clay grade tuff into wet, unconsolidated sand.

(iv) Locality 9

Matrix- and clast- supported conglomerates outcrop here. The sub-angular to subrounded andesite pebbles have been flattened in the plane of the cleavage, and the matrix is of sand grade tuff (Plate 56B). The rounding and moderate sorting are thought to indicate reworking in a high energy environment, but the lack of additional evidence precludes further interpretation.

D. Parallel-Bedded Tuffs

(i) Occurrence

Bedded tuff horizons are known from several localities around Thirlmere. Andesitic bedded tuffs are interbedded with andesite flows at localities 2, 6 and 37 (Figures 4.4a, 4.5) and acid bedded tuffs occur between ash flow units in the Airy's Bridge Group (Figures 4.1a, 4.2b).

(ii) Primary Structures

The most common features of these rocks are thin, laterally continuous, even, parallel beds, often with parallel lamination, and normal or reverse distribution grading (Plate 57). Often thicker sand grade beds are separated by thinner silt-clay beds (Plate 58A). Individual beds are moderately well sorted, and the grain size ranges from clay to granules, with occasional lapilli. Current generated structures are generally absent, although occasional ripple cross-lamination occurs (Plate 58A). Soft sediment faulting, brecciation of finer grained beds (Figure 4.14) and plastic folding are common, and the bases of some beds are loaded. Slight angular discordances between sets of parallel beds are seen at locality 6. Detailed sequences from parallel-bedded tuffs are presented in tables 4.4 and 4.5.

TABLE 4.4

Detailed section measured in a varnished slice of parallel-bedded tuffs from locality 6. Beds are described in descending order.

Specimen Th6,11

	top not seen
6mm	slightly graded VFS-MS grade tuff
	sharp base
4mm	parallel-laminated bed, graded from FS-MS at the base to VFS-silt at the top
	sharp base
9mm	normally graded from FS-MS to VFS silt; rare 2-3mm clasts of silt grade tuff
	sharp base
2mm	VFS-silt grade tuff, with very fine parallel-lamination;slightly finer at the base
	sharp base
0.5mm	silt-clay grade bed
	sharp base
3mm	MS grade tuff
	sharp base, with incipient loading
1mm	continuous clay grade bed, slightly coarser in the centre
	gradational base
5mm	VFS-silt grade tuff with very fine, continuous parallel-lamination; slightly finer at the base
	sharp base
4mm	FS grade tuff
	base not seen

TABLE 4.5

Detailed section measured in a varnished slice of parallel-bedded tuffs from locality 6. Beds are described in descending order.

Specimen Th6.13

top not seen

5mm silt-clay grade tuff, with two 1mm thick graded laminae at the base

sharp, planar base

7mm VFS-silt grade tuff, normally graded, but there is also a finer grained basal layer; suggestion of ripple cross-lamination near the top

sharp, slightly erosive base

6mm Finely laminated silt-clay gaade tuff; some of the laminations are graded; small soft sediment faults

sharp, planar base

7mm VFS-silt grade tuff;normal grading

sharp, slightly irregular base

5mm VFS to silt-grade tuff with slight normal grading and very small scale soft sediment faults; the basal 0.5mm is finer grained

sharp, planar base

16mm FS-VFS grade tuff; slight normal grading over the top 5mm

gradational planar base

5mm VFS-silt grade tuff with faint parallel-lamination;slight upward coarsening

sharp planar base

8mm silt-clay grade tuff with faint colour banding; slightly finer at the base and top

base not seen

(iii) Petrography

Occasional 20 to 50cm thick beds at localities 2 and 37 appear, in both outcrop and thin section, to be welded, with agglutinated shards wrapping around crystals and lithic fragments. One such bed at locality 2 has an erosive base.

A single bed of accretionary lapilli tuff occurs at each of localities 6 and 37. Each bed contains both whole lapilli and fragments of their pellicles. The lapilli are up to 1cm long, and are flattened by the cleavage (Plate 58B). Most have a very fine sand grade core, which grades outwards into a silt to clay grade pellicle. Rarely, they may contain up to four concentric bands.

The andesitic tuffs are poorly to moderately sorted, and consist of subangular grains of vitric andesite and plagioclase, either of which may predominate. The andesite may be aphyric or plagioclase-phyric, and sometimes has a trachytic texture. Plagioclase is usually highly altered, but at locality 2, compositions of An_{33} and An_{34} have been obtained. Plagioclase often occurs in glomeroporphyritic clusters. Pumice, altered to calcite and chlorite, is locally abundant, and cuspate shards, replaced by quartz, occur occasionally. Other constituents include detrital chlorite (after pyroxene) and quartz, and rare garnet and sandstone grains. Many tuffs contain a high proportion of fine-grained matrix, much of which may be secondary.

(iv) Interpretation

In detail, these tuffs are very similar to the parallel-bedded tuffs of Brown Knotts (Chapter 3, section III,D.v) and are interpreted as ashfall deposits. The rare welded beds may represent hot ashfall deposits, or thin pyroclastic flows, which were buried so rapidly by the overlying ashfall material that sufficient heat was conserved to allow welding. There was very little reworking of the tuffs, indicating deposition in a low energy environment, but there are no diagnostic environmental indicators. Much of the soft sediment deformation present can be attributed to disruption by overlying lava flows.

V. ENVIRONMENTAL SYNTHESIS.

A. The Volcanic Environment

Interpretation of the Thirlmere Andesite sequence is very difficult, as much of the evidence is negative, and diagnostic environmental features are lacking. During the accumulation of some 2500m of andesitic rocks, the environment may have changed several times. There were intrusions into wet sediment, but this does not necessarily indicate a subaqueous environment: the peperite complex described by Schmincke (1967a) was formed subaerially, when burrowing lavas interacted with wet, unconsolidated sediments. Other indicators of a 'wet' environment are common at many levels in the section: these include hyaloclastites/hyalotuffs and local pillows. It is tentatively suggested that a subaqueous environment predominated for at least part of the time, but it is impossible to tell whether this was marine (below wavebase) or lacustrine.

Welded subaqueous ash flow deposits are known (Mutti, 1965; Francis and Howells, 1973), and it is possible that the isolated ignimbrites within the Thirlmere Andesites were deposited subaqueously. However, thick sequences of welded ash flow sheets like that of the Airy's Bridge Formation have only been described from subaerial situations. Whatever the conditions during the accumulation of the Thirlmere Andesites, a subaerial environment was in existence during the deposition of the major ignimbrites

B. Sources.

Some of the dykes seen in the Thirlmere area may represent feeders for lava flows, but no major volcanic sources have been identified. It has been suggested (Wadge et al, 1974) that the St. John's Threlkeld microgranite laccolith (and, by implication, the related Armboth Dyke) might be coeval with the upper part of the volcanic pile. They are similar in composition to the Airy's Bridge ignimbrites, and could represent their source. Such close associations between ignimbrites and granitic plutons have been demonstrated in the Andes (e.g. Myers, 1975).

FIGURE 4.1

(a) Outcrop map of the Thirlmere area, based on 1:10,560 Ordnance Survey map. The line of the Coniston Fault (Moseley, 1972) is taken from Hartley's (1941) map.

(b) Locality map of the Thirlmere area. Numbers refer to outcrops mentioned in the text.

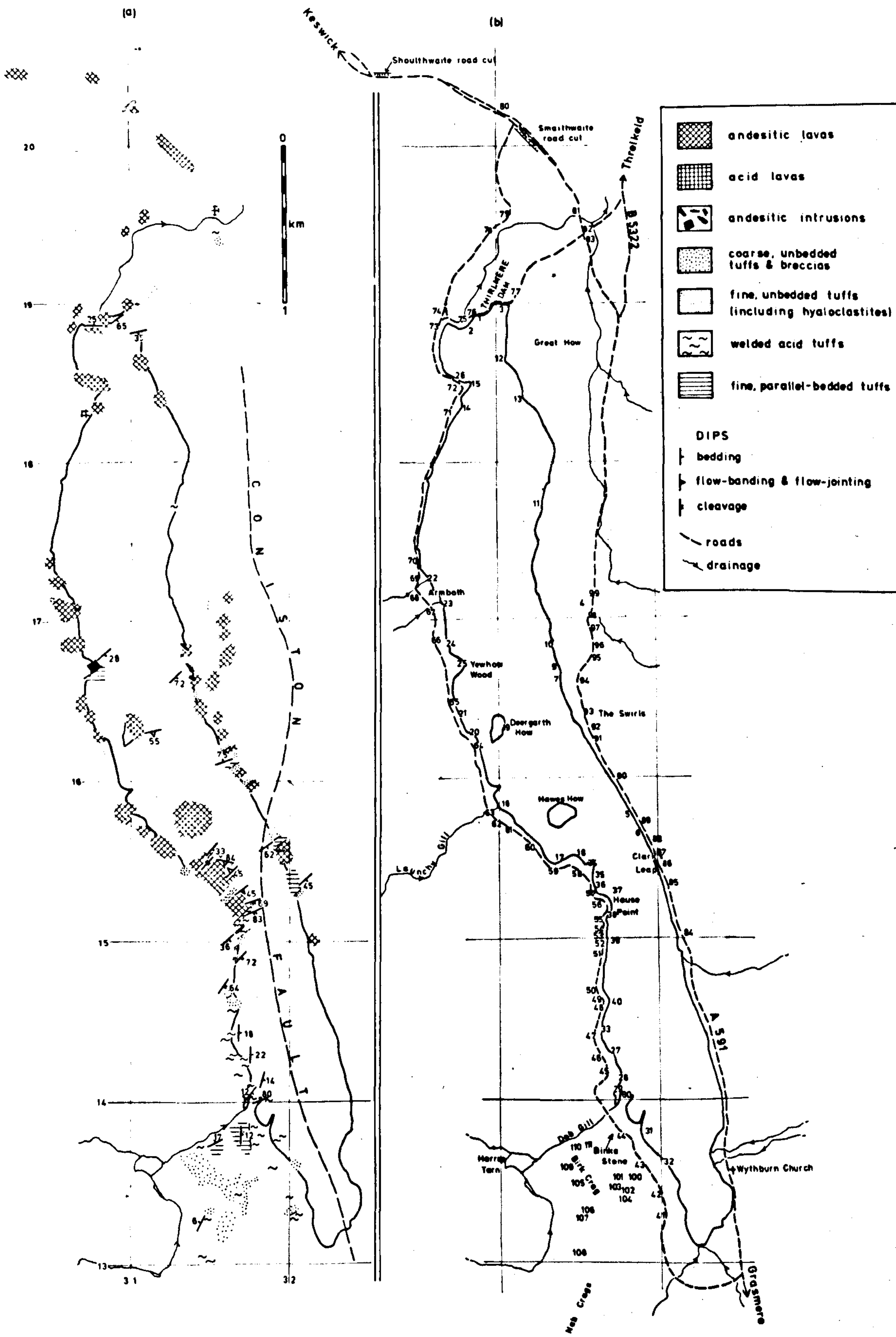

(a)
(b)
km
C O N I S T O N   F A U L T
Keswick
Shoulthwaite road cut
Smaithwaite road cut
Threlkeld
B 5322
THIRLMERE DAM
Great How
Armboth
Yewhow Wood
Deergarth How
Hawes How
The Swirls
Launchy Gill
Clark's Leap
Hause Point
A 591
Dob Gill
Birk Crag
Birks Stone
Harrop Tarn
Wythburn Church
Hob Crags
Grasmere
andesitic lavas
acid lavas
andesitic intrusions
coarse, unbedded tuffs & breccias
fine, unbedded tuffs (including hyaloclastites)
welded acid tuffs
fine, parallel-bedded tuffs
DIPS
bedding
flow-banding & flow-jointing
cleavage
roads
drainage

FIGURE 4.2

(a) - (c) Structural data from the Thirlmere area:

(a) Joint orientations (only joints steeper than 60° are shown).

(b) Orientations of minor faults. Classes in (a) and (b) are 10° wide.

(c) Lower hemisphere stereographic projection of poles to bedding, flow jointing of lavas and cleavage.

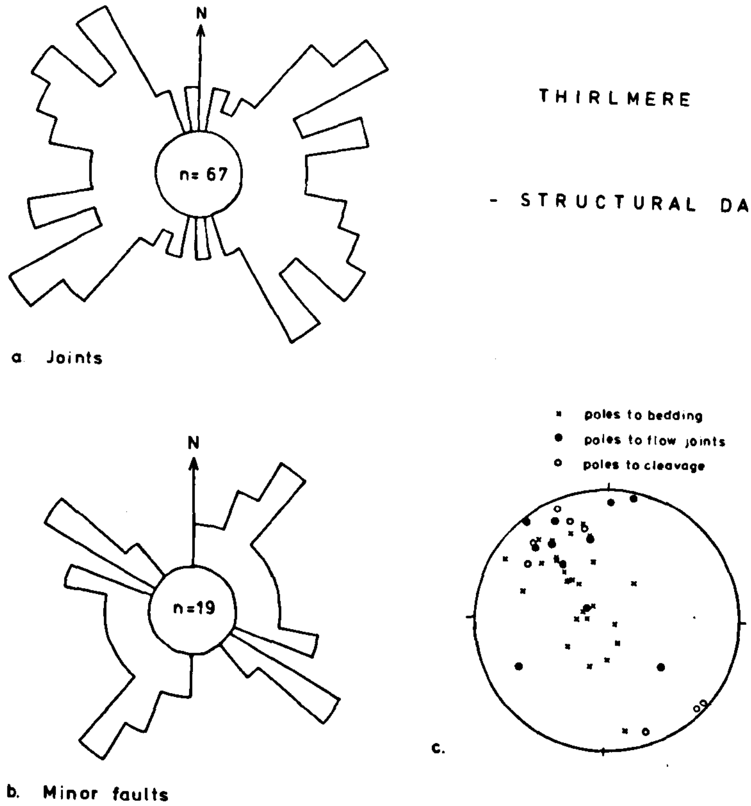
(d) Diagrammatic succession for the Thirlmere area, compiled from outcrop maps. Thicknesses are approximate, and small gaps in the succession are not all shown. Key as for Fig 4.1.

h - indicates presence of hyaloclastites/ hyalotuffs

t - indicates presence of tuff units

p - indicates presence of peperites

THIRLMERE - STRUCTURAL DATA



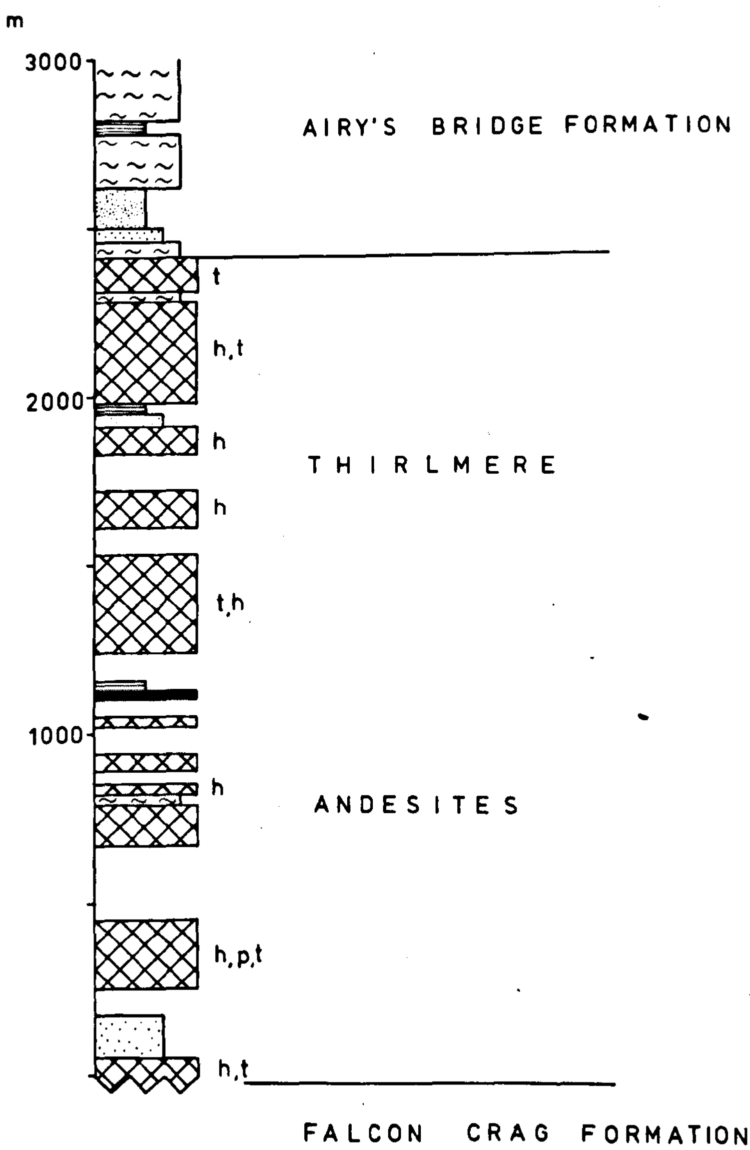
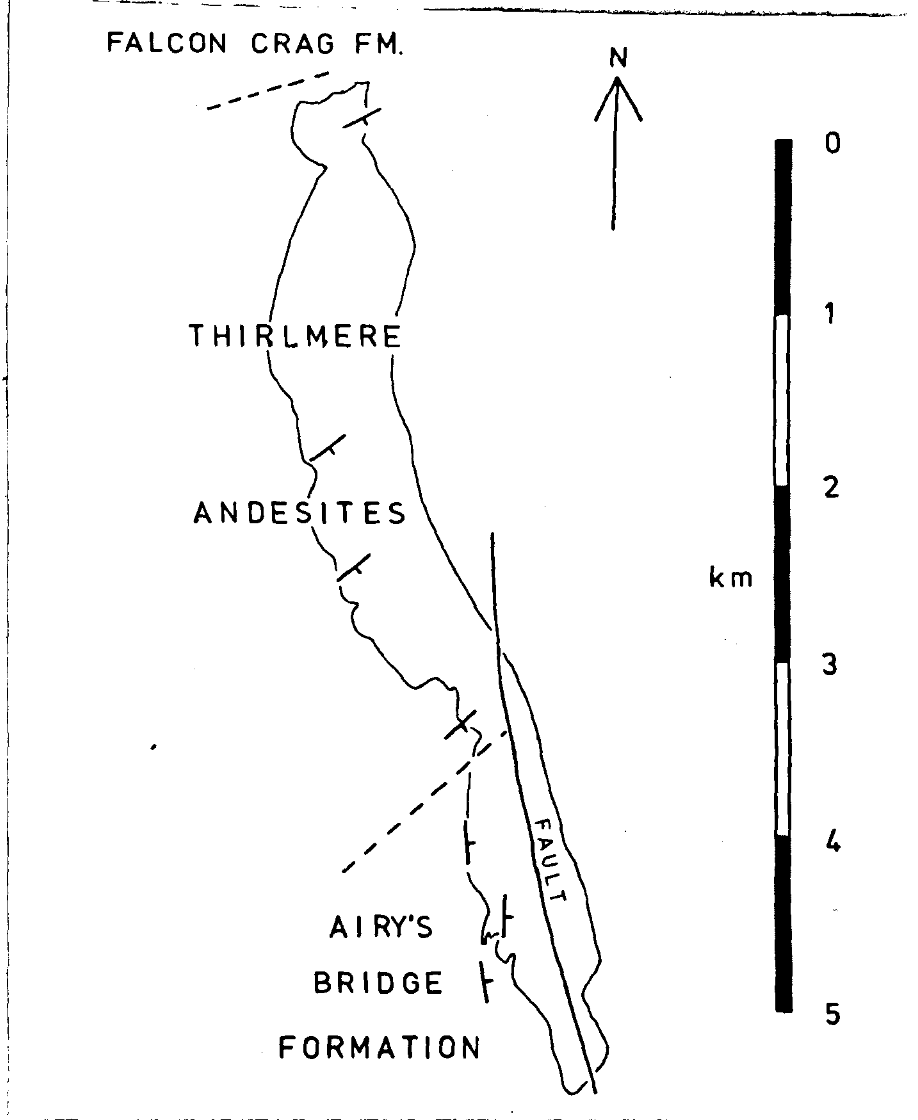


FIGURE 4.3

(a) Map showing the general structure and stratigraphy of the Thirlmere area.

(b) Lithostratigraphy of the Thirlmere area.



STRATIGRAPHY OF THE THIRLMERE AREA

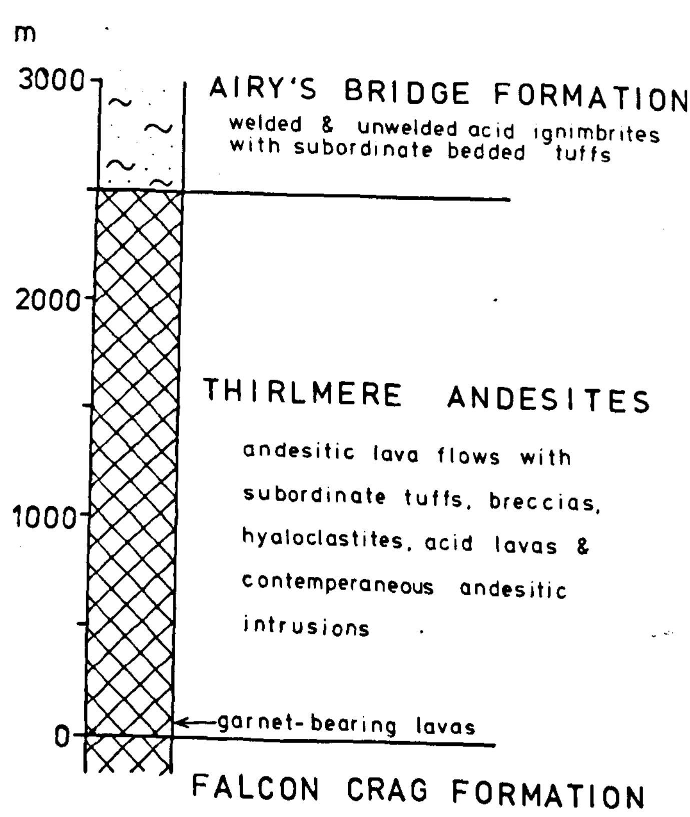
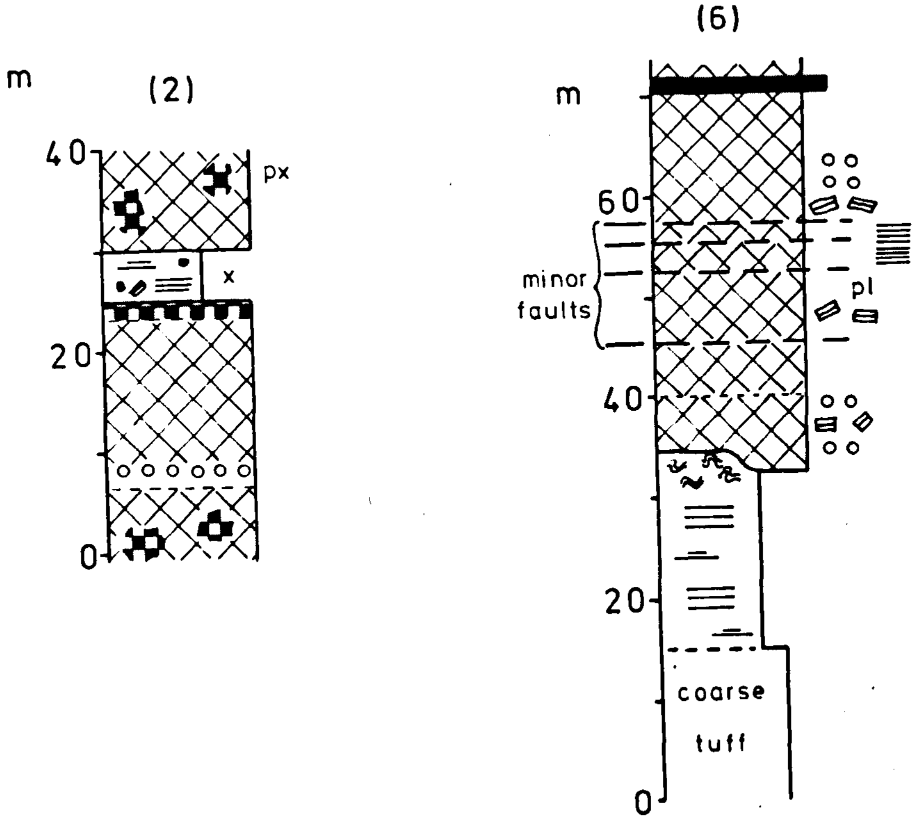


FIGURE 4.4

Sections in the Thirlmere Andesites. Key as for Figure 3.23

(a) Localities 2 (west side of Thirlmere Dam) and 6 (north of Clark's Leap).

(b) Locality 17 (north of Hause Point). Measured during low lake level.


m
(2)
40
20
0
px
x
(6)
m
60
40
20
0
minor faults
pl
coarse tuff

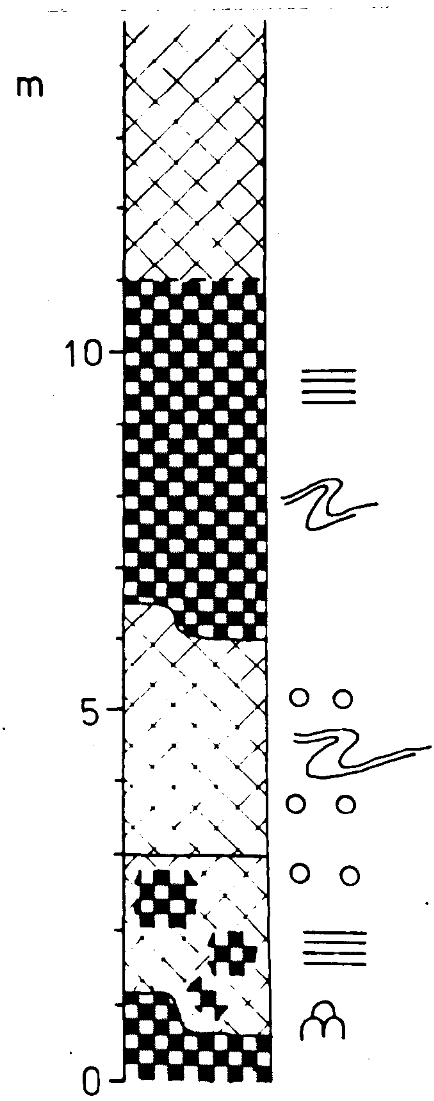
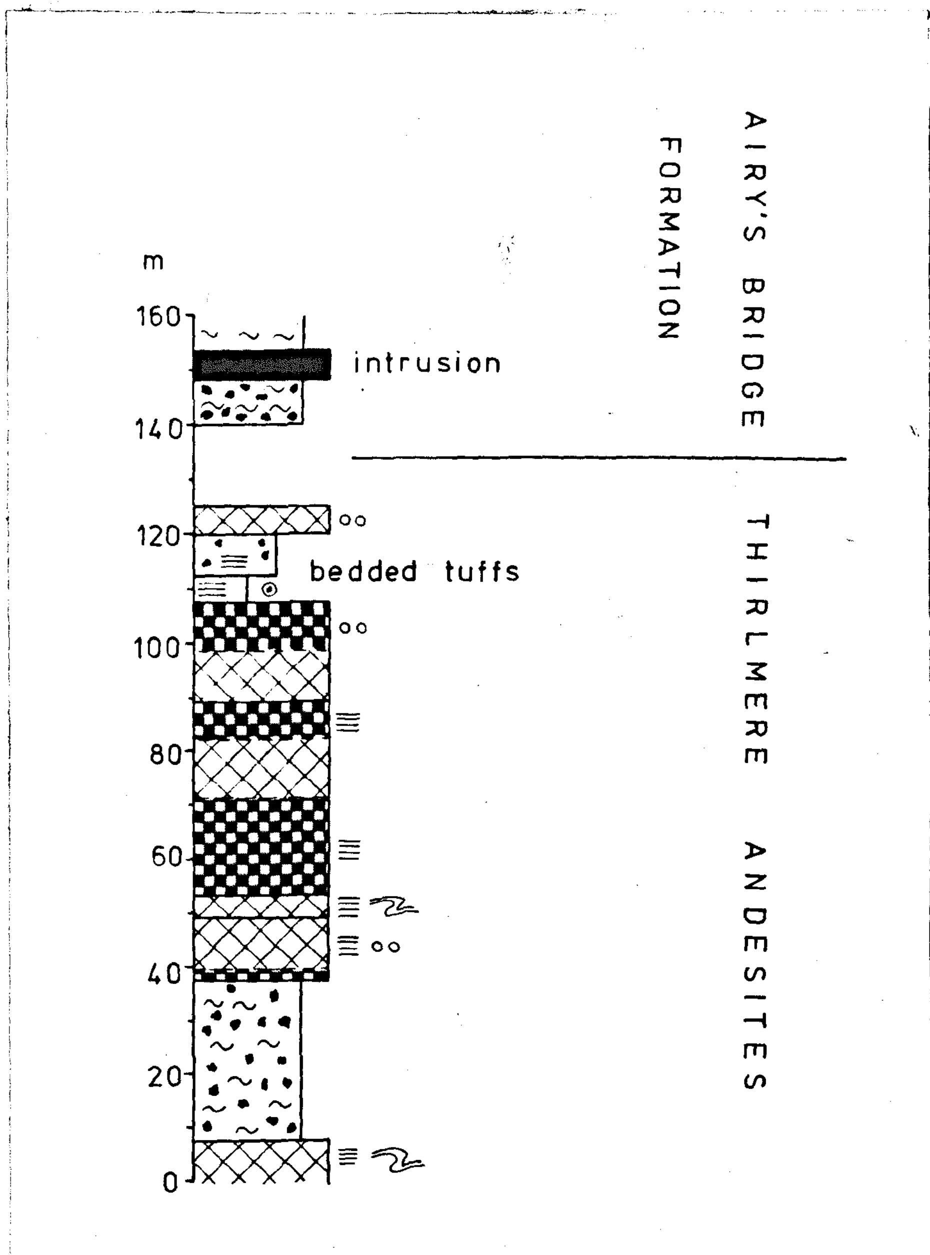

m
10
5
0

FIGURE 4.5

Section in the upper part of the Thirlmere Andesites and the lower part of the Airy's Bridge Formation, localities 37 and 38 (Hause Point). Key as for Figure 3.23.



m
160
140
120
100
80
60
40
20
0
intrusion
bedded tuffs
AIRY'S BRIDGE FORMATION
THIRLMERE ANDESITES

FIGURE 4.6

(a) Cross section of andesitic lava, showing flow folding truncated by the overlying planar flow banding. Locality 37 (Hause Point).

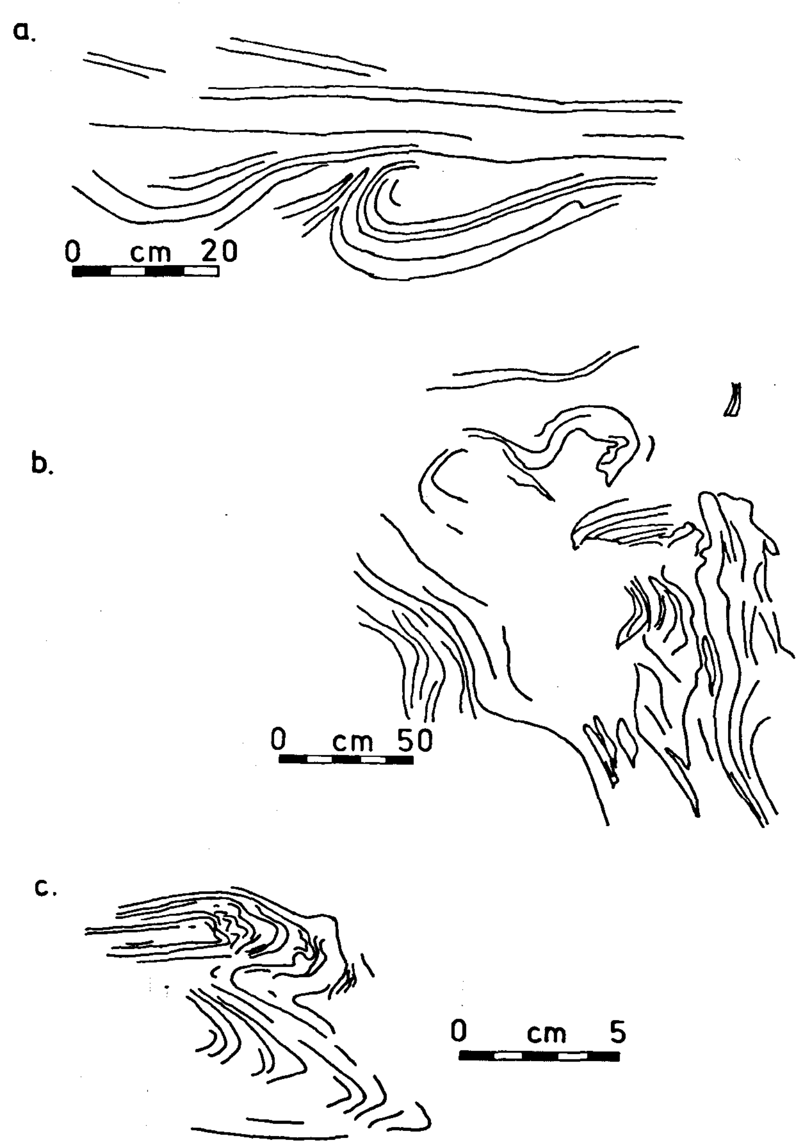
(b) Highly irregular flow folding in andesitic lava. Locality 18 (north of Hause Point). Horizontal section in lava dipping approximately 30° southeast.

(c) Small scale flow folding in glassy andesitic lava. Vertical section in gently dipping flow. Shoulthwaite road cutting.

(d) Autobrecciated andesite, with a matrix of fine grained, chilled lava. Note the "jigsaw fit" between some of the blocks. Loose boulder, locality 17 (north of Hause Point).

(e) Andesitic autobreccia, showing a "jigsaw fit" between many of the blocks. The matrix is of comminuted andesite debris. Locality 6.

Drawings from photographs.


a.
0 cm 20
b.
0 cm 50
c.
0 cm 5


0 cm 15
d.
e.
0 cm 30

FIGURE 4.7

Section through gently dipping andesitic lavas in the north side of the north-bound carriageway of the A591 at Smaithwaite road cutting. In spite of the gentle dip, contacts between different andesite facies are commonly steep, and tend to be gradational. The matrix of the autobreccias is fragmental, unless otherwise shown, and clasts are often partially rounded. Some small faults are omitted. Section measured by tape. Vertical scale is approximate.

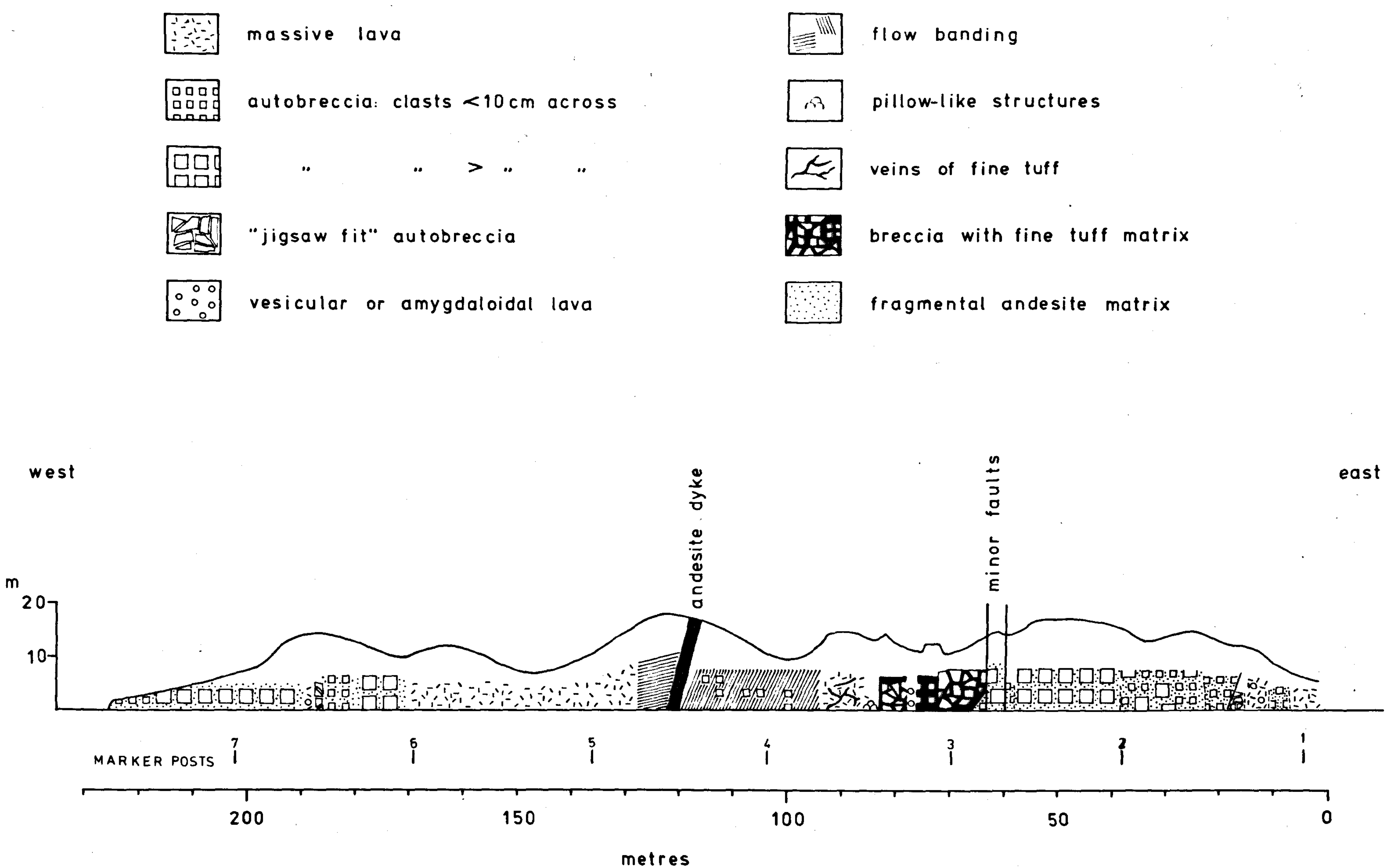

massive lava
autobreccia: clasts <10 cm across
" " > " "
"jigsaw fit" autobreccia
vesicular or amygdaloidal lava
flow banding
pillow-like structures
veins of fine tuff
breccia with fine tuff matrix
fragmental andesite matrix
west
east
andesite dyke
minor faults
m
20
10
MARKER POSTS
7
6
5
4
3
2
1
200
150
100
50
0
metres

FIGURE 4.8

Accurate large-scale map of the upper part of an andesitic lava flow at the west end of Thirlmere Dam (locality 2). Overlying bedded tuffs dip at 25° to the north. The outcrop was mapped at a scale of 1:50, using a 1m grid chalked on the rock surface.

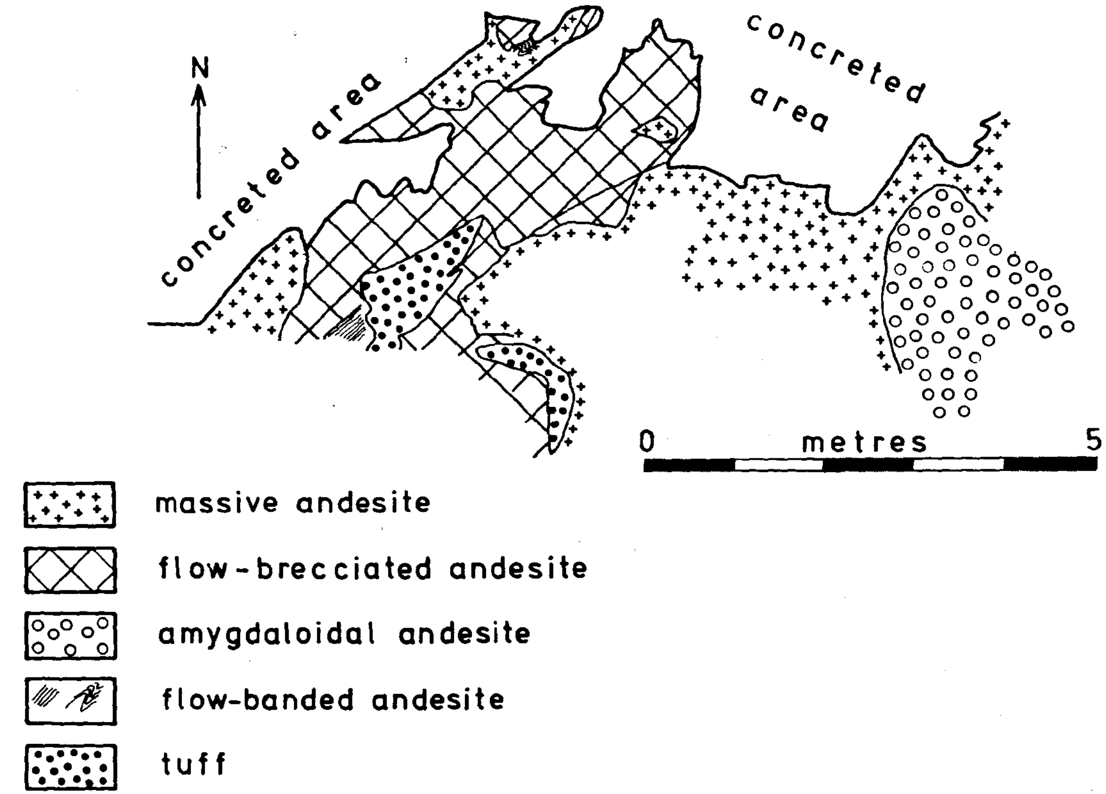

N
concreted area
concreted area
0
metres
5
massive andesite
flow-brecciated andesite
amygdaloidal andesite
flow-banded andesite
tuff

FIGURE 4.9

Grain size characteristics and clast shapes of autobrecciated andesites from three localities in the Thirlmere Andesites.

(a) locality 12 (south of Thirlmere Dam). Measurements on surface nearly normal to dip.

(b) locality 18 (north of Hause Point). Measurements on near horizontal surface.

(c) locality 25 (Yewhow Wood). Analyses from two different surfaces, both nearly normal to the dip, in the upper part of an intrusive andesite sheet.

Inset map shows location of sections.

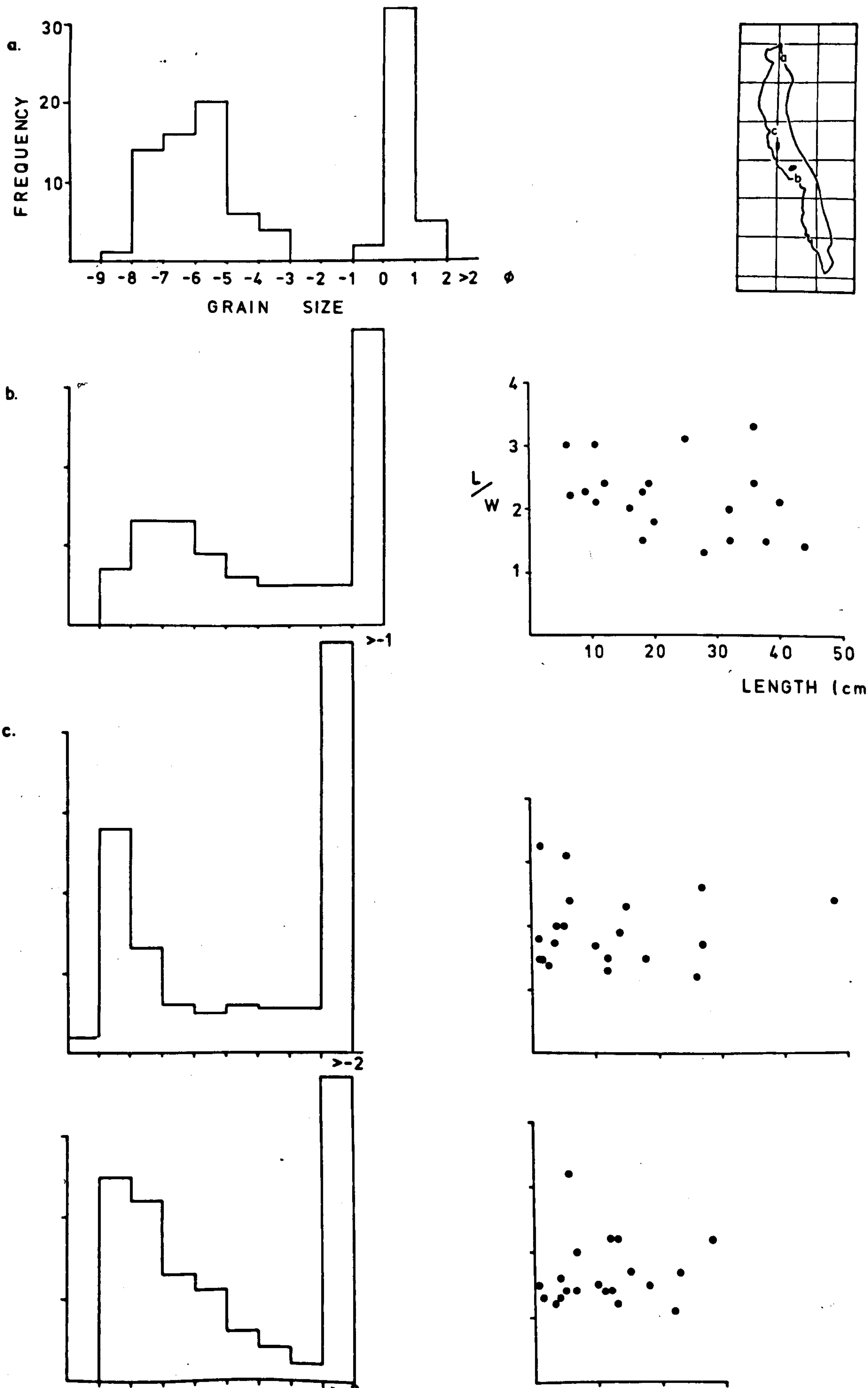
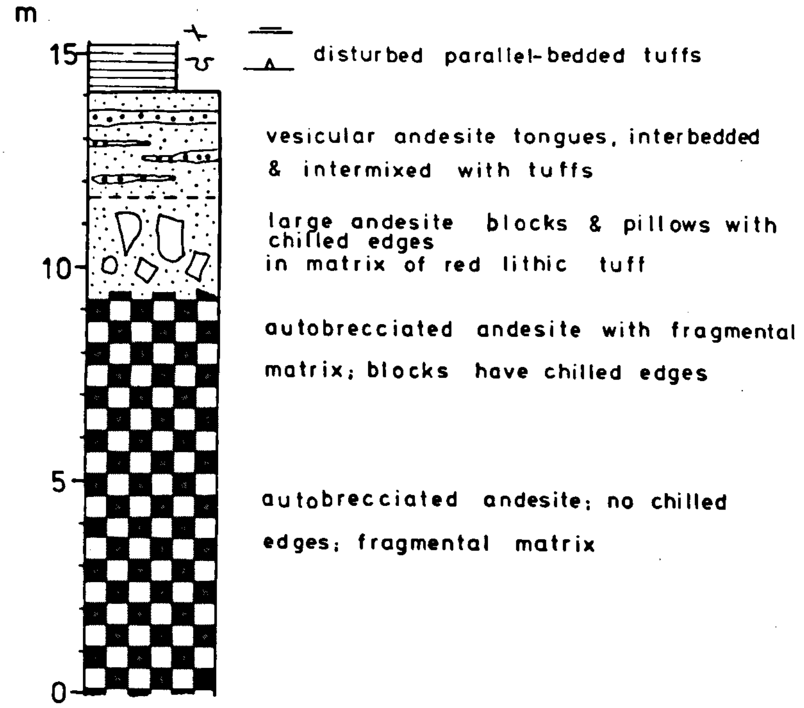

a.
30
20
10
FREQUENCY
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 >2 φ
GRAIN SIZE
a
c
b
b.
4
3
2
1
L/W
10 20 30 40 50
LENGTH (cm)
>-1
c.
>-2
>-2

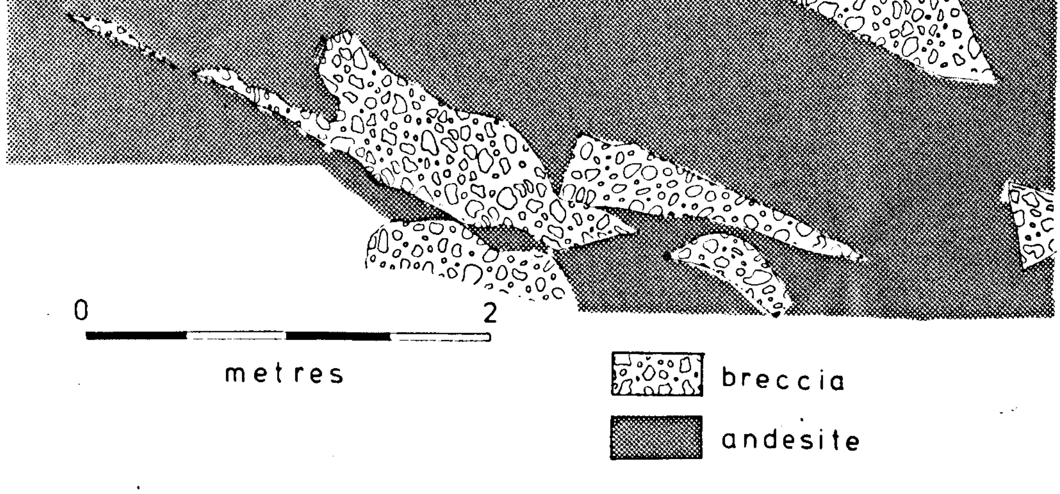
FIGURE 4.10

(a) Section through the upper part of an intrusive andesite sheet at locality 25 (Yewhow Wood).

(b) Masses of andesitic breccia caught up in a high level andesite intrusion. Some of the breccia "rafts" are imbricated. Locality 9 (west of The Swirls). Drawing from photograph.



m
15
10
5
0
disturbed parallel-bedded tuffs
vesicular andesite tongues, interbedded & intermixed with tuffs
large andesite blocks & pillows with chilled edges in matrix of red lithic tuff
autobrecciated andesite with fragmental matrix; blocks have chilled edges
autobrecciated andesite; no chilled edges; fragmental matrix



0
2
metres
breccia
andesite

FIGURE 4.11

Tracing from thin section of probable hyaloclastite.

Locality 12. Note the presence of small plagioclase phenocrysts in some of the vitric andesite fragments.

?HYALOCLASTITE FROM THIRLMERE

Vitric andesitic fragments in feldspar crystal tuff matrix.

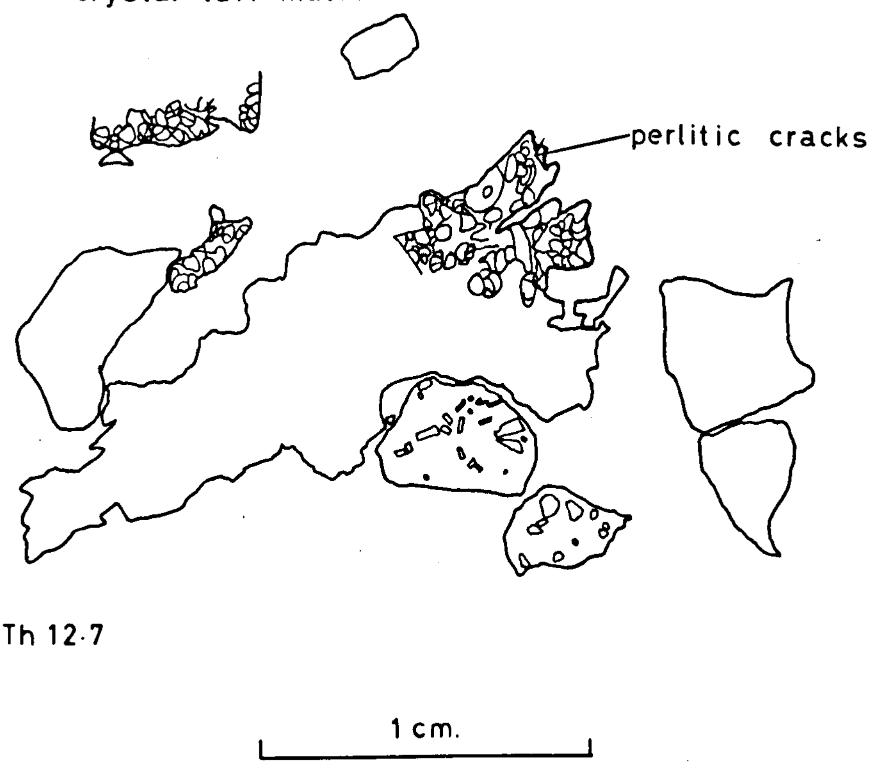
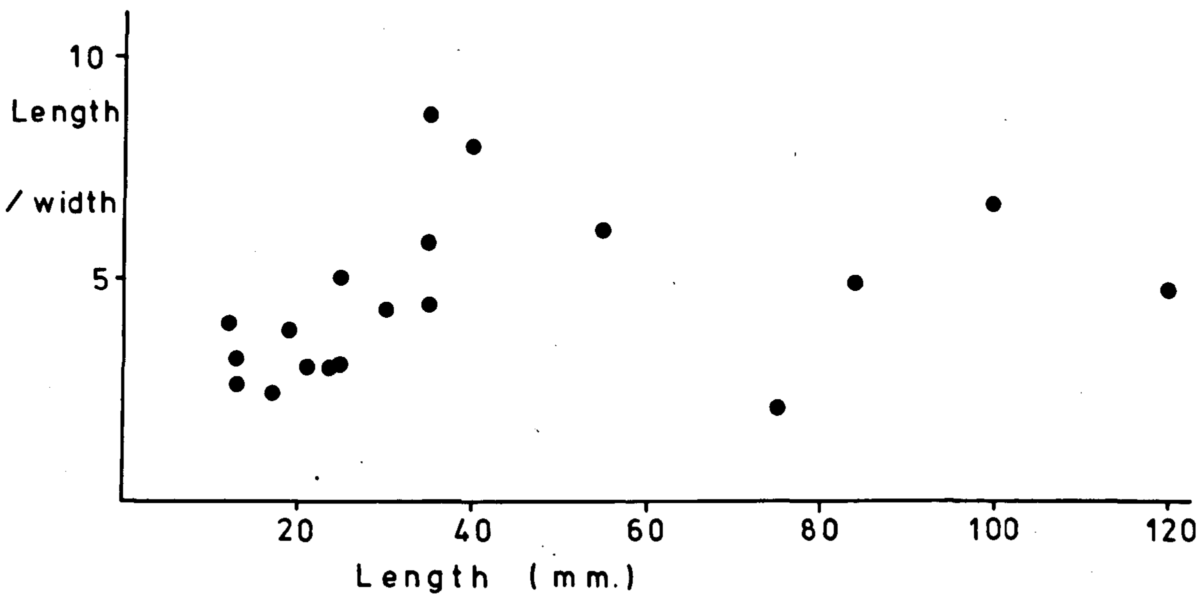


FIGURE 4.12

(a) Plot of length versus length:thickness ratio for fiammé from the welded tuffs at locality (27), Thirlmere. The measurements were made on a surface of the outcrop which is approximately normal to the dip and parallel to the strike. (N.B. for width read thickness on the diagram)

(b) Plot of length versus length:thickness ratio for fiammé from eight specimens of welded tuffs of the Airy's Bridge Formation of Thirlmere and Langdale. The measurements were made on varnished slices of each rock, cut at 90° to the eutaxitic foliation. Points marked with the same symbol are from a single specimen.


10
Length
/ width
5
20
40
60
80
100
120
Length (mm.)

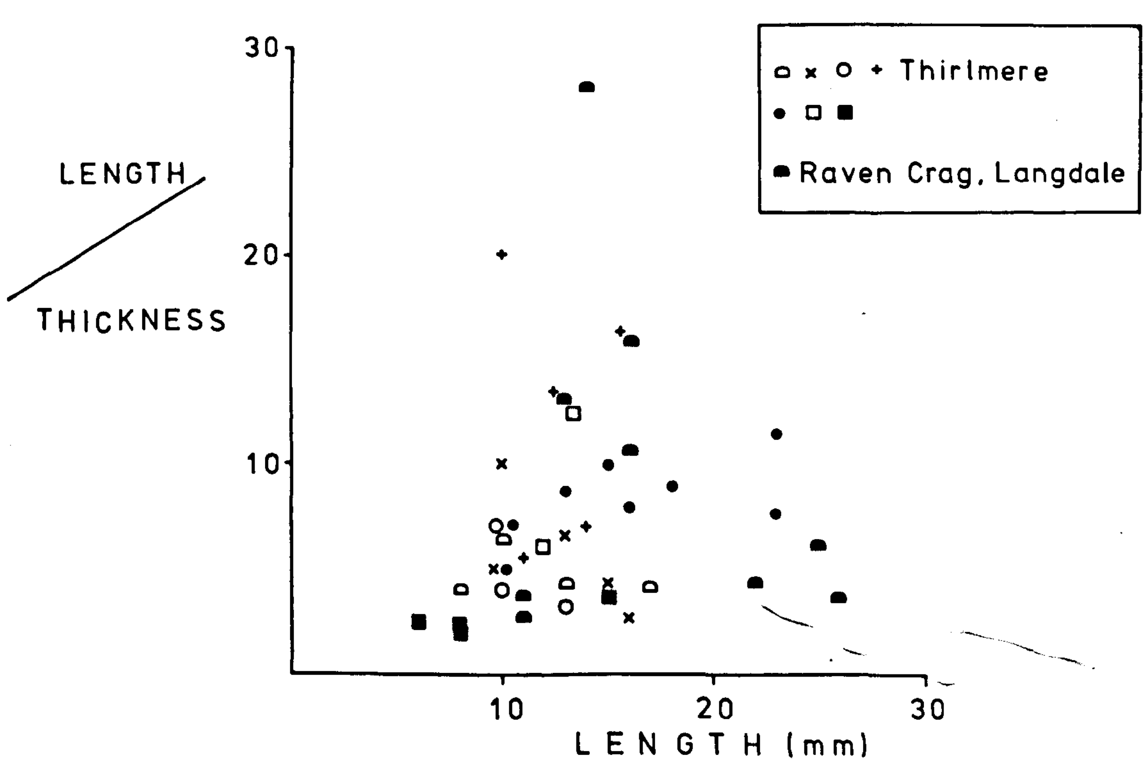

30
20
10
LENGTH
THICKNESS
Thirlmere
Raven Crag, Langdale
10
20
30
LENGTH (mm)

FIGURE 4.13

Grain size characteristics of the polymict breccias at locality 3 (east side of Thirlmere Dam). The measurements were taken on westward-dipping surfaces oblique to the bedding, using a 10 cm grid chalked onto the rock.

(a) Histogram and cumulative curve from one surface.

(b) Histogram and cumulative curve from a second surface

(c) Length versus length:width ratio for clasts on the second surface.

Inset map shows location of section.

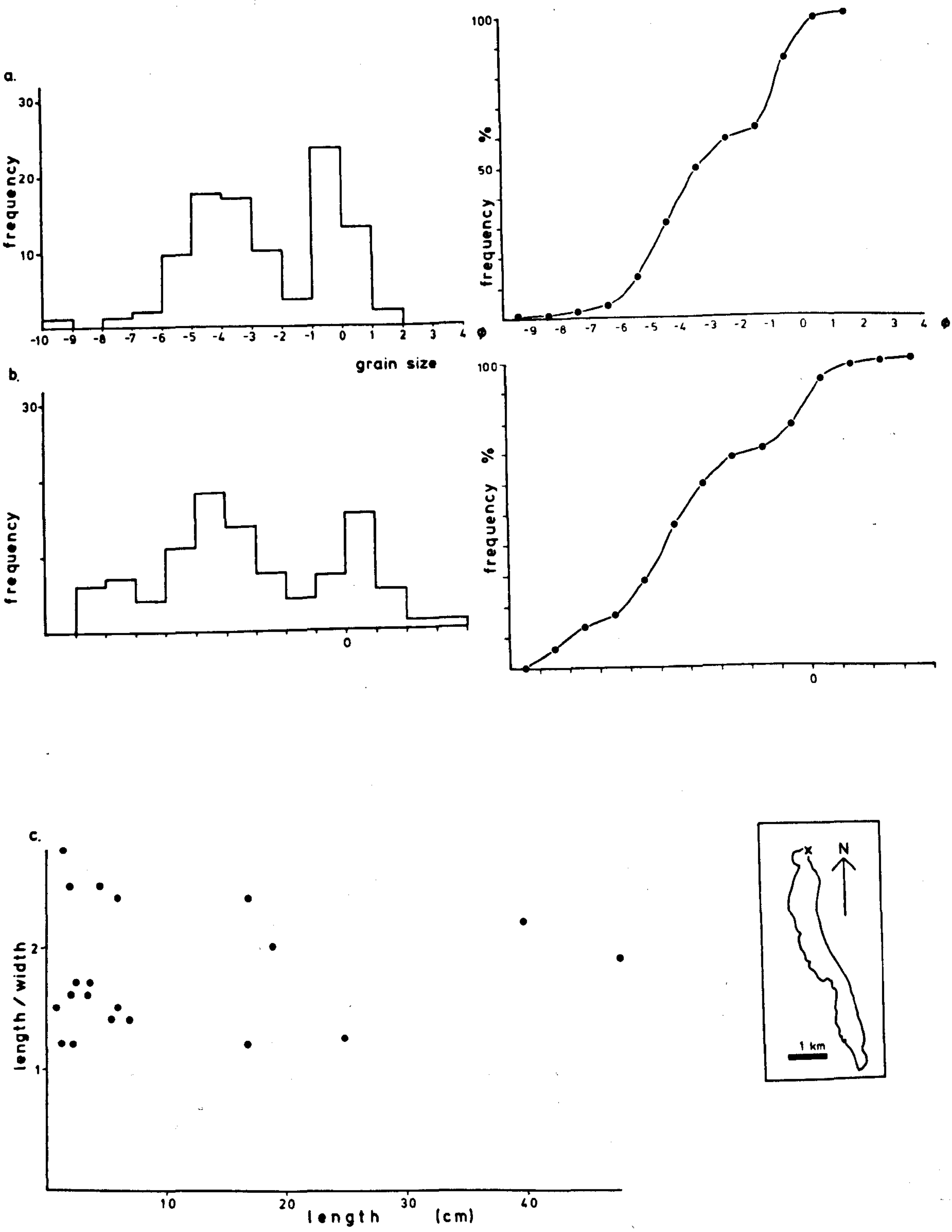

a.
frequency
30
20
10
-10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 φ
grain size
100
%
50
frequency
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 φ
b.
30
frequency
0
100
%
frequency
0
c.
length / width
2
1
10
20
30
40
length (cm)
x
N
1 km

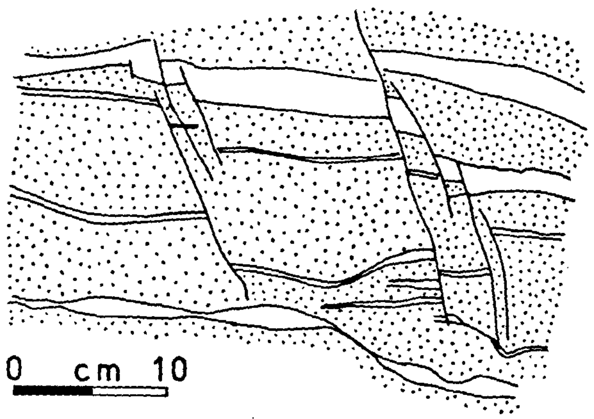
FIGURE 4.14

Penecontemperaneous brittle deformation in bedded tuffs of Thirlmere.

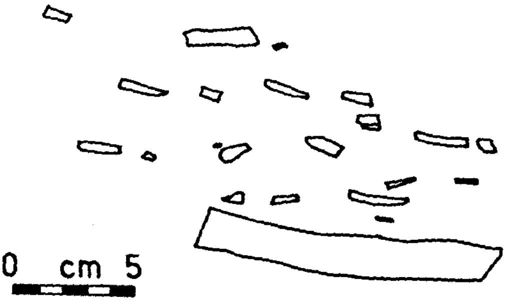
(a) Soft-sediment faulting in sand (stippled) and silt grade bedded tuffs. Loose block.

(b) Brecciated porcellanous clay grade beds in a matrix of very fine sand to silt grade. Bedded tuffs at locality 2 (west end of Thirlmere Dam).

a.



b.



CHAPTER 5. THE SOUR MILK GILL SECTION, BORROWDALE

I. INTRODUCTION

A. General

This area lies toward the southern end of Borrowdale (fig 5.1), west of Seathwaite Farm (NY 235 122). Lavas and volcaniclastic rocks are well exposed in the bed of Sour Milk Gill, and to its north and south. A thick bedded tuff unit is less resistant to erosion than the adjacent lavas and welded tuffs, and the lip of Gillercombe, the corrie at the top of Sour Milk Gill, and the Gill itself, are eroded into it. Good bedding plane exposures in the bedded tuffs here, exhibiting a variety of sedimentary features, are atypical of the Borrowdale Volcanic Group as a whole and rare in the other areas covered by the present research. To the south, the massive acid rocks at the top of the measured sequence form the prominent crags of Hanging Stone (NY 228 120).

There are serious errors in Oliver's (1961) map of this area. He shows a thick development of andesitic lavas underlying the welded tuffs south of Sour Milk Gill. In fact, the whole of the area between the Gill and the welded tuffs of Hanging Stone is occupied by unmistakeable bedded tuffs (fig 5.1). Strens'(1962) map is also highly inaccurate for this area.

The sections were measured accurately by tape. The area was studied over a shorter period than those of Chapters 3, 4 and 6, and no microscope work has been undertaken.

B. Structure.

The area lies on the northern limb of a major fold, the Scafell Syncline (Oliver, 1961) (fig 1.7). The structure is well shown by the bedded tuffs, which dip uniformly to the south-southeast and south at 48° to 60°. Cleavage is generally absent, even in the fine-grained tuffs, and accretionary lapilli appear to be flattened mainly in the plane of the bedding. The bedded tuffs often show well-developed joint sets (plate 64A). No faults were observed in the area, and evidence for the thrust shown on Oliver's (1961) map is completely lacking.

C. The General Sequence

The base of the measured section coincides with that of a bedded tuff unit which overlies brecciated andesitic lavas (fig 5.2). These tuffs are up to 24m thick, and are succeeded by an andesitic lava flow 36m thick, with autobreccias at its base and top. Overlying this is the major bedded tuff unit with a thickness of 160m. In turn, this is succeeded by massive acid welded tuffs with minor bedded tuffs. The section ends some 100m up in the welded tuffs, but this is only the basal part of a major acid sequence more than 1000m thick (Oliver, 1961).

D. Stratigraphy and Correlation.

The bedded tuffs and associated andesitic lavas belong to Oliver's (1961) Birker Fell Andesite Group. This name should, therefore, have priority, and has been modified to the Birker Fell Formation (fig 5.2). The major bedded tuff unit is named the Sour Milk Gill Tuff Member (new name) which is a part of the Birker Fell Formation. The base of the Formation has not been defined, although the top of Strens' (1962) Seatoller Tuff Group might be a suitable position (fig 3.8). The Birker Fell Formation may also be tentatively correlated with andesitic sequences underlying the major acid sequence in other areas (fig 1.8), such as the Mosedale Andesites of Hartley (1932) and the upper part of Moseley's (1960, 1964) Ullswater Group.

The overlying welded tuff sequence is the lowest part of Oliver's (1961) Airy's Bridge Group; this name is retained as the Airy's Bridge Formation. Undoubtedly, the base of this thick sequence, which is taken at the base of the first welded tuff (fig 5.2) is the same as that seen at Hause Point, Thirlmere (fig 5.3) and the two are probably synchronous (see Chapter 1.111.A.(ii)). Below this level, the andesitic sequences cannot be matched exactly between the two sections, but there are striking lithological similarities, and they probably represent similar volcanic regimes. Bedded tuffs containing accretionary lapilli are present a short distance below the base of the Airy's Bridge Formation at both Sour Milk Gill and Hause Point. This may be important in correlation if such horizons are as widespread as Soper and Numan (1974) suggest.

On Rosthwaite Fell, 3 km to the east of Sour Milk Gill, rocks at the same stratigraphic level are exposed (D. Millward, unpublished section). The succession is similar to that of Sour Milk Gill, although the Sour Milk Gill Tuff Member is considerably thinner (fig 5.3). At Hause Point, Thirlmere (fig 5.3) bedded tuffs at this level are much thinner again. If the bedded tuffs at all three localities are part of the same unit, there is a marked eastward thinning, from 160m at Sour Milk Gill to 50m or less at Hause Point (fig 5.3)

Millward's Rosthwaite Fell section includes a "pyroclastic breccia" unit 25m thick, whose base lies 20m above the base of the Sour Milk Gill Tuff Member (fig 5.3). In the author's opinion, this is likely to be the lateral equivalent of the breccias of section 3, Sour Milk Gill (fig 5.4) which are of comparable thickness, and occur at a similar level. If this correlation is correct, the thinning between Sour Milk Gill and Rosthwaite Fell occurs within the upper part of the Member.

II. THE LAVA FLOWS.

A. Lower Unit.

Two andesite units were observed within the Birker Fell Formation. The one at the base of the measured section (fig 5.2) is dark green in colour, and contains feldspar phenocrysts. Its top is brecciated, consisting predominantly of andesite clasts, but also incorporating disrupted bedded tuff. The breccias are poorly sorted and unbedded and are sharply overlain by undisturbed parallel-bedded tuffs. They are interpreted as flow breccias, and the undisturbed top contact indicates that the andesite was extrusive at this locality. The disrupted bedded tuff may have been derived by the andesite intruding through or ploughing into wet sediment at another point.

B. Upper Unit.

(i) Field Relations.

This lava occurs immediately below the Sour Milk Gill Tuff Member (fig 5.2) and has well developed breccias at its base and top (plate 59). Its base is very irregular and the underlying tuffs are highly disrupted and indurated immediately below the andesite. They show complex small-scale folding and faulting. The top is also irregular, and the overlying bedded tuffs are disturbed over a thickness of up to 50 cm. At one point, the bedded tuffs are draped over blocks at the top of the lava. In one example, bedded tuff mantling a large block has a dome-like form.

In the measured section, this unit is 36m thick, and shows no evidence of substantial changes in thickness within the study area. It was traced laterally for a distance of some 600m (fig 5.1), and probably extends much further. Thus, its aspect ratio is greater than 17.

(ii) Primary Structures

The brecciated basal zone, approximately 2m thick, consists mainly of andesite blocks up to 1m in diamter. This is best seen in crags (NY 231 123) north of Sour Milk Gill. Within the breccia occur contorted blocks of bedded tuff, up to 2m long. In part, the matrix of the breccia consists of fine-grained, compact, aphyric lava, which stands out on weathered surfaces. In other places, the matrix is fragmental.

The massive central portion of the andesite is 28m thick (fig 5.2) with no obvious primary structures. Overlying it is a breccia 6m thick, which consists largely of andesite blocks up to 1m across (plate 59A) with a fragmental matrix containing angular chips of lava. This is particularly well exposed in the slabs at the top of Sour Milk Gill (NY 228 123). Further east, large blocks of deformed bedded tuff are found within the breccia. In the bed of the Gill (NY 230 123) a different type of brecciated andesite is found (plate 59B). Here, there is a "jigsaw-fit" between the fragments, which must have moved little relative to each other. The interstices are filled with fine-grained, light green tuff.

(iii) Petrography and Composition.

The rock varies in colour from light grey near its base to dark grey at the top, and weathers with a thin white patina. It is glassy in appearance, and largely aphyric, with rare dark green phenocrysts (possibly of pyroxene, or of chlorite after pyroxene) 0.5 to 1mm long. A specimen from the fragmental matrix of the basal breccia shows sharp, highly angular, equant glassy lava fragments set in very fine-grained tuff. The form of the fragments is reminiscent of that seen in hyaloclastites (e.g. Honnorez & Kirst, 1975).

Some of the lavas in this and adjacent areas were analysed by Oliver (1961) and Fitton (1971). One is from the top of the upper unit in Sour Milk Gill (NY 224 121). It contains 57.57% SiO_2, and hence is a basaltic andesite (fig 2.1) (Fitton, 1971). Of seven other analyses by the same authors from lavas at or slightly below this horizon in adjacent areas, six are basaltic andesites, with silica contents ranging from 54.43% to 57.65%, and the seventh is a basalt with 49.64% SiO_2.

(iv) Interpretation.

It is proposed that the upper and lower breccias of this andesite are flow breccias produced as the base and top of the advancing lava flow were chilled, and then fractured by continuing movement (see chapters 3 and 4 for fuller explanations). The draping of bedded tuffs over the upper breccia suggests that the andesite is an extrusive lava flow.

The bedded tuff blocks in the basal breccia were probably incorporated into the lava flow as it moved over and disrupted the underlying sediments. The hyaloclastic appearance of parts of the matrix may be the result of granulation of the lava by thermal shock, caused by rapid chilling against water or wet sediment. The bedded tuff blocks in the upper breccia are less easy to explain. It may be that the andesite was erupted through unconsolidated tuff, or that at some stage it ploughed through wet sediment, parts of which it incorporated.

The "jigsaw fit" autobreccia within the upper breccia may be the result of local steam explosions within the lava, or of thermal shock, caused by contact with water or wet sediment. At a later stage, the interstices of the autobreccia were filled with fine ash, which probably infiltrated from above.

III. THE VOLCANICLASTIC ROCKS

A. The Bedded Tuffs.

(i) Field Relations

Both the lower bedded tuff unit and the Sour Milk Gill Tuff Member sharply overlie brecciated lava flows. Neither of these contacts shows evidence of erosion. The top of the lower tuff unit has been indurated and deformed by the overlying lava. The bedded tuffs at the top of the Member are overlain by welded tuffs of the Airy's Bridge Formation and the junction, although sharp, is planar and apparently non-erosive. The lower bedded tuff unit thins to the west, and is possibly represented by a 1 to 2m thick bedded tuff at Raven Crag (NY 224 124), 800m WNW of the point at which it is 24m thick. Over the area studied, the Sour Milk Gill Tuff Member does not show any appreciable change in thickness. A few thin bedded tuff horizons are interbedded with the welded tuffs of the Airy's Bridge Formation.

A typical section of bedded tuffs is shown in figure 5.9.

(ii) Primary structures

(a) Parallel Bedding

Throughout both the lower bedded tuff unit and much of the Sour Milk Gill Tuff Member, the most prominent feature is thin to very thin, even, parallel bedding (as defined by Reineck & Singh, 1975) (plate 60). These tuffs are termed Facies 1 (fig 5.2). Beds are mostly 0.5 to 2cm thick, and laterally very continuous, and erosion surfaces are not common. Most beds have sharp, planar bases, but slight irregularities, such as small scours, are often mantled by an overlying bed of uniform thickness (plate 63A). Two types of thin-bedded tuffs are seen (fig 5.9): in one, fine to medium sand grade beds predominate (plate 60A) and in the other the majority of beds are of silt to clay grade (plate 60B). The first type is the most common. Very finely spaced parallel lamination is common, particularly in the finer grained tuffs (plate 60B) and laminae less than 1mm thick are traceable over the width of an outcrop.

Some 60m up into the Sour Milk Gill Tuff Member, thicker beds of sand grade tuff appear (plate 61). These are 10 to 50 cm thick, have sharp, non-erosional bases and sharp tops and tend to be structureless internally. Some are graded or, less commonly, reverse graded. This facies (Facies2, figure 5.2) is interbedded with Facies 1, and either may predominate.

(b) Graded Bedding

Graded bedding is commonly seen in parallel-bedded tuffs of Facies 1 and 2, although most beds are apparently ungraded. Normal distribution grading is the predominant type, but reverse distribution grading also occurs, and occasional concentration of lithic fragments towards the top of a bed results in "coarse tail" reverse grading.

(c) Ripples

Although the tuffs of this area are largely parallel-bedded, well developed ripple marks are seen at several horizons in both the lower tuff unit and the Sour Milk Gill Tuff Member. The ripples may be exposed either on bedding planes (plate 62), best seen at Seathwaite Slabs (NY 233 122) or in cross section (plate 63A). They are developed largely in fine to medium sand grade tuffs, but also in those of silt to clay grade. Ripples in sand grade tuff very commonly have a thin drape of clay grade material of uniform thickness (fig 5.5a)

Symmetrical ripples with straight to slightly sinuous crests are predominant. Those observed have constant wavelengths within a single set of ripples, on the order of 2 - 5cm, and amplitudes up to 0.7cm. Ripple indices range from 5 to 25, although these have almost certainly been affected by compaction. In one set of symmetrical ripples, continuous wavy lamination was seen in cross section (figure 5.8e). In the bed of Sour Milk Gill (NY 230 122) sinuous crested symmetrical ripples show bifurcations (plate 64A). The form of the symmetrical ripples, and their similarity to modern ripples observed by the author, supports their interpretation as wave ripples (Reineck & Singh, 1975). There is a wide range in the wave directions measured (figure 5.6) and no firm conclusions are drawn.

In one example (plate 62B) there is a subordinate ripple trend transverse to the main one; in another (figure 5.8d) broadly polygonal ripples are seen. These are probably varieties of wave interference ripples. Asymmetrical ripples with straight to slightly sinuous crests also occur, and one example shows short, steep lee faces and broad, gentle stoss sides (plate 62A). These ripples have a wavelength of 10cm and an amplitude of 0.5cm, giving a ripple index of 20. They are interpreted as current ripples. In the classification of Reineck and Singh (1975) these are "undulatory small ripples", regarded as intermediate between low energy straight-crested small ripples and higher energy linguoid small ripples.

On a beddingplane in Sour Milk Gill (NY 230 122) some 30m above the base of the Sour Milk Gill Tuff Member, and another 3 cm below it, are irregular, elongate, ripple-like structures developed in silt grade tuff (plate 63B). They are more or less symmetrical with rather steep faces, having a wavelength of 0.5 to 1cm and an amplitude of approximately 0.3cm. These structures may be raindrop imprints, but the preferred orientation is more consistent with some kind of ripple.

In form and size they are very similar to adhesion ripples observed by the author, which formed by the action of a strong wind blowing over moist sand on the delta of the Tana River, North Norway. The structures at Sour Milk Gill also resemble adhesion ripples and wrinkle marks figured by Reineck and Singh (1975). The author believes that they formed by wind action on subaerially exposed moist silt grade volcanic ash. Their crests are thought to be normal to the wind direction and in the absence of any marked asymmetry, two wind directions are possible (figure 5.6).

(d) Cross Bedding

Cross bedding is seen at only two localities. A tabular set 20cm thick (figure 5.5b) is developed in medium sand grade tuff at Seathwaite Slabs, below the prominent rippled bedding planes. Its upper and lower contacts with parallel bedded tuffs are planar and non-erosive. 50cm higher in the section is a second cross-bedded set, 0 to 10cm thick, and thinning towards the east. Both sets are directed towards the north west (figure 5.6). They represent the migration of dunes with straight or slightly sinuous crests and indicate two quite distinct, short-lived episodes of aqueous current activity.

A different type of cross bedding is seen in a 3.1m thick bedded tuff unit at the base of the Airy's Bridge Formation (figure 5.2; plates 69, 70). These tuffs are predominantly of very fine sand grade. They are underlain by a 3m thick welded tuff unit, and overlain by "normal" parallel bedded tuffs. Accretionary lapilli up to 1cm in diameter are abundant (plate 69) but less so within the cross sets than in the more massive beds between them. Most of the cross bedding is low angled, and gentle dune structures may be seen.

These may be draped by an overlying unit showing thinning of the beds over the dune crest (plate 70). Individual cross-bedded sets are 5 to 20cm thick, and there are gentle, often erosional surfaces between them. Laminae within cross sets are laterally very continuous. The features displayed by the dune structures, including low relief, gentle slopes, low angle lamination, more or less symmetrical form and draping of laminae, resemble those of antidunes (Reineck & Singh 1975). They are tentatively interpreted as such.

One surface shows sets of climbing ripple laminae up to 3cm thick, with marked thinning of the laminae on the stoss sides (plate 69A). This set passes downwards into plane beds and is sharply overlain by a thin massive bed rich in accretionary lapilli. The climbing ripples may represent a lower flow regime than that which produced the low angle cross beds. The cross laminae indicate transport towards the east.

(e) Mudcracks

At several localities within the Birker Fell Formation, well-developed mudcracks are seen (plates 64, 65; figs 5.2, 5.7, 5.8). The best example, in the lower bedded tuff unit north of Sour Milk Gill (NY 232 124), shows cracks up to 5mm wide in silt grade tuff (plate 65A, fig 5.7). These define flat, polygonal mudflakes with diameters of 10 to 30cm. Within them are smaller cracks, branching from the larger ones. In places, thin ridges of clay grade tuff protrude through the mudflakes. The mudcracks are filled with very fine sand grade material, but are not exposed in cross-section, so their depth and three-dimensional form are unknown. In another example, slightly higher in this unit at the same locality individual cracks up to 3cm long and 0.2cm wide are isolated and do not join together to form polygons (fig 5.8c).

Mudcracks also occur at several horizons within the Sour Milk Gill Tuff Member; Close to its base, on the south side of the wall at the top of the Gill (NY 228 123), polygonal to rectangular mudflakes on a bedding plane of clay grade tuff show curled-up edges. The clay grade layer is less than 0.5cm thick, and the polygons are from 5 to 10cm across. Higher up the Member at the same locality, and extending a considerable distance laterally, abundant examples are seen in cross section, very commonly with curled-up edges (plate 64B). They are best developed in thin silt to clay grade laminae interbedded with thicker sand grade beds. Mudcracks are not seen in thicker silt-clay grade beds. Closely associated with the mudcracked layers are fine-grained beds showing small scale folding, with broad, gentle synclinal troughs and sharp, narrow anticlinal culminations (e.g. near the base of plate 64A). These appear to be an early stage in mudcrack formation, the process being completed by fracture at the anticlinal crests.

Mudcracks may form either by subaerial shrinkage due to drying of wet sediment (desiccation), or by subaqueous shrinkage caused by salinity changes (synaeresis). The mudcracks at Sour Milk Gill bear much more resemblance to desiccation cracks as typically seen in dried-out puddles or lake beds (e.g. plate 65B) than to synaeresis cracks, such as those observed by the author in sediments of the late Precambrian Vadsø Group, North Norway (interpretation: H.D. Johnson, personal communication). Thin mud layers would dry out more quickly than thicker ones, and thus have a greater chance of showing desiccation cracks. Intermittent drying out of wet, fine-grained volcanic ash is indicated.

(f) Soft Sediment Deformation

Soft sediment deformation is common in the bedded tuffs of the

Birker Fell Formation but tends to be concentrated at certain levels, the intervening strata showing little or no deformation. Both brittle and plastic deformation are seen.

Normal and reverse faulting occur, and both step-faulting and small graben structures may be seen (plate 66B). In some of these the downfaulted block has sagged. Individual faults, although commonly having throws of 1cm or less, may affect a thickness of up to 2m of bedded tuffs. Faults with larger throws are occasionally seen (plate 67A). The faulting is sometimes closely associated with brecciation of silt-clay grade bedded tuff (upper part of plate 66B).

These faults are believed to be of synsedimentary rather than tectonic origin for several reasons: individual faults affect a limited thickness of strata, with no breaks in the beds above and below; the fault planes are perfectly healed, with no mineralization along them; faulting is confined to specific horizons; some faults show evidence of injection of wet sediment along them.

Small scale folding of bedded tuff layers is occasionally seen, but more common are cross-cutting bodies of fine to medium sand grade material (fig 5.8 a & b). These commonly take the form of irregular diapirs or clastic dykes and sills, which are often 10 to 20 cm in height, but may extend more than 1m vertically from their source (fig 5.8b). The walls of the intrusions may have a step-like form, following the bedding of the silt-clay grade tuffs which they cut (fig 5.8a). Sometimes these bodies contain clasts of bedded tuff identical to the wall-rock. Small scale faulting is often associated with these structures.

In several examples, there is evidence of upward movement of incoherent volcanic sand into coherent but sometimes plastic silt to clay grade tuffs. At the top of Sour Milk Gill (NY 227 122) a sand grade diapir has domed up the overlying bedded tuffs (fig 5.8b). In the lower tuff unit north of the Gill (NY 232 124) diapirs extend more than 40cm upwards from an 80cm thick sand grade tuff bed (fig 5.8a) which is roughly wedge shaped, probably as a result of loss of material to the diapirs. A bedding plane here shows a hummock of medium to coarse sand grade material (plate 66A) which is circular in plan, with a diameter of some 15cm, and a height of about 5cm. The structure is covered by a thin layer of clay grade tuff. It may be a sand volcano, built up on the sediment surface by upward movement of sand and later draped by clay grade ash, or it may be an injection structure which domed the overlying bedded tuffs but did not reach the surface. In some cases, upward movement of sand has evidently followed pre-existing desiccation cracks (e.g. plate 64B).

The diapirs at Sour Milk Gill are interpreted as water escape structures resulting from the upward intrusion of liquefied or fluidized (Lowe, 1975) volcanic sand along fractures in partly consolidated silt to clay grade bedded tuffs. In some cases, the upward moving sediment-water mixture incorporated fragments of the wall-rock. The common association with soft sediment faults suggests that early faults in the bedded tuffs may have been exploited by the upward moving fluids. The sand involved in these structures may ori ginally have been deposited rapidly, allowing insufficient time for maximum packing.

Some of the deformation of the bedded tuffs can be ascribed to moving lava flows, as discussed above. A thin disturbed zone at the base of the Sour Milk Gill Tuff Member, showing mainly brittle fracturing, probably results from settling and compaction of the tuffs over the irregular, blocky surface of the underlying lava.

The remaining soft sediment deformation tends to be confined to horizons a few metres thick, separated by greater thicknesses of very similar, but undeformed tuffs. The deformation in these horizons may have been triggered by earth tremors associated with the volcanicity, when liquefaction and/or fluidization of unconsolidated, wet, sand grade layers resulted. A fuller discussion of wet sediment deformation is given in Chapter 6.

(iii) Petrography

The bedded tuffs of the Birker Fell Formation are acidic in composition, closely resembling those at the same horizon at Hause Point, Thirlmere (see Chapter 4). The fine-grained bedded tuffs are medium to light grey in colour, and small feldspar fragments and vitric grains may be distinguished in hand specimen. Small pits on the surface of some of these tuffs suggest calc areous weathering.

The sand grade and coarser bedded tuffs consist mostly of light to medium grey acid vitric material, sometimes with perlitic fragments. The fragments are highly angular, and some cuspate glass shards are distinguishable. These tuffs are rather well sorted, with little or no fine-grained matrix. In the upper part of the Sour Milk Gill Tuff Member, feldspar crystal fragments become a conspicuous, sometimes predominant, component of the sand grade tuffs.

(iv) Interpretation of Bedded Tuff Sequences

Thin, even, parallel bedding is ubiquitous in the tuffs of Sour Milk Gill. The lateral continuity of these beds, and the way in which they mantle irregularities suggest that the sediment accumulated by vertical settling rather than lateral transport. All the features described, including normal and reverse grading, are characteristic of ashfall deposits, in which parallel bedded ashes are produced by a large number of separate explosions, often separated by very short intervals. Each bed represents a single fall unit, and each fall unit is the result of a single explosion (Schmincke, 1974). The thicker, coarser beds are probably the result of more powerful explosions than the thin, fine-grained beds if both are from the same source. Within individual ash showers, the larger fragments will tend to fall out first, with the fine ash falling last, resulting in a graded bed.

The non-vesiculated components of the tuffs, and their striking similarity to ashfall deposits of the 1888 - 1890 eruption of Vulcano, Italy (plate 30B) suggests that they are the deposits of ash clouds produced by Vulcanian explosions. The genesis of ashfall deposits is discussed in more detail in Chapter 3.

Although much of the succession shows little sign of reworking, wave and current ripples are present at several horizons (see above) indicating that some, at least, of the tuffs were deposited in shallow water and reworked to a limited extent. The thin cross-bedded horizons at Seathwaite Slabs suggest occasional rather stronger, short lived currents. The presence of adhesion ripples and desiccation cracks indicates the periodic emergence of wet volcanic ash.

A different origin is proposed for the cross-bedded tuffs at the base of the Airy's Bridge Formation. It is unlikely that accretionary lapilli, which are very fragile, could survive transport by upper flow regime currents capable of producing antidunes. However, accretionary lapilli-bearing tuffs with cross bedding and antidune cross bedding have recently been described from the deposits of base surges (e.g. Schmincke et al, 1973; Mattson & Alvarez, 1973; Bond & Sparks, 1976) (see Chapter 2 for description of base surge mechanisms). The sizes and internal structures of the dunes at Sour Milk Gill closely resemble those reported from Death Valley, California and Sugarloaf Mountain, Arizona (Crowe & Fisher, 1973; Sheridan & Updike, 1974, 1975). In particular, the low angle dunes are very similar to the "Type IV" dunes from the Laacher See, West Germany (Schmincke et al, 1973). The close association of cross beds with plane beds and more massive beds at the base of the Airy's Bridge Formation is comparable with, and on a similar scale to those at Sugarloaf Mountain, and it is possible that they represent the three distinct types of base surge flow postulated by Sheridan & Updike (1974, 1975). They thought that the plane beds represent high concentration inertia flows, the massive deposits represent dense fluidized flows and the cross beds represent dilute fluidized flows.

Although the beds at Sour Milk Gill are in close proximity to welded ignimbrites, the author does not believe them to be the deposits of the hot dry surges which may accompany or precede incandescent pyroclastic flows (Sparks & Walker, 1973), as it is unlikely that accretionary lapilli could form in such an environment. Rather, it is thought that they were deposited by relatively cold base surges, rich in steam, resulting from phreatic eruptions.

B. The Bedded Breccias.

(i) Field Relations

Within the Sour Milk Gill Tuff Member, a series of breccias is seen at some localities, commencing some 25m above the base of the Member. At Seathwaite Slabs (NY 233 122) the lowest exposed breccias lie 3m above the rippled tuffs. The contact is not exposed. The breccias here have a thickness of 27.5m and are sharply overlain by parallel-bedded tuffs (fig 5.4, section 3).

200m to the west, higher up Sour Milk Gill (NY 230 122) a single 3m thick breccia unit occurs at this level (fig 5.4, section 2). It is underlain by highly contorted bedded tuffs which are partly incorporated within the base of the breccia (plate 68A). Silt grade tuffs are draped over and banked against the uppermost blocks of the breccia (plate 68B). Banking occurred when the face of a block was too steep to be mantled by an ash bed; the banked beds have upturned edges.

At the top of Sour Milk Gill (fig 5.4, section 1) there are no breccias at this level, nor anywhere within the Sour Milk Gill Tuff Member, suggesting that the breccias die out rapidly to the west. To the east, however, the "pyroclastic breccia" on Rosthwaite Fell may be the lateral equivalent (see I.D. above and fig 5.3).

(ii) Primary Structures and Textures

The breccias at Seathwaite Slabs show thick to very thick, even, parallel-bedding. There are some 10 to 15 beds, up to 3m thick. Most contacts between breccia beds are planar, although occasional load structures with a relief of up to 5cm are seen. Most beds are graded showing both a marked upward decrease in the size and frequency of blocks and an overall upward decrease in the grain size of the matrix (e.g. the lowest breccia bed of plate 67B). For example, the matrix of one 1.3m thick bed is of very coarse sand to granule grade at the base and decreases gradually upward to medium sand grade, and then abruptly to silt-clay grade in the top 2cm. The upper 30cm of the bed contains no blocks (bed above rucksack, plate 67B). Several beds grade upwards from clast-supported breccia to matrix-supported breccia to silt-clay grade tuff without blocks. Others start in matrix-supported breccia and grade up into tuff. The single breccia unit of plate 68 is matrix-supported throughout, but shows an upward decrease in clast size. Near its base are blocks up to 1m across.

The breccias contain blocks which are large in proportion to the bed thickness. A 2.8m thick bed contains a block 2m long, and most of its clasts are more than 30cm in diameter whilst the clasts in the 1.3m thick bed described above are up to 80cm across. Most of the blocks are angular, but some are sub-rounded, and the predominant lithology is massive, compact lava similar in appearance to the andesites of the Birker Fell Formation. Blocks of unbedded medium sand grade tuff, unlike any rock type seen in the section, also occur.

(iii) Interpretation

The planar bases of these units preclude the possibility of their being pyroclastic fall deposits, as impact structures would surely have been produced by such large blocks falling through either air or water. The grading and lack of internal structure suggest emplacement by a series of mass flows, which must have been very competent to carry blocks of this size. Subaerial pyroclastic flows often show coarse tail grading of lithic blocks, but not distribution grading of the matrix (Sparks, 1976). The breccias show some of the attributes of mudflows or debris flows. Debris flow deposits commonly have a nearly flat upper surface and a non-erosive base (Crandell, 1957), they are poorly sorted and polygenetic, containing angular to rounded blocks (Baker, 1963) and they may show normal grading, particularly if deposited from rather fluid flows (Cooke & Warren, 1973, p 183-4; Reineck & Singh, 1975, p 236). Volcanic mudflow deposits in the western U.S.A. contain blocks up to 3m across in flow deposits 1 to 5m thick (Schmincke, 1967). These figures compare closely with the presently described breccias, and with mudflows observed during the 1963-5 eruption of Irazu, Costa Rica (Waldron, 1967) and at Wrightwood, California (Morton & Campbell, 1974). Many mudflow deposits, however, are ungraded, and may have a fine grained basal layer (Schmincke, 1967; Middleton & Hampton, 1973), a feature not seen at Sour Milk Gill.

Subaqueous pyroclastic flow deposits have been described by Fiske (1963). Although on a much larger scale than those at Sour Milk Gill, they show well developed grading of both clasts and matrix, polygenetic clasts and planar tops and bases. They do not, however, contain clasts much larger than 10cm across. A similar interpretation has been put on Ordovician rocks (termed "pyroturbidites") from County Waterford, Eire (Stillman, 1976), and concentrations of large clasts near the bases of these units have been observed by the present author.

However, the features and the scale of the bedded breccias at Sour Milk Gill are thought more similar to those of the deposits of mobile debris flows or flash floods than of either subaerial or subaqueous pyroclastic flows. The absence of interbeds and reworked tops suggests a series of flows following in quick succession, possibly related to a single eruption. During the 1963-5 eruptions of Irazu, (Waldron, 1967) a debris flow was triggered by each heavy rainstorm falling onto recently erupted ash and during 1964, a total of 90 debris flows was observed in one valley. Similarly, during the 1968 eruption of Mayon (Moore & Melson, 1969) torrential rainstorms turned unconsolidated ash into destructive mudflows. It is suggested that such a model may be valid for the breccias in the Sour Milk Gill Tuff Member, and that they may have been deposited within a very short space of time.

C. The Welded Tuffs.

(i) Field Relations

The acidic rocks of the Airy's Bridge Formation lie above the tuffs of the Birker Fell Formation with apparent conformity. Within the lowest 10m, there is interbedding of welded tuffs with bedded tuffs more typical of the underlying formation (fig 5.2). Only the lowest part of the formation was studied and its top is not seen in the present area.

(ii) Primary Structures

Typically, the welded tuffs occur in thick, massive units, from 3 to 38m thick in the measured section. The highest unit (unit C, fig 5.2) whose top is not seen here, is much thicker than this. It shows well developed, large scale columnar joints, normal to the lower surface of the unit and to the regional dip. They are best seen from the north side of Gillercomb. Fiammé up to 5cm long and 1cm thick are abundant (plates 71, 72), although they are generally smaller than this. They also invariably weather inwards. Undeformed acid lava blocks, up to 15cm across, are common in some welded tuff units (plate 72A).

At several levels in the formation, parallel-bedding occurs within the welded tuffs. Two types are seen: the first is a vague parallel banding which stands out on weathered surfaces, occurring in a 0.8m thick band in the centre of unit A and within the basal part of unit C (fig 5.2). The second type is well defined, laterally continuous, even, parallel-bedding with sharp bases and tops, and is seen between units A & B (plate 72B). 10 to 50 cm thick beds of welded tuff are separated by 2 to 10cm beds of massive medium sand to silt grade tuff, which may be parallel-laminated.

Interbedded with the welded tuffs are relatively thin horizons of unwelded tuff identical with those of the Birker Fell Formation, but showing no sedimentary structures other than even, parallel-bedding and parallel-lamination. In places, they are highly indurated and flinty.

(iii) Petrography and Composition

Although no thin section has been taken of these rocks, the presence of abundant fiammé, and a well developed eutaxitic texture in many cases, leaves no doubt that they are welded tuffs. Most are poorly sorted and matrix-supported, with large fiammé and undeformed lava blocks in a matrix varying from very coarse sand grade to very fine-grained. The predominant component of the matrix is undeformed medium grey angular vitric fragments with small light grey fiammé and whole or broken pink or white feldspar crystals. Euhedral garnets 1 to 2 mm across are abundant at one locality near the base of the succession.

The parallel-bedded tuffs within unit A and at the base of unit C appear identical to the adjacent unbedded welded tuffs. They have a good eutaxitic texture, with dark fiammé up to 2cm long and 0.05 to 0.1cm thick. Angular, undeformed glass fragments up to 1cm long are more abundant than the fiammé. The very fine-grained glassy matrix probably consists of vitric dust.

In their appearance, the rocks of the Airy's Bridge Formation are undoubtedly of acid composition. Fitton (1971) analyzed several welded tuffs from the east side of the Seathwaite Valley, starting near the base of the formation. They all lie within a restricted range of silica contents, from 66.87% to 68.94% and hence are dacitic in composition (fig 2.1).

(iv) Interpretation

The welded tuffs south of Sour Milk Gill are very similar to those at the same horizon on Thirlmere. The thick, massive welded tuffs are interpretated as pyroclastic flow deposits, and their genesis is discussed more fully in Chapter 4. The fiammé represent fragments of pumice or glass which were plastic upon coming to rest and were flattened by the weight of the overlying material. The abundance of undeformed vitric fragments and acid lava blocks suggests that much of the material was solid before being incorporated in the flows. The planar upper and lower surfaces of the welded tuff units seen here is typical of pyroclastic flow deposits and columnar jointing may occur in both welded and unwelded ignimbrites (MacDonald, 1972, p 159-160). It results from contraction on cooling.

In considering the origin of bedding in welded tuffs it is necessary to examine the mechanisms involved in pyroclastic flows. Flows observed in recent eruptions consist of two distinct parts (R.L. Smith, 1960). At the base is a fragmental flow or avalanche which carries most of the load, and above and overriding it is an expanding cloud of gas and fine ash. Recent authors have suggested that the basal avalanche is a fluidized flow of solid particles in volcanic gas moving under the influence of gravity, the high degree of fluidization supporting the included blocks (Moore & Melson, 1969; MacDonald, 1972; Francis, 1976). Sparks (1976), however, on quantitative grounds has proposed that pyroclastic flows are more akin to debris flows and that the larger clasts are supported in a matrix of fluidized fine ash, much as boulders are supported by the strength of the matrix in a mudflow. He attributes poor sorting to high particle concentration, rather than turbulence, and suggests that laminar flow is predominant in medium scale pyroclastic flows. Larger flows may be turbulent at first, but as the flow deflates and decelerates, laminar flow is developed (Schmincke, 1974; Sparks, 1976).

Stratification, although not common in pyroclastic flow deposits, has been described from both welded and non-welded examples (R. L. Smith, 1960; Curtis, 1968; MacDonald, 1972; Bond and Sparks, 1976; Sparks, 1976). Bedding may result from laminar flowage within a single flow unit, or may represent a series of distinct thin flow units.

Interbedding of ashfall deposits with pyroclastic flow units has also been recorded (Curtis, 1968; Bond and Sparks, 1976), and these probably originate from the expanding ash cloud above the fragmental flow. In the 1968 eruption of Mayon (Philippines) the larger nuées ardentes generated torrential rainstorms (Moore and Melson, 1969). Downflushing of fine ash by the rain could produce ash beds interbedded with the flow deposits. Fine-grained bedded units might also be deposited by ground surges intimately associated with the pyroclastic flows.

The banded welded tuffs within unit A and at the base of unit C are very similar to the associated unbedded welded tuffs and there are no obvious compositional changes between bands. It is tentatively suggested that these may represent the local development of laminar flow during slower flow rates, or alternatively, if laminar flow is the dominant mechanism in pyroclastic flows (Sparks, 1976) they may represent the passage of a more dilute flow, allowing the development of bedding. The bedding in unit A may represent a slowing of the eruptive rate between the major flow units which deposited the massive lower and upper parts of the unit. That at the base of unit C may result from a slower eruptive rate in the early stages of a major flow unit.

The well-bedded welded tuffs between units A & B are thought to represent thin ash flow units. The finer grained beds between them may be ashfall deposits, possibly assisted by rain flushing through the dust cloud above the flow. Alternatively, they may represent finer grained ash flow units or ground surge deposits. Recently, welded ashfall units have been reported (e.g. Sparks, 1976) but the paucity of literature makes comparison impossible.

Although these bedded tuffs may represent thin flow units, they must be part of much thicker cooling units, in order to retain sufficient heat for welding to occur. Thus, the bedded tuffs within unit A must be part of the same cooling unit as the massive upper and lower parts, and that below unit B must be part of the same cooling unit as unit B (possibly A and B belong to a single, large cooling unit). The bedded tuff below unit C is part of the same thick cooling unit as the massive, columnar jointed tuff, which itself may consist of more than one flow unit.

The unwelded bedded tuffs below units A and C are interpreted as ashfall deposits of the same type as those of the Birker Fell Formation.

IV. ENVIRONMENTAL SYNTHESIS.

A. The Overall Sequence.

If the above interpretations of the processes involved in the deposition of each facies are correct, it is possible to reconstruct the chain of events which produced the sequence seen in the Sour Milk Gill area.

Following the effusion of andesitic lavas, a prolonged series of

Vulcanian explosions deposited a thick sequence of acid ashfall units. Some of these underwent limited reworking by waves and currents in very shallow water, with occasional emergence. The lowest part of the tuff sequence (fig 5.9) contains 85 fall units in a 4.6m thickness of tuffs; extrapolation, taking into account the thicker ashfall units in the upper part of the Sour Milk Gill Tuff Member, indicates that a total of some 2500 beds was deposited, each representing a single explosion.

During the early stages of this eruption, a thick andesitic lava flow was extruded. Shortly after this, a series of explosions of different character generated a considerable thickness of debris flow deposits. Ashfalls continued for some time after this, before a change in eruption style was heralded by the first thin welded tuff.

A short episode of phreatic explosions deposited a thin layer of base surge material before the first major pyroclastic flows reached the area. These were extensive flows of the type which deposited the ignimbrite plateaus of the Andes and New Zealand. They are on a much larger scale than the topographically confined, unwelded pyroclastic flows of volcanoes such as Pelée (Martinique) and Mayon (Philippines).

B. The Volcanic Environment

The andesitic lavas of this section give no firm indications of the environment into which they were erupted, although the upper lava appears to have flowed over and disrupted wet sediments. The bedded tuffs of both the lower tuff unit and the Sour Milk Gill Tuff Member are more rewarding.

Although there are indications of shallow water deposition and reworking, much of the sequence consists of parallel-bedded tuffs containing no environmental indicators. This could be the result of a rapid succession of ash falls, with insufficient time for reworking between them, or because they were deposited in a low energy environment. In those horizons where ripples and mudcracks developed, all the evidence suggests very gentle reworking: there is, for example, no sign of movement or breakage of mudflakes formed by desiccation. If the parallel-bedded tuffs were deposited subaerially, they would be expected to show signs of erosion, such as gullying, as seen in the Brown Knotts section (Chapter 3). Such deposits are very susceptible to erosion in modern volcanic areas. However, erosional features are rare, and it seems likely that much of the tuff succession was deposited in a low energy, shallow water environment. The lack of palaeoslope indicators, such as are seen in the Brown Knotts and Langdale sections (Chapters 3 and 6) suggest that the bedding was originally horizontal or very gently dipping. Ripples and desiccation cracks occur at frequent intervals throughout the bedded tuff sequence, except for the top 40m of the Sour Milk Gill Tuff Member, suggesting that conditions remained almost constant whilst the uncompacted equivalent (perhaps more than 400m) of 200m of bedded tuff accumulated.

Although such sediments could accumulate in a low energy shallow marine environment, such as a coastal lagoon or inner tidal flats, it is unlikely that such conditions could persist during subsidence of this magnitude. To explain the absence of other shallow marine facies, it would require sedimentation to have kept pace almost exactly with subsidence. Moreover, the author considers these ashfall deposits to have accumulated in a period of a few years at most, and it is improbable that this amount of subsidence could have taken place in so short a time.

A more feasible model, not necessarily involving any subsidence, is that the ashfall deposits infilled an inland intravolcanic basin. Within this basin, bodies of standing water are thought to have developed. It is likely that some, at least, of these were ephemeral, that they accumulated largely by runoff and direct precipitation from rainstorms caused by violent eruptions, and that they drained away after a period of a few hours or days. Many of the ashfalls were deposited in these lakes, and were sometimes gently reworked by wind and waves. As the water dried up or drained away, desiccation cracks formed in fine-grained ash. In this way the basin was gradually filled. Such ephemeral lakes existed at Paricutin, Mexico, during its eruptions. In some cases they were impounded by lava flows or alluvial fans, and mudcracks were a common feature. (Segerstrom, 1950).

The cross bedded units at Seathwaite Slabs (Figure 5.5b) probably represent incursions by small, ephemeral streams into the basin from the southeast. Single tabular cross sets with an irregular to planar lower surface have been described from transverse and longitudinal bars of ephemeral streams in Utah (Picard and High, 1973, p.173-5). Wet sediment deformation structures also developed, possibly triggered by earthquakes, or resulting from overloading caused by rapid deposition of ash into water, or both.

It is also necessary to explain the rapid westward thinning of the breccias within the Sour Milk Gill Tuff Member. There is no evidence of their being removed by erosion. It is possible that the debris flows deposited their load on an extensive fan, extending perhaps 3 km to the east (see I.D. above), and that the edge of the fan is exposed at Sour Milk Gill. The observed thinning from 27.5m to 3m over a distance of 160m implies a surface slope of 8^{o} to 9^{o} for this cross section of the fan. A second possibility is deposition in a broad valley, with similar slopes on its side. In this case, Sections 1 and 2 (Figure 5.4) would be upslope from Section 3, and the single flow unit of Section 2 would be equivalent to the highest flow unit in Section 1. A third alternative, using the same slope configuration, is that the flows originated in the west and flowed downslope, becoming detached from their source (a common feature of mudflows: Walker, 1974) and that we are seeing a section close to the "upstream" end.

If the correlation of the breccias with those at Rosthwaite Fell is correct, the eastward thinning between the two sections (Figure 5.3) occurs within the upper part of the Sour Milk Gill Tuff Member and may be the result of non-deposition or of erosion at the top of the Member. The former is thought to be the most likely, as there is no evidence of unconformity at the base of the Airy's Bridge Formation in the study area. Possibly the source of the ashfall tuffs lay to the west, accounting for this thinning. If the tuffs at Hause Point, Thirlmere are synchronous with those at Sour Milk Gill and Rosthwaite Fell, then this is further evidence for a westward source. (Figure 5.3).

The succeeding welded ashflow sheets are thought to have been deposited in a subaerial environment, as they bear much more resemblance to subaerial ignimbrites than to subaqueous ashflow deposits.

C. Sources

As with the rest of the Borrowdale Volcanic Group, it is very difficult to pinpoint sources. It is tentatively suggested that the bedded tuffs were erupted from a vent to the west. One possible source is the 300m wide breccia-filled vent at Burtness Combe, Buttermere, 6 km to the north west (Clark, 1964) (Figure 7.1). The presence of abundant thin fine-grained beds and the absence of blocks in the tuffs indicates that they are some distance from their source.

There is no indication of flow direction in the andesite lavas. Large scale pyroclastic flows are generally associated with calderas (e.g. Crater Lake, Oregon: Williams, 1942) or large fissure systems, (e.g. South Kenya Rift Valley: Baker, 1976), but neither has so far, to the author's knowledge, been identified within the Borrowdale Volcanic Group. The widespread nature of the Airy's Bridge Formation and its correlatives indicates that any source could be several tens of kilometres away from the present outcrop.

FIGURE 5.1

Sketch map of the geology of the Sour Milk Gill area, Borrowdale. Geological boundaries based partly on mapping by I. Evans.

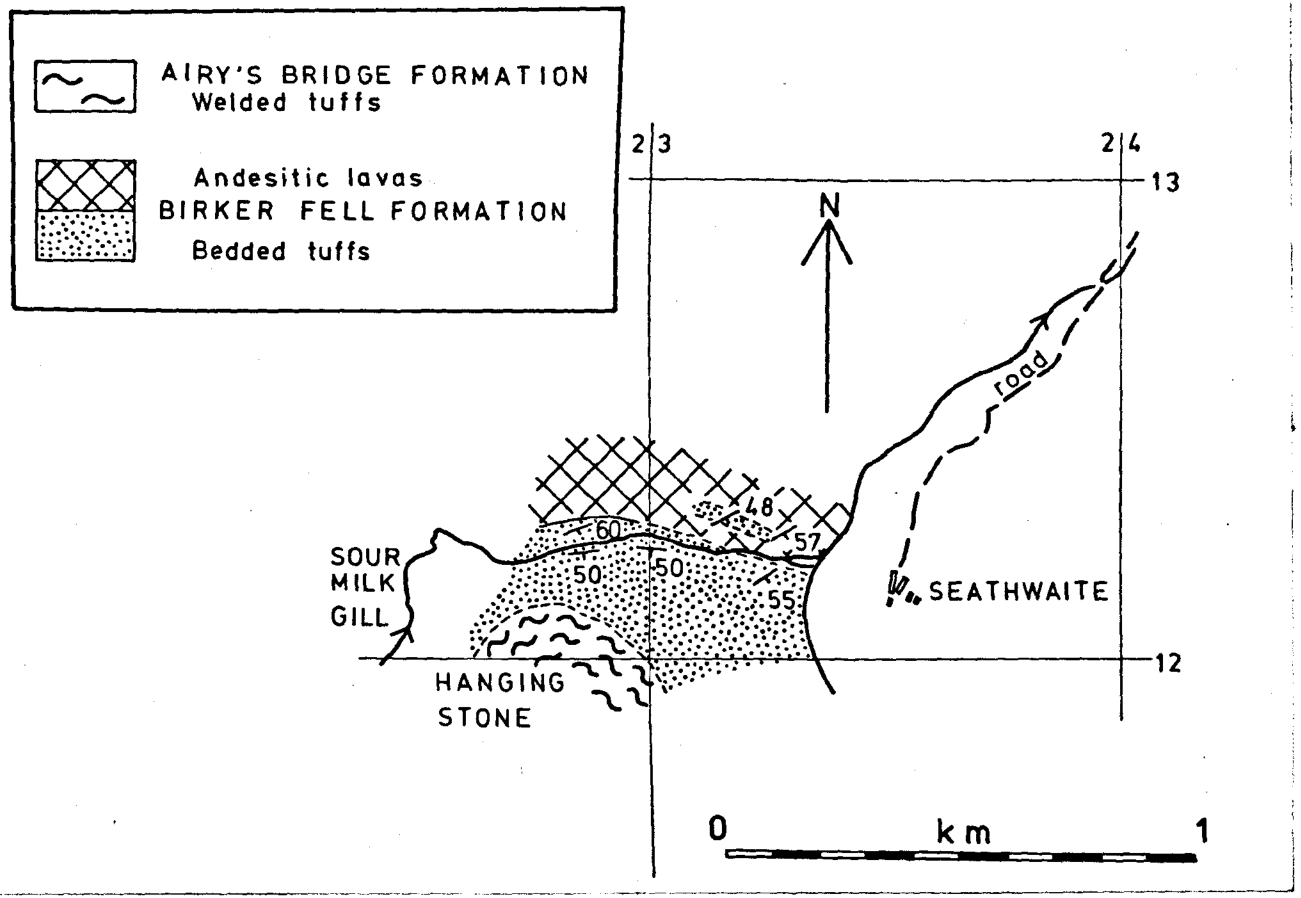

AIRY'S BRIDGE FORMATION
Welded tuffs
Andesitic lavas
BIRKER FELL FORMATION
Bedded tuffs
2|3
2|4
13
12
N
road
SEATHWAITE
SOUR
MILK
GILL
HANGING
STONE
60
48
57
50
50
55
0
km
1

FIGURE 5.2

Composite measured section through the volcaniclastic rocks and lavas of Sour Milk Gill, Borrowdale. See Figure 3.3 for key.

Facies 2 is always interbedded with facies 1: the left hand column indicates the predominant facies in each part of the section. The Sour Milk Gill Tuff Member was measured in detail at Section 1 (Figure 5.4), and therefore the bedded breccias are not shown.

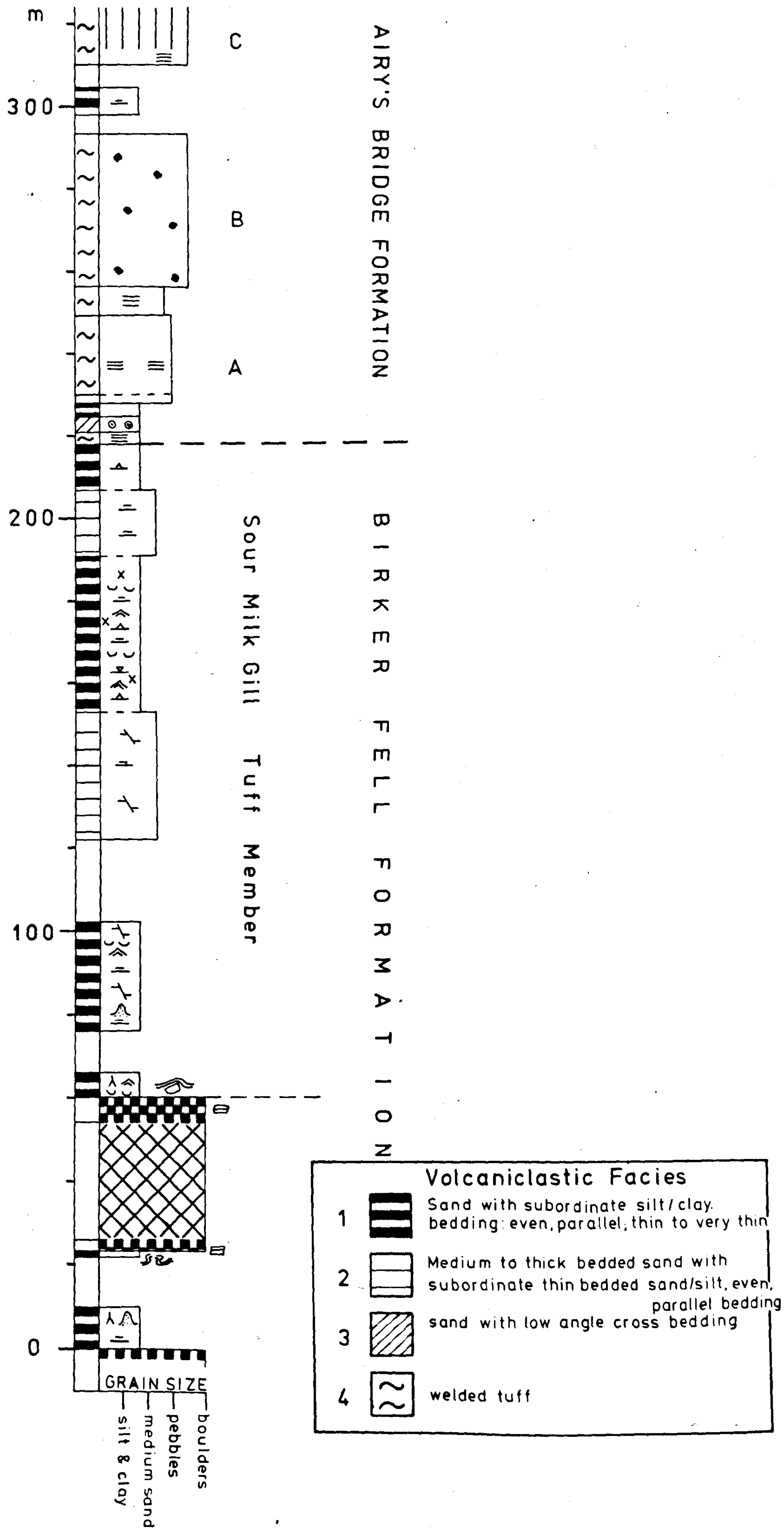

m
300
200
100
0
C
B
A
AIRY'S BRIDGE FORMATION
Sour Milk Gill Tuff Member
BIRKER FELL FORMATION
GRAIN SIZE
silt & clay
medium sand
pebbles
boulders
Volcaniclastic Facies
1 Sand with subordinate silt/clay. bedding: even, parallel, thin to very thin
2 Medium to thick bedded sand with subordinate thin bedded sand/silt, even, parallel bedding
3 sand with low angle cross bedding
4 welded tuff

FIGURE 5.3

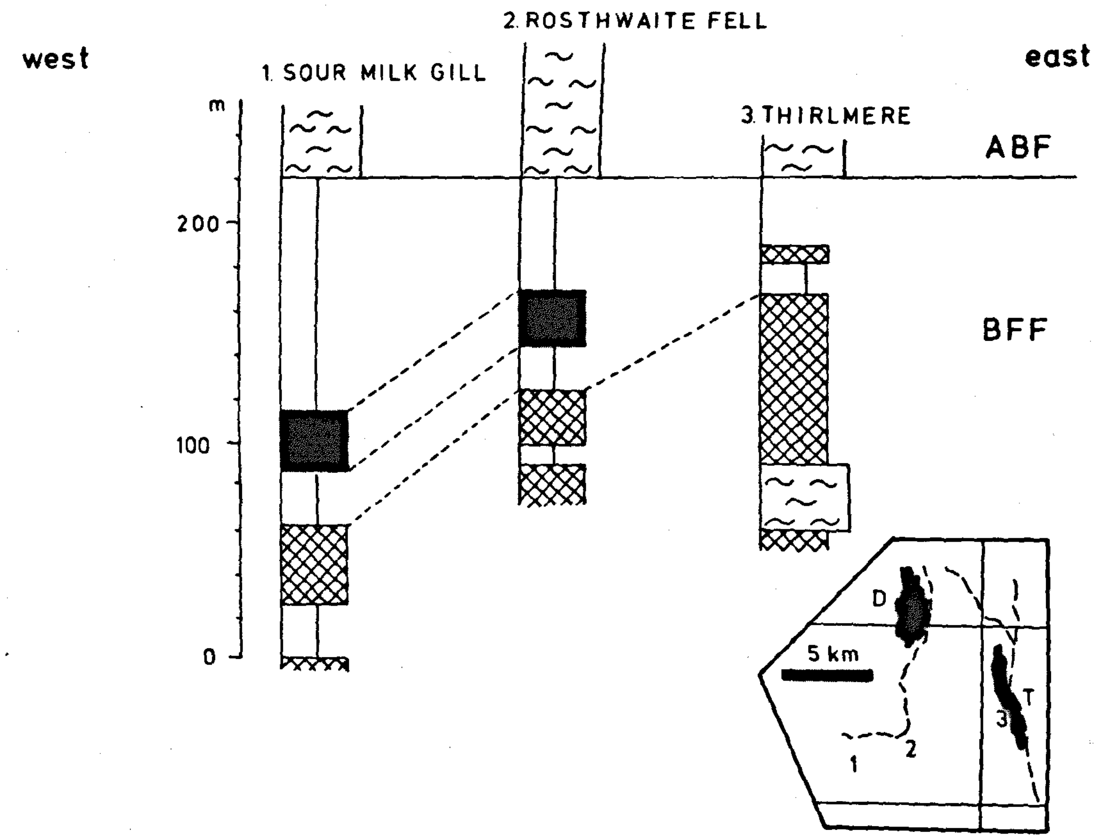
Correlation of sections in the upper part of the Birker Fell Formation (BFF) and the lower part of the Airy's Bridge Fromation (ABF) between Borrowdale and Thirlmere.

1. Sour Milk Gill, Borrowdale (present account) (composite section)
2. Rosthwaite Fell, Borrowdale (after an unpublished section by D. Millward)
3. Hause Point, Thirlmere (present account)

See text for discussion. Key as for Figure 5.4.

Inset Map shows location of sections:

------	main roads
D	Derwentwater
T	Thirlmere



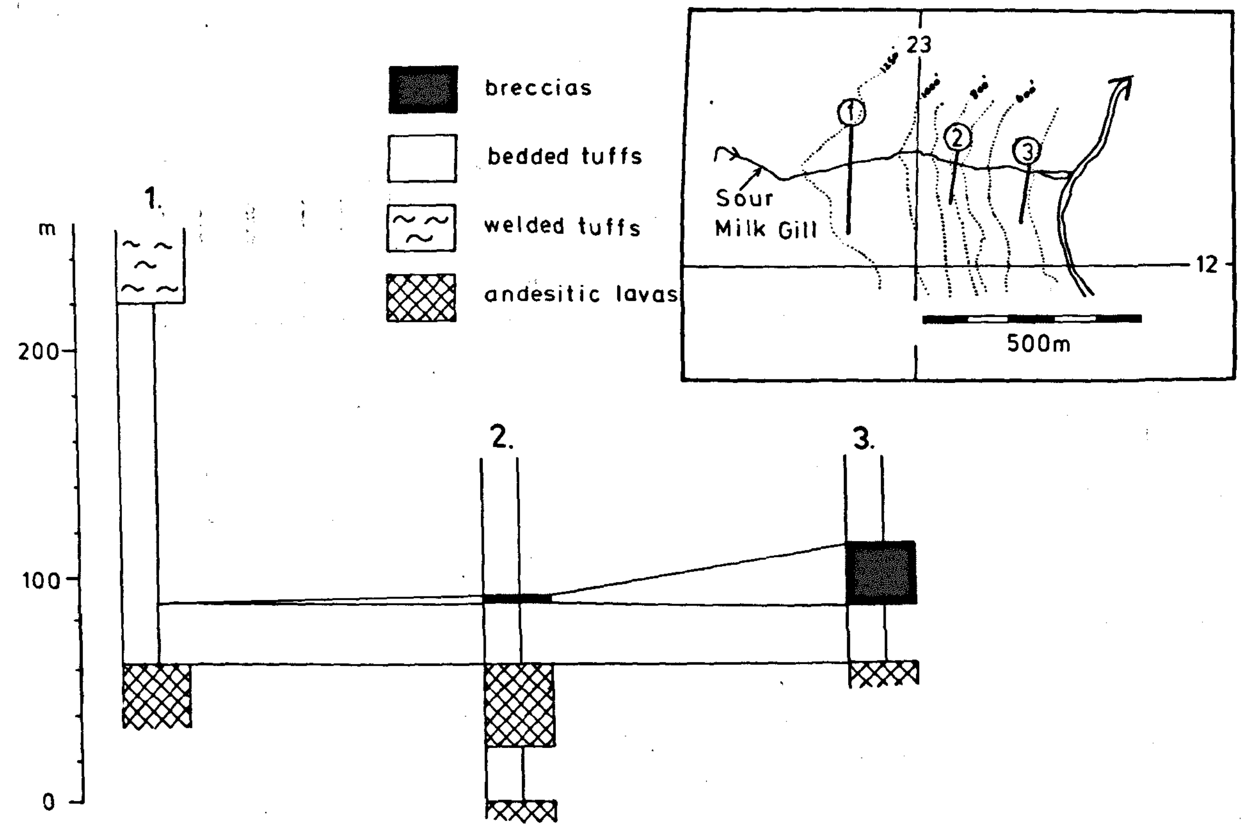
west
east
1. SOUR MILK GILL
2. ROSTHWAITE FELL
3. THIRLMERE
m
200
100
0
ABF
BFF
D
T
5 km
1
2
3

FIGURE 5.4

Diagram to show the westward thinning and disappearance of the breccias in the Sour Milk Gill Tuff Member at Sour Milk Gill, Borrowdale.

1. Mouth of Gillercombe
2. Steep section of Sour Milk Gill, below wall
3. Seathwaite Slabs area, lower end of Sour Milk Gill

Inset map shows locations of sections.



breccias
bedded tuffs
welded tuffs
andesitic lavas
m
200
100
0
1.
2.
3.
Sour
Milk Gill
23
12
500m

FIGURE 5.5

(a) Parallel-bedded, rippled fine sand to clay grade tuffs. Most of the ripples are in fine sand, with clay grade drapes. Both symmetrical and asymmetrical ripples are represented. Thick lines denote clay grade laminae. Drawing from photograph. Sour Milk Gill Tuff Member, top of Sour Milk Gill (NY 227 122).

(b) Tabular cross-bedded unit in medium sand grade tuff, underlain and overlain by parallel-bedded tuff. Drawing from photograph. Sour Milk Gill Tuff Member, Seathwaite Slabs (NY 233 122).

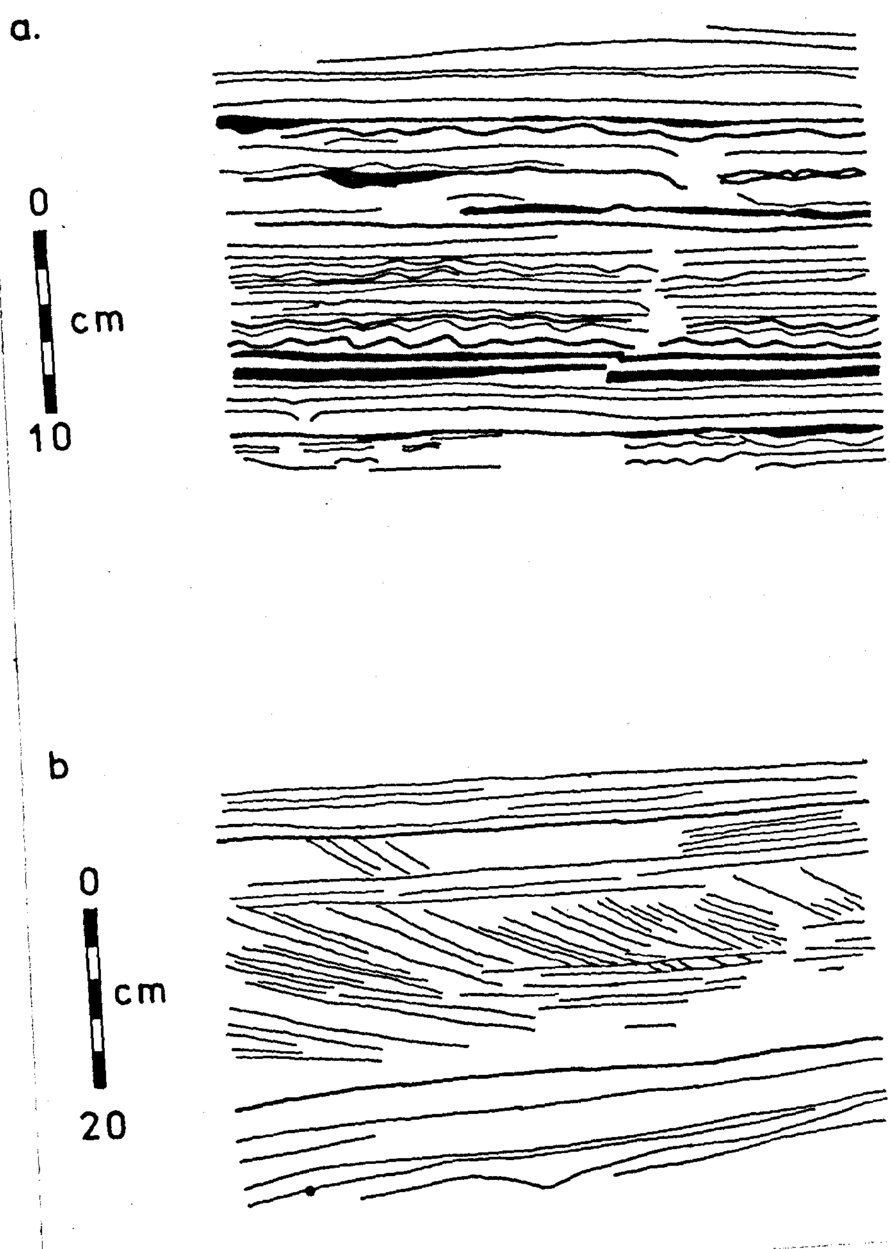

a.
0
cm
10
b
0
cm
20

FIGURE 5.6

Directional sedimentary structures from the Sour Milk Gill area. In the case of asymmetrical structures (current ripples and cross bedding) current directions are shown. For symmetrical structures (wave ripples and adhesion ripples), both possible directions of wind or waves are shown for each. Measurements have been rotated into the horizontal plane about the strike of the beds. 10° classes.

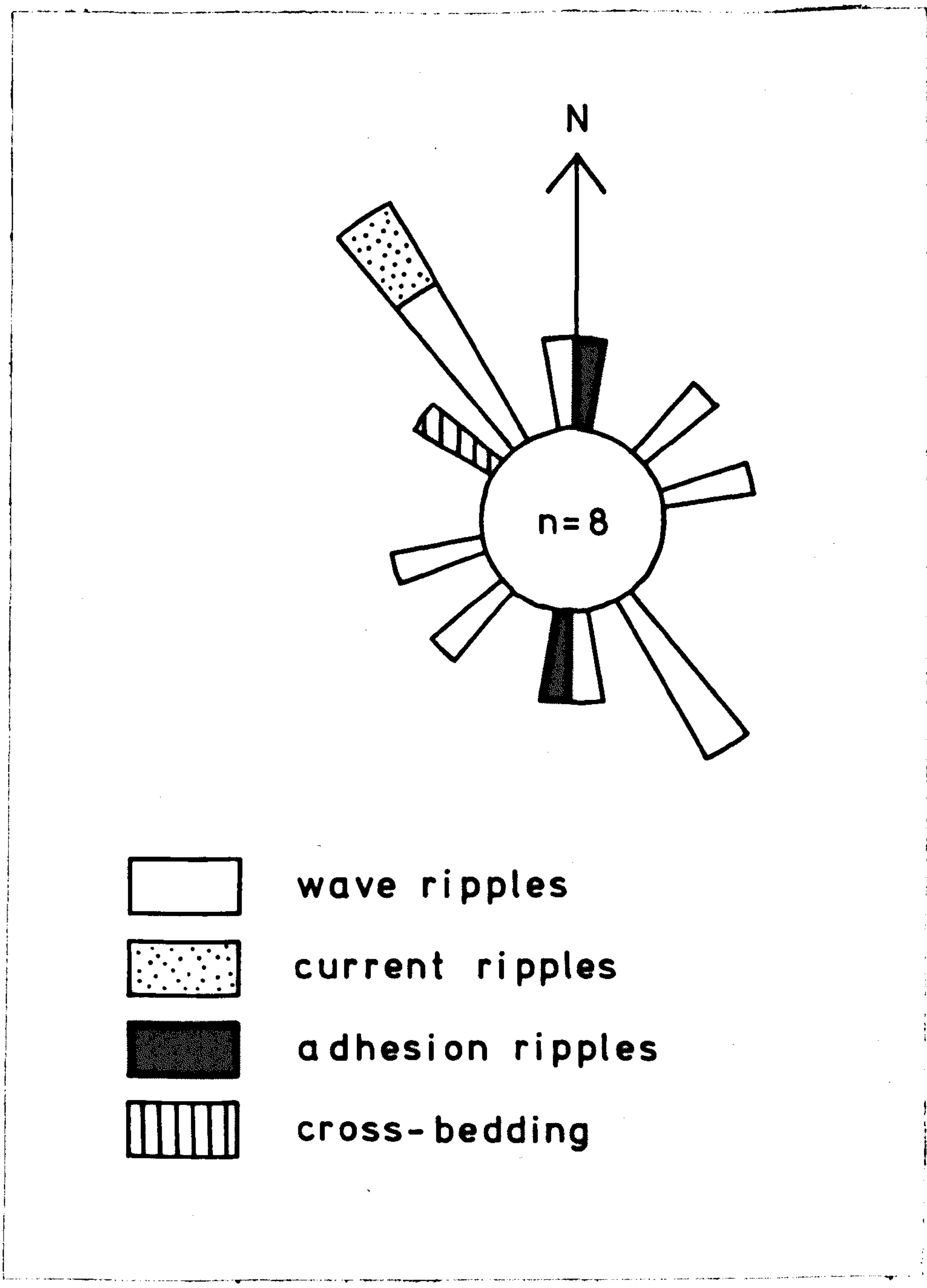
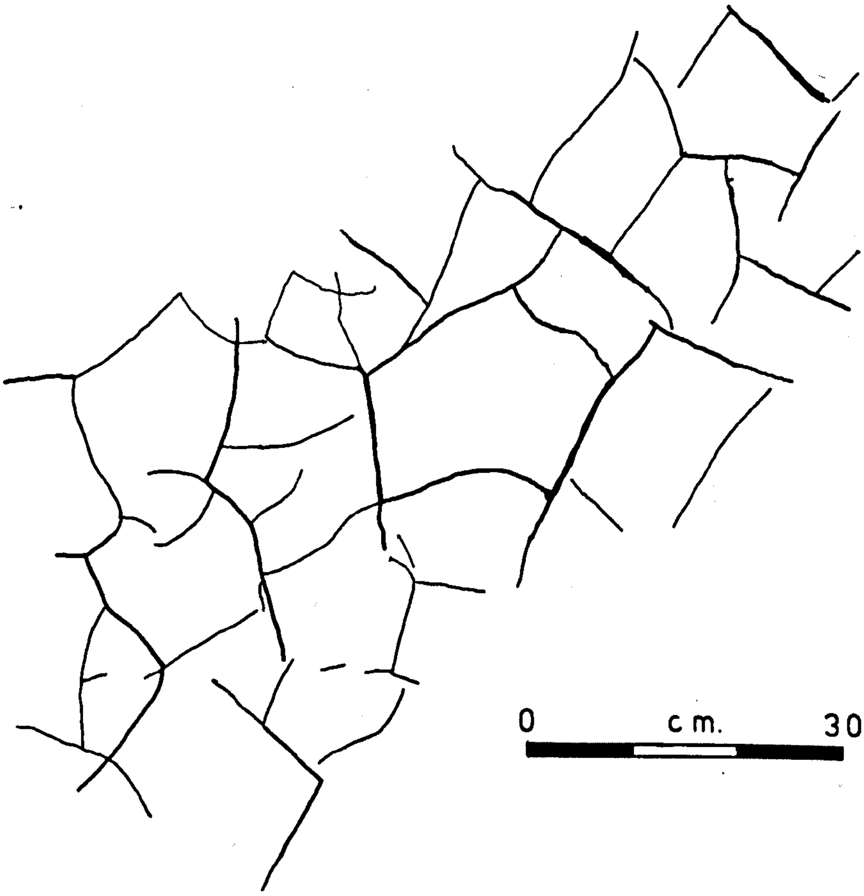

N
n=8
wave ripples
current ripples
adhesion ripples
cross-bedding

FIGURE 5.7

(a) Mudcracks exposed on a bedding plane of silt to clay grade tuff. The cracks have infillings of very fine sand grade material. Drawing from photograph. Lower tuff unit north of Sour Milk Gill (NY 232 124).

(b) Detail of (a). Drawing from photograph.


0
cm.
30

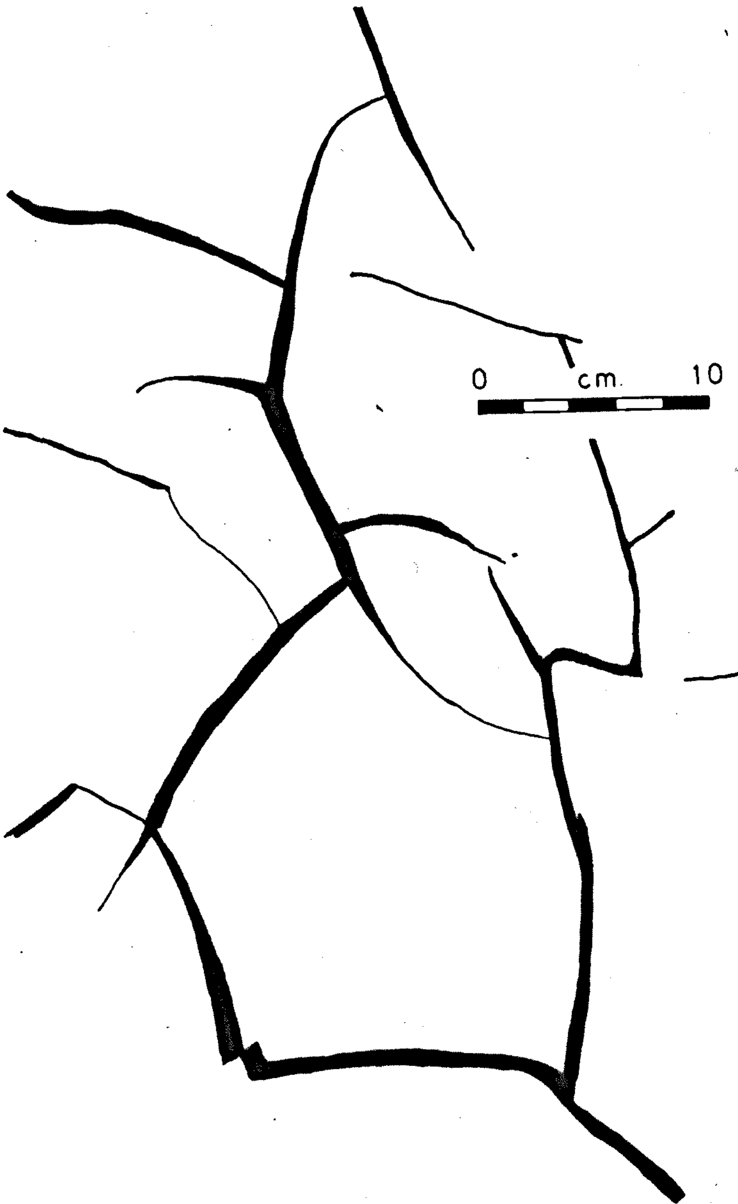

0
cm.
10

FIGURE 5.8

(a) Injection structure of medium to coarse sand grade tuff through bedded silt to clay grade tuff. The sand has been injected upwards from the bed near the base of the diagram. Lower tuff unit, north of Sour Milk Gill (NY 232 124).

(b) Injection structure of massive fine sand grade tuff through bedded silt to clay grade tuffs. The sand has been injected upwards, and has domed up the bedded tuffs. Note associated soft sediment faulting. Sour Milk Gill Tuff Member, top of Sour Milk Gill (NY 227 122).

(c) Small scale mudcracks in clay grade tuff. Lower tuff unit, north of Sour Milk Gill (NY 232 124).

(d) Probable wave interference ripples in silt to clay grade tuff. Hachuring denotes downward slope from crest into flat-floored ripple. Loose block, Sour Milk Gill.

(e) Wavy lamination in symmetrical ripples. Lower tuff unit, north of Sour Milk Gill (NY 232 124).

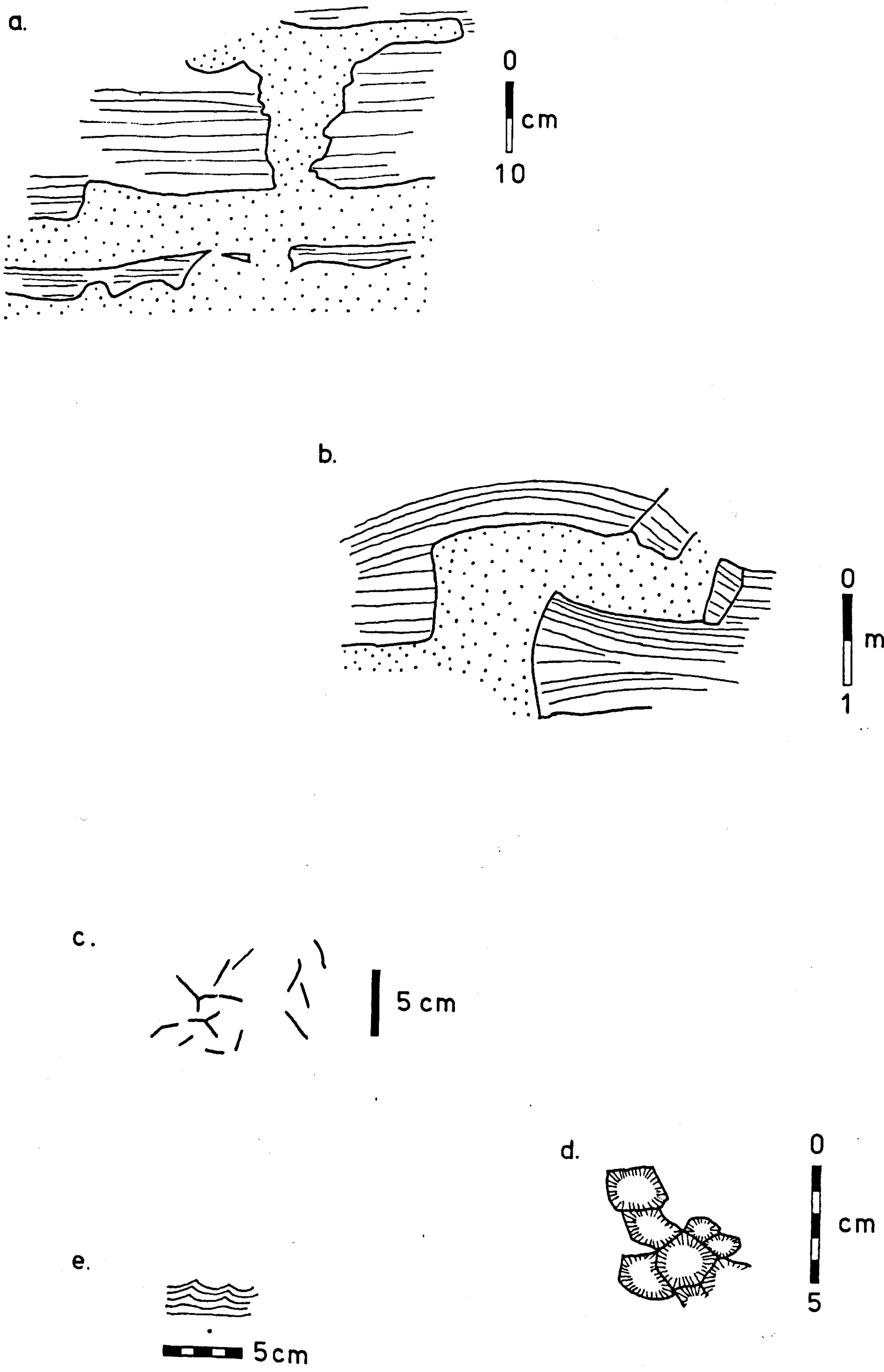

a.
0
cm
10
b.
0
m
1
c.
5 cm
d.
0
cm
5
e.
5cm

FIGURE 6.1

(a) Geological map of the Chapel Stile - Elterwater area of Langdale, after an unpublished map by S.M. Smith.

T - Thrang Quarry.

(b) Sketch map of Thrang Quarry, Langdale, showing positions of measured sections (numbered). Not to scale.

CHAPTER 6. THE LANGDALE SECTION

I. INTRODUCTION.

A. General

The bedded tuffs and lavas of the area around Thrang Quarry, near Chapel Stile, Great Langdale, have been mapped, on a large scale (Figure 6.2), and detailed sections have been measured through them. Reconnaissances have been made into the areas to the south and west, following an unpublished map by Mrs. S. M. Smith (Figure 6.1a) which proved to be accurate. Thrang Quarry was formerly worked for 'green slates' which are still quarried at Elterwater and Spout Crag, outside the present area.

B. Structure

The area lies on the northern limb of the rather tight Wrynose Anticline (Soper and Numan, 1974) and dips in the Thrang Quarry area are around 20° to the NNE (Figures 6.2a, 6.3a). The fine-grained tuffs have a strong slaty cleavage which dips steeply to the NW and NNW, and there is considerable flattening in this direction. Several minor faults and bedding plane thrusts have been noted in the quarry.

C. General Sequence

At the base of the Thrang Section (Figure 6.3b) 120m of fine-grained parallel-bedded tuffs with abundant evidence of wet sediment deformation are exposed in the quarry. Their contact with the underlying acid breccias is not exposed here, but is seen further to the northeast. Sharply overlying the fine tuffs are some 40m of cross-bedded sand grade tuffs, succeeded by a thin unit of fine tuff. This, in turn, is overlain by a series of flow brecciated and massive andesite units, forming bold crags on both sides of the valley (Plate 73). The studied section terminates within these lavas.

D. Stratigraphy

The acid breccias and tuffs at the base of the section are the upper part of Oliver's (1961) Airy's Bridge 'Group' (Figure 3.8), and so they are assigned to the Formation of that name. The total thickness of the Formation is unknown, as the ground between its base, at

Thirlmere and in southern Borrowdale, and its top, in Langdale, has not been studied by the present author. The 'Langdale Tuff Phase' and 'Wrengill Andesites' of S. M. Smith (personal communication) have been retained as Formations of the same names. Both die out to the west and north (Figures 3.8, 6.1a). The name 'Wrengill' is used with some reservations, as it was originally applied (Mitchell, 1929) to rocks at Kentmere, some 14km to the east. However, Soper and Numan (1974) believe that the two units may be correlated.

II. THE LAVA FLOWS

A. Lava in the Langdale Tuff Formation

(i) Field Relations

At locality 17 (Figure 6.2) a 1m thick andesite occurs near the contact of the fine and coarse tuffs. The upper 20cm of the underlying beds are plastically deformed, and, within 5mm of the contact, baked. Large, elongate vesicles follow the irregular base of the lava flow (Figure 6.4a), which incorporates small fragments of tuff. Within the flow, vesicle trains roughly define flow folding. The irregular top is draped by the overlying parallel-bedded tuffs.

(ii) Petrography

The lava contains abundant ½ to 1mm long green plagioclase phenocrysts, whose zoning may be discerned in hand specimen (Plate 74A). These form 22% of the rock, and subordinate chlorite (after pyroxene) phenocrysts are also present (Table 6.1). The plagioclase is almost completely altered to sericite and calcite. The very fine-grained brown groundmass, consisting of feldspar, chlorite, calcite and opaque oxides, represents devitrified glass, and contains sparse ovoid amygdales, filled with interbanded chlorite and calcite.

(iii) Interpretation

Unfortunately, the lateral extent of this lava flow cannot be determined due to lack of exposure. It is thought that such a thin flow cannot be far from its source, as it would have been rapidly chilled and frozen, whether in a subaqueous or subaerial environment.

TABLE 6.1: Modal analysis of specimen CS 6 (Langdale Tuff Formation)

		%
plagioclase phenocrysts	..	22.0
pyroxene phenocrysts ..	..	2.8
groundmass plagioclase	..	9.3
fine-grained groundmass	..	65.3
amygdales (chlorite & calcite)		0.5
TOTAL:	..	99.9

386 points counted

B. The Wrengill Andesite Formation

(i) Field Relations and Primary Structures

The Wrengill Andesites lie sharply, with a roughly planar base, above the Langdale Tuff Formation. The basal 20m is flow brecciated, with lava fragments up to 1m across in a matrix of lighter coloured chilled lava, which stands out on weathered surfaces (Plate 74B). This is succeeded by 20m of massive andesite and then a further 20m of flow breccia. A second massive andesite unit forms the top of the measured section.

(ii) Petrography

The massive lava contains abundant ½ to 2 mm completely altered plagioclase phenocrysts (sometimes zoned), subordinate chlorite (after pyroxene) and rare apatite prisms. The dark green groundmass consists of very fine grained devitrification products, with occasional small chlorite amygdales. At the base of the flow, ragged lava fragments are contained in a fine-grained tuff matrix, and similar textures, resembling those of subaqueous tuffs (Honnorez and Kirst, 1975) are seen in thin sections from the higher flow breccias.

(iii) Composition

An analysis from the Wrengill Andesite Formation at Raven Crag, Walthwaite (NY 325 057), 700m east of Thrang Quarry, is given by Fitton (1971). The rock is an andesite, with 58.60% silica.

(iv) Interpretation

The section exposed is thought to represent two rather thick blocky lava flows, with brecciated bases and tops. The lavas may have flowed into water, producing hyaloclastite-like rocks by thermal shock or steam explosions on contact with wet sediment.

III THE VOLCANICLASTIC ROCKS

A . Parallel- bedded Tuffs

(i) General

The tuffs exposed in Thrang Quarry show laterally continuous, even, parallel bedding, and the beds range in thickness from less than 1cm to more than 1m. Sometimes bedding is obscured by weathering (the thick, massive units in Figures 6.13 and 6.14 are undivided for this reason). The thin beds tend to be concentrated in groups, separated by thicker beds (Figure 6.4c). The tuffs are predominantly of fine sand to clay grade. At some horizons, large calcareous concretions are abundant (Plate 85A). A single occurrence of accretionary lapilli has been recorded from the fine tuffs some 10m below the base of the Wrengill Andesite Formation (Plate 85B). Sections through the tuffs are shown in Figures 6.12 to 6.14. Much sedimentological information has also been gleaned from loose blocks in the quarry.

(ii) Petrography

These rocks appear highly altered in thin section, and much of the original texture is obscured by the strong cleavage. The predominant components are altered green plagioclase crystal fragments and dark green vitric fragments. Pumice, replaced by chlorite with calcite amygdales, is locally very abundant, and vesicles may be tubular or ovoid. The fine-grained groundmass is rich in calcite, and may be partly of secondary origin.

(iii) Depositional Sedimentary Structures

(a) Massive Graded Beds

Massive graded beds with sharp, planar bases and tops are common. They are often either very thick (more than 50cm) or thin, (less than 2cm) (Plate 75). They generally contain abundant pumice granules or lapilli, often with irregular shapes, which tend to be concentrated at the tops of the beds (Plate 77B). Thus a reverse coarse tail (size) grading may be superimposed on the normal distribution grading. Multiple grading occurs occasionally. Some of the massive beds contain discontinuous layers or deformed clasts of bedded silt-clay grade tuff (Figures 6.4b, 6.9b). Care must be taken to distinguish truly massive graded beds from those in which the sedimentary structures are obscured by weathering.

(b) Graded Beds with Sedimentary Structures

These beds also have sharp tops and bases. The bases are mostly planar, but occasionally evidence of erosion is seen (Figure 6.6B). In a few cases, cross sections of probable flute marks (cf. Dzulynski and Walton, 1965) occur (plate 80A, Figure 6.6a) The most abundant sedimentary structures are parallel lamination and climbing ripple lamination. The simplest sequence is a normally graded bed, parallel-laminated throughout and often with pumice concentrated towards its top (Plate 77A). The more complex beds can be related to complete and partial Bouma sequences, of which the most common are cde and de (Figure 6.5, Plate 79). Where climbing ripple lamination is present, it often shows an upward increase in the angle of climb, and a transition from erosive-to non-erosive based ripples to sinusoidal lamination (Plate 79B). In some cases the ripple morphology is preserved, and draped by the overlying silt or clay grade bed (Figure 6.5). Two loose blocks have bedding planes with poorly defined linguoid current ripples.

(iv) Post-Depositional Sedimentary Structures

(a) Plastic Deformation

The most common structures of this type are loads and flames, developed where a coarser bed overlies a finer bed (Plates 80B to 82); (Figure 6.7). In several cases, spacings between load or flame structures are rather constant (Plate 80B; Figure 6.7B). There are several possible causes for this: differential loading (Dzulynski and Walton, 1965) may occur when original erosional structures (e.g. regularly spaced flutes) are over-deepened by sinking of the overlying sand, or when a layer of uneven thickness (e.g. rippled sand) is deposited on unconsolidated mud (in this case, loading will be greatest below the ripple crests). Alternatively, the surface of the mud may be thrown into waves by a seismic shock (Dzulynski and Walton, 1965). A fourth possibility is the development in the fine-grained layer of 'ripples', streaked out in the direction of the flow by the drag of the current depositing the overlying bed (Ballance, 1964). Some of Ballance's illustrated examples have almost exact counterparts in the Thrang Quarry (Plate 81B; Fig.6.7a,b)

It is difficult to decide which mechanism is most likely in this case. The preferred orientation of some of the structures could be interpreted as either a palaeocurrent direction, a palaeoslope direction, or the direction of propagation of seismic waves.

Other plastic deformational structures include highly complex tongues, folds and lobes of tuff (Figures 6.8a,b,c,d,f), which may have been produced by similar processes to the loads and flames. Several laterally continuous beds of rather constant thickness show complex folding and mixing of sand and silt-clay grade tuff (plate 83A; Figure 6.10a). Similar extensive horizons are known from the Ordovician tuffs and sediments of North Wales (Dr. M. F. Howells, personal communication), and from modern lake sediments in California (Sims, 1975). Both have been interpreted as the result of liquefaction due to seismic shock. This is a feasible mechanism in an active volcanic area, and is proposed for the beds described above.

(b) Brittle Deformation

At several places in Thrang Quarry, arcuate slump scars may be seen (Plate 83B; Figues 6.8e, 6.9a). These are thought to result from the failure of partially consolidated sediment by downslope movement or by overloading. Fracturing and pulling apart of thin silt-clay grade beds is another common feature (Plate 84), and soft sediment faults are often developed (Figure 6.8a). In some cases, fractured blocks of silt-clay grade tuff have foundered into the underlying sand (Figure 6.10a, 6.11b). In others, there appears to have been upward movement, in pipelike bodies, of siltstone or mudstone clasts in a sand grade matrix (Figure 6.11a). Possibly this resulted from fluidization of wet sand under load, causing it to move upwards and break through the finer beds.

(v) Palaeocurrent and Palaeoslope Directions

Exact measurements are difficult, due to the strong deformation and the commonly two-dimensional exposure. However, ripple cross-lamination generally has a component towards the north, as have most of the directional load and flame structures described above.

(vi) Interpretation

Graded beds with partial and complete Bouma sequences, indicating waning currents, are interpreted as turbidites. The massive graded beds are more difficult to interpret. Certainly those which contain deformed silt clasts must have been emplaced from flows capable of eroding the substrate, and other features, such as the presence of multiple grading and thin discontinuous silt-clay grade beds, are reminiscent of amalgamated turbidite beds. However, it is possible that subaqueously emplaced ash shower deposits are also present. In particular, the thin pumiceous graded beds (e.g. Plate 75A) may have this origin.

The frequency of load and flame structures indicates rapid deposition, with insufficient time for one bed to consolidate before the overlying one was deposited. In other cases, however, silt-clay grade tuffs at the surface were sufficiently coherent to be fractured and incorporated in turbidity currents. Early fluid and plastic sediment deformation may have been partly the result of seismic shocks. Later, there was brittle and semi-brittle behaviour of partly consolidated silt-clay grade tuff whilst the interbedded wet sand was still unconsolidated and, apparently, capable of fluidization. It is not clear how long after deposition, or at what depth, this occurred.

B. Cross Bedded Tuffs

(i) Field Relations

The junction of the cross-bedded tuffs with the underlying fine tuffs appears to be gradational, with interbedding of the two facies over a thickness of 1m. The basal unit of coarse tuff is also about 1m thick, and in places is massive and unbedded. A typical sequence at this level is shown in Figure 6.15.

(ii) Petrography

These are lithic tuffs, consisting mainly of green, pink and grey lava fragments, with subordinate altered plagioclase fragments (Plate 88).The grains are subangular to subrounded, and the amount of fine-grained matrix is small. The tuffs are crudely cleaved, sometimes with kink bands (Plate 88).

(iii) Primary Structures

There seem to be no ordered sequences within this unit, but flat-bedding and tabular, trough and wedge-shaped cross sets on the order of 10 to 20cm thick are randomly interspersed (Figures 6.15,6.16 ; Plate 86). Small, sometimes steep-sided channels are commonly filled with cross beds, and may have a basal lag of small lava pebbles. Dewatering structures are also seen (plate 86B). Occasional thin, laterally extensive silt grade horizons occur; these may be parallel-laminated, and a few show ripple cross lamination. They are commonly contorted or brecciated.

(iv) Palaeocurrents

There are insufficient measurable cross bedding directions for any conclusions to be drawn, and those which have been determined show a wide scatter (Figure 6.16b). There appears, however, to be a slight bias toward the northwest.

(v) Interpretation

These tuffs evidently represent a sudden influx of volcaniclastic material, and dewatering structures suggest rapid deposition. The sparse laterally continuous parallel beds are thought to represent ashfalls, but the rest of the unit is reworked.The limited degree of rounding and rather poor sorting indicate local derivation.

There are certain resemblances to the reworked tuffs of Borrowdale (Chapter 3) and probably reworking in a fluvial or alluvial fan environment is the most likely interpretation. The evidence is not conclusive, however, and shallow marine reworking cannot be ruled out.

C. Massive Breccias

West of the present area, and within the feather edge of the Langdale Tuff Formation, coarse bedded tuffs and breccias are developed (NY 311 069). Cross-bedded tuffs are sharply overlain by a thick breccia unit containing 10cm lava blocks, some of them pumiceous (Plate 76B). These are probably a form of mass flow deposit,and might possibly represent the proximal equivalents of some of the graded units in Thrang Quarry.

IV. ENVIRONMENTAL SYNTHESIS

A. Volcanic Environment

Acid breccias and welded tuffs of probable subaerial origin at the base of the sequence are overlain by turbidites and probable ashfall material, deposited in a quiet subaqueous environment. These are abruptly succeeded by coarse tuffs which were reworked in a high energy shallow subaqueous or subaerial environment. At the top of the sequence, lava flows show some evidence of emplacement into water or onto wet sediment.

Differantial subsidence of the area into which the Langdale Tuffs were deposited may have been initiated along an intravolcanic axis to the west of the present area (S. M. Smith, personal communication). Two environments are possible for the deposition of the fine-grained bedded tuffs: either lacustrine or marine (below wavebase). If the environment was marine, there must have been considerable uplift before the deposition of the cross-bedded tuffs, but there is no evidence of disconformity at their base. Perhaps deposition into a rather depp lake in an intravolcanic basin is more likely. The turbidites may have been generated by the failure of unstable accumulations of ashfall material, or possibly by pyroclastic flows entering the lake. Possibly a series of large ashfall eruptions, with accompanying rainstorms producing torrential floods,was responsible for the rapid influx of large quantities of vitric ash. Following this, there was a temporary reversion to tranquil lacustrine conditions, during which the upper fine tuff was deposited. It appears that the Wrengill Andesites might have been emplaced into or onto wet sediment, producing peperites or hyaloclastites.

B. Sources

As stated above, the source of the thin andesite flow must be close at hand, and certainly within 1km of Thrang Quarry. There are indications that the fine-grained sediments, and possibly also the coarse tuffs, were derived from the (present) south or southeast.

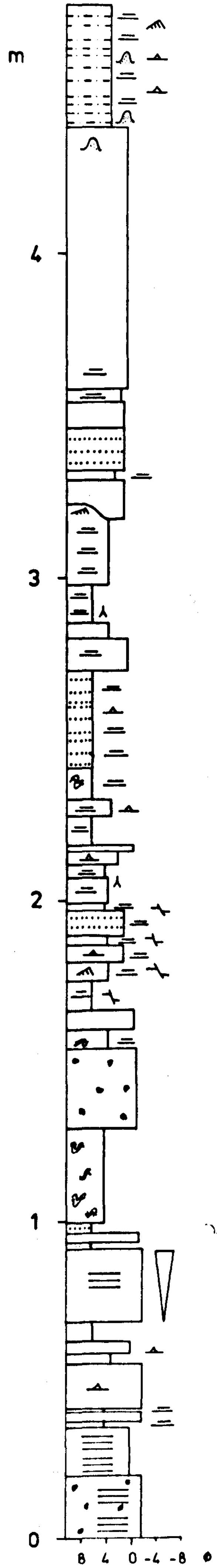
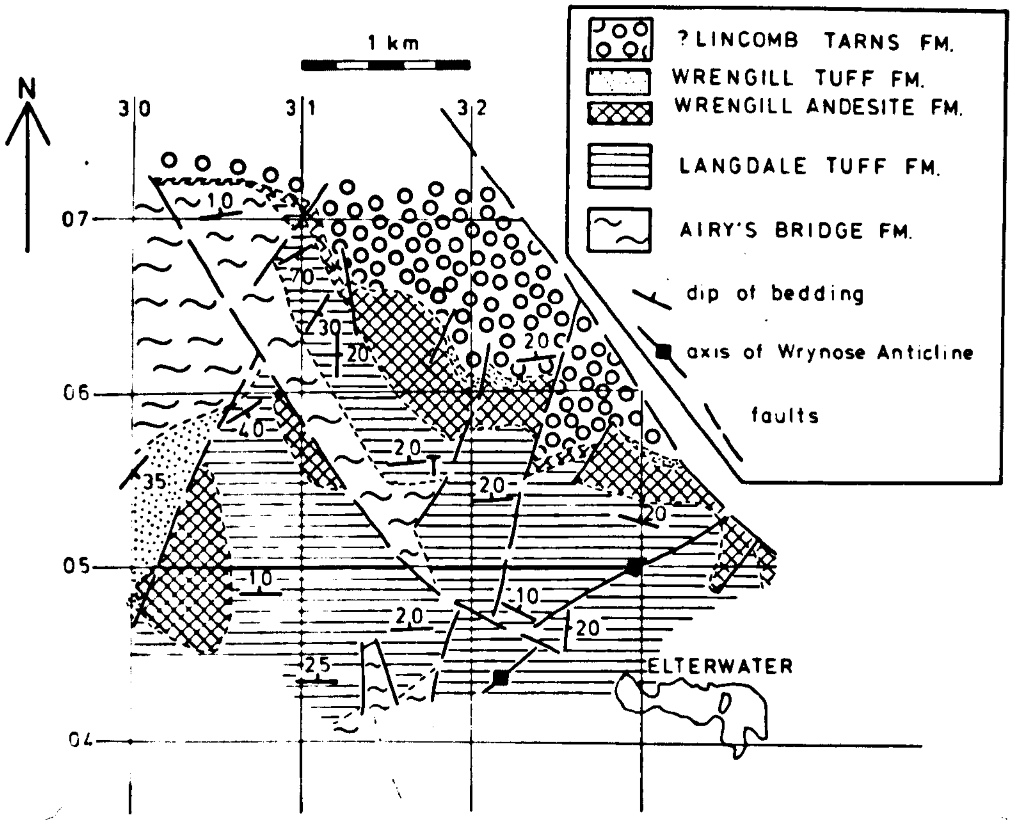
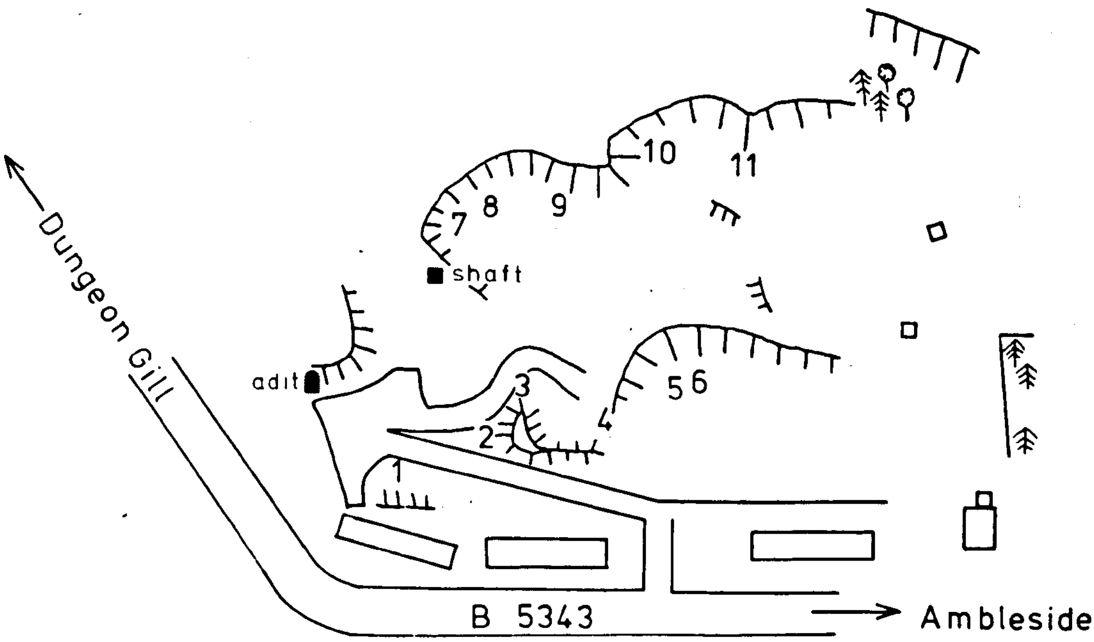

m
4
3
2
1
0
8 4 0 -4 -8 φ

FIGURE 5.9

Detailed section through the lower part of the lower bedded tuff unit. The section starts 5 m above the underlying andesitic lava. See Figure 3.23 for key. North of Sour Milk Gill (NY 232 124).



1 km
N
3|0
3|1
3|2
07
06
05
04
?LINCOMB TARNS FM.
WRENGILL TUFF FM.
WRENGILL ANDESITE FM.
LANGDALE TUFF FM.
AIRY'S BRIDGE FM.
dip of bedding
axis of Wrynose Anticline
faults
ELTERWATER

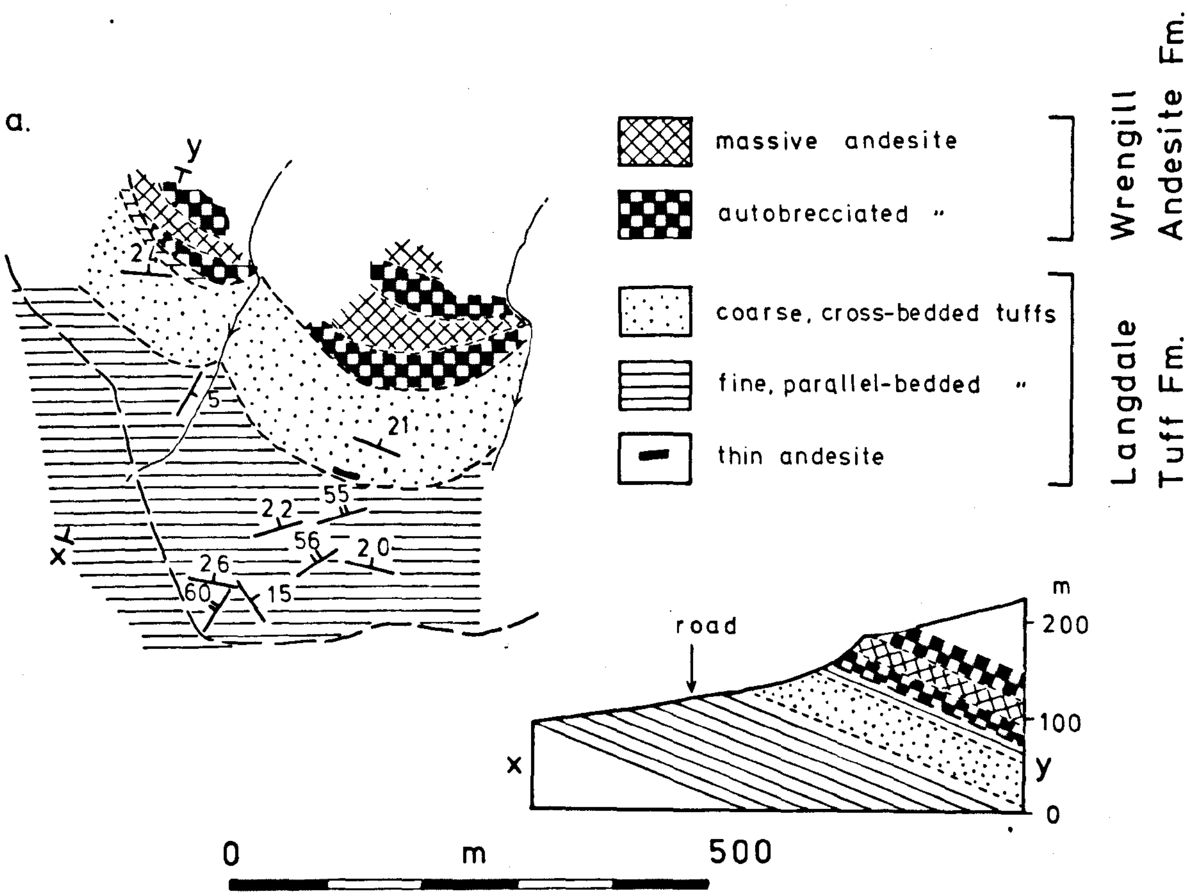


Dungeon Gill
shaft
adit
B 5343
Ambleside
1
2
3
4
5 6
7
8
9
10
11

FIGURE 6.2

(a) Geological map and cross section of the area around Thrang Quarry, Langdale. Based on enlarged 1:10,560 Ordnance Survey Map.

(b) Locality map of the area (localities 1 to 11, in Thrang Quarry, are shown in Figure 6.1b).


a.
y
x
massive andesite
autobrecciated "
coarse, cross-bedded tuffs
fine, parallel-bedded "
thin andesite
Wrengill Andesite Fm.
Langdale Tuff Fm.
road
m
200
100
0
0
m
500

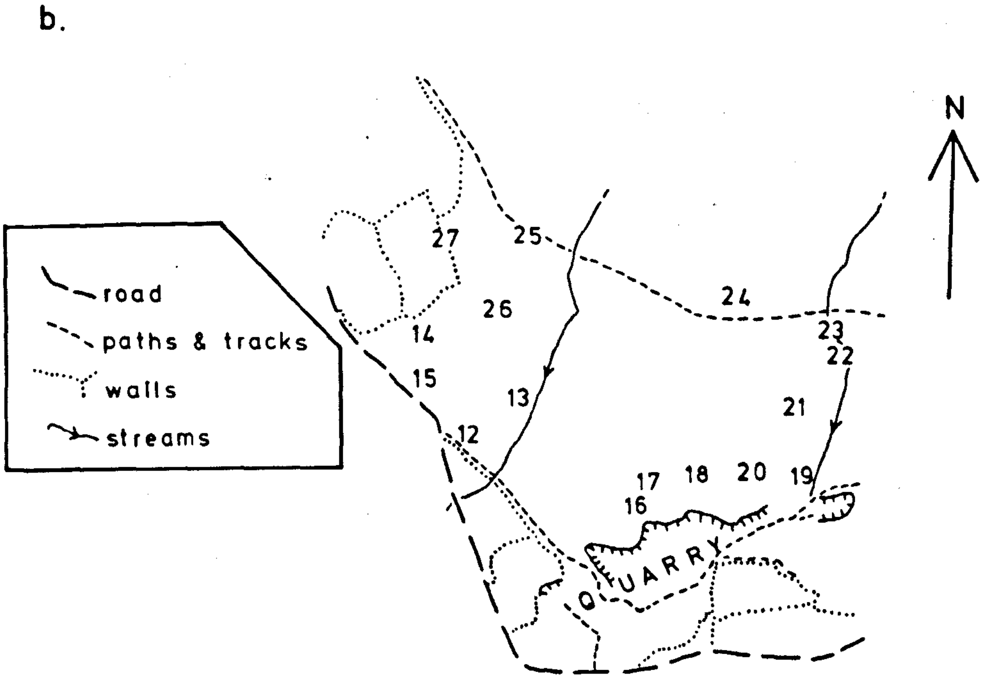
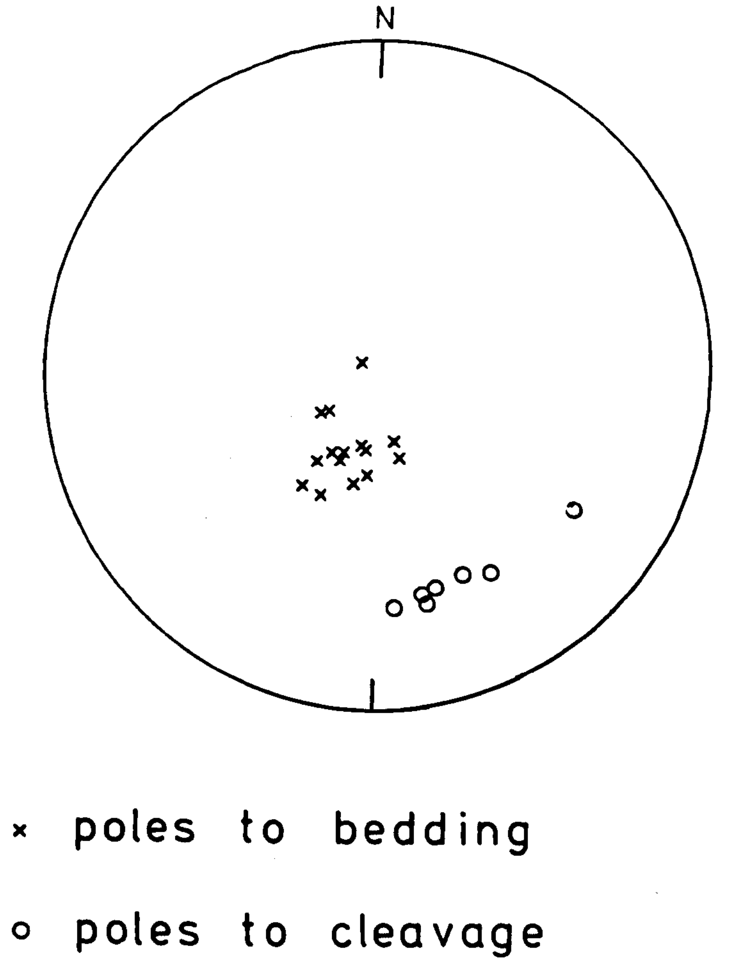

b.
road
paths & tracks
walls
streams
N
QUARRY

FIGURE 6.3

(a) Lower hemisphere stereographic projection of structural data from the Thrang area, Langdale.

(b) The stratigraphy of the volcanic rocks of the Chapel Stile area, Langdale. See Figure 3.23 for key.


N
× poles to bedding
○ poles to cleavage

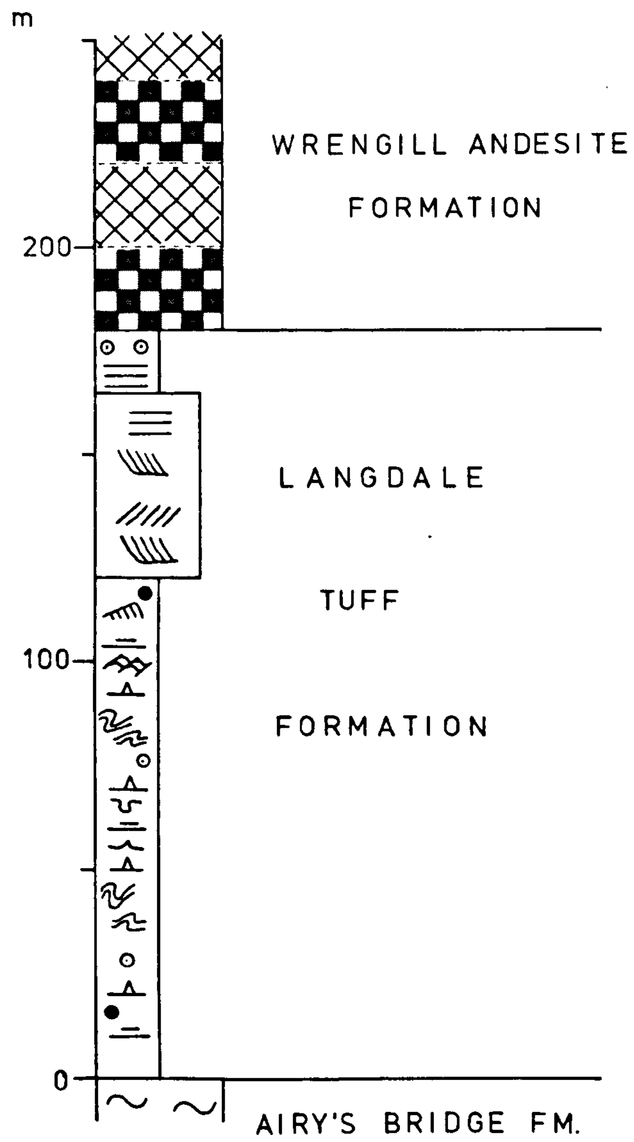
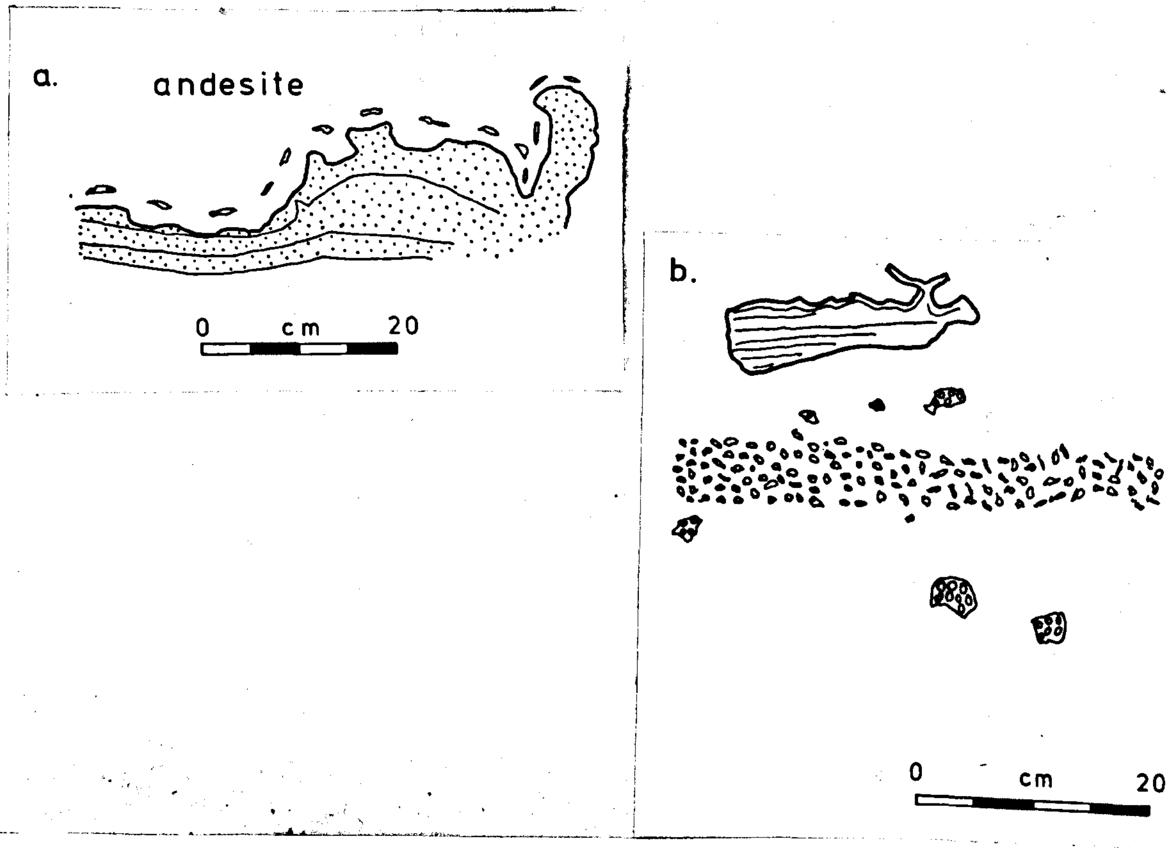

m
200
100
0
WRENGILL ANDESITE FORMATION
LANGDALE TUFF FORMATION
AIRY'S BRIDGE FM.

FIGURE 6.4

(a) Irregular base of a thin andesitic lava. The underlying bedded tuffs (stippled) are disturbed and indurated. Large vesicles are elongated parallel to the base of the flow. Locality 17.

(b) Thick bed of tuff with abundant pumice and a large block of deformed bedded tuff in a matrix of very fine sand to silt grade. Banks Quarry, Langdale (NY 316 044).

(c) Bed thickness variation with height in section. Thrang Quarry.


a.
andesite
0 cm 20
b.
0 cm 20

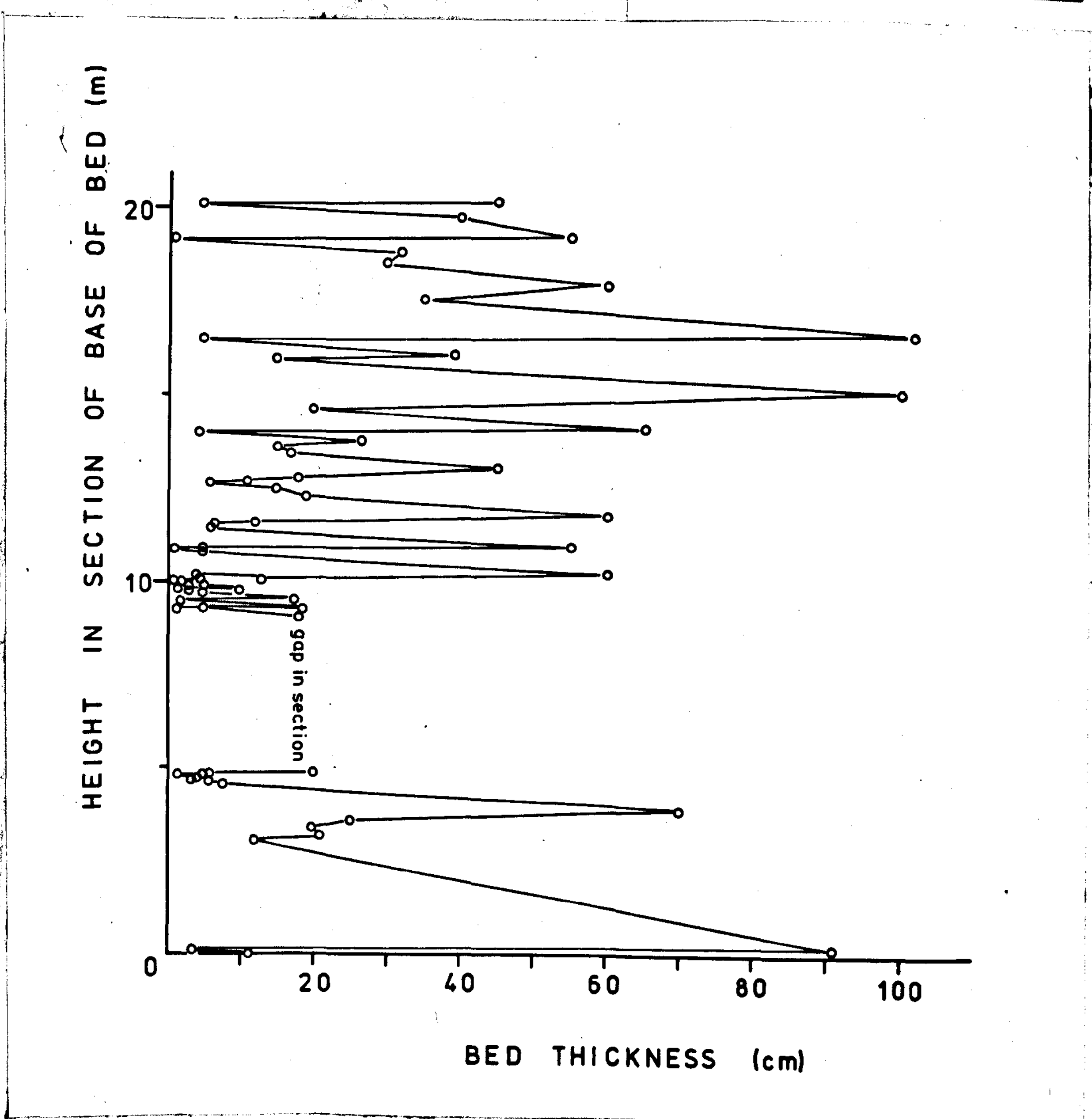

HEIGHT IN SECTION OF BASE OF BED (m)
0
10
20
gap in section
20
40
60
80
100
BED THICKNESS (cm)

FIGURE 6.5

Sedimentary structures in loose blocks from Thrang Quarry. Most structures are seen on cleavage faces: since cleavage is oblique to bedding, vertical exaggeration by a factor of up to 1.5 results. Letters a to e on the diagrams refer to interpretation in terms of divisions of the Bouma sequence. Accurate tracings from specimens.

(a) Low angle climbing ripple lamination, showing erosion of stoss sides of ripples. A few lithic clasts up to 1 cm across. Current right to left. Specimen L 21.

(b) Low angle climbing ripple lamination , with erosion surfaces between sets. Current left to right. Specimen L 22.

(c) Two complete graded beds, showing Bouma divisions c to e. Note the low angle climbing ripple lamination, with preservation of stoss sides. Current right to left. Specimen L 4.

(d) Complete graded bed, showing Bouma divisions c to e. Note low angle climbing ripple lamination, with partial preservation of stoss sides, and concentration of silt grade material on the lee sides of ripples. Current right to left. Specimen L28.

(e) Two graded beds showing partial Bouma sequences. Note preservation of ripple morphology, draped by finer material, in the upper bed. Load structures on base of upper bed. Current left to right. Specimen L 3.

(f) Graded beds showing partial Bouma sequences and over-steepened ripple cross-lamination, convolute lamination, and microloading. Current right to left. Specimen L 23.

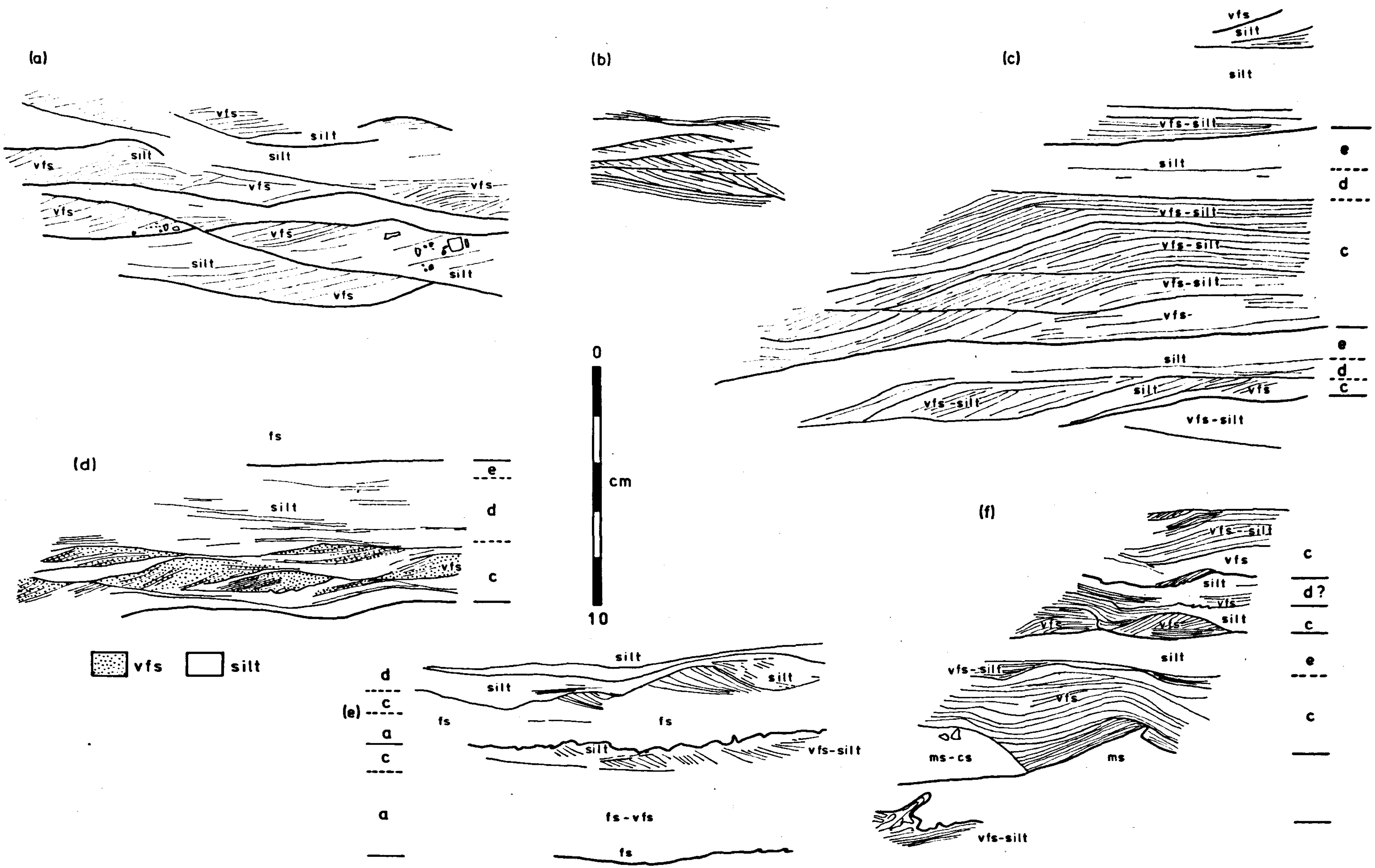

(a)
vfs
silt
silt
silt
vfs
silt
vfs
vfs
vfs-
vfs
silt
silt
vfs
(b)
(c)
vfs
silt
silt
vfs-silt
e
silt
d
vfs-silt
vfs-silt
c
vfs-silt
vfs-
e
silt
d
silt
vfs
c
vfs-silt
vfs-silt
0
cm
10
(d)
fs
e
silt
d
c
vfs
vfs
silt
(e)
d
c
a
c
a
silt
silt
silt
fs
fs
silt
vfs-silt
fs-vfs
fs
(f)
vfs-silt
c
vfs
silt
d?
vfs
vfs
vfs
silt
c
silt
e
vfs-silt
vfs
c
ms-cs
ms
vfs-silt

FIGURE 6.6

(a) Erosive base of a graded tuff bed, cutting through laminations in the underlying silt grade beds. The structures seen may be cross sections of groove or flute casts. Section 2, Thrang Quarry.

(b) Small channel seen in loose block from Thrang Quarry.

coarse stipple	-	coarse sand
fine stipple	-	fine to medium sand
unshaded	-	silt

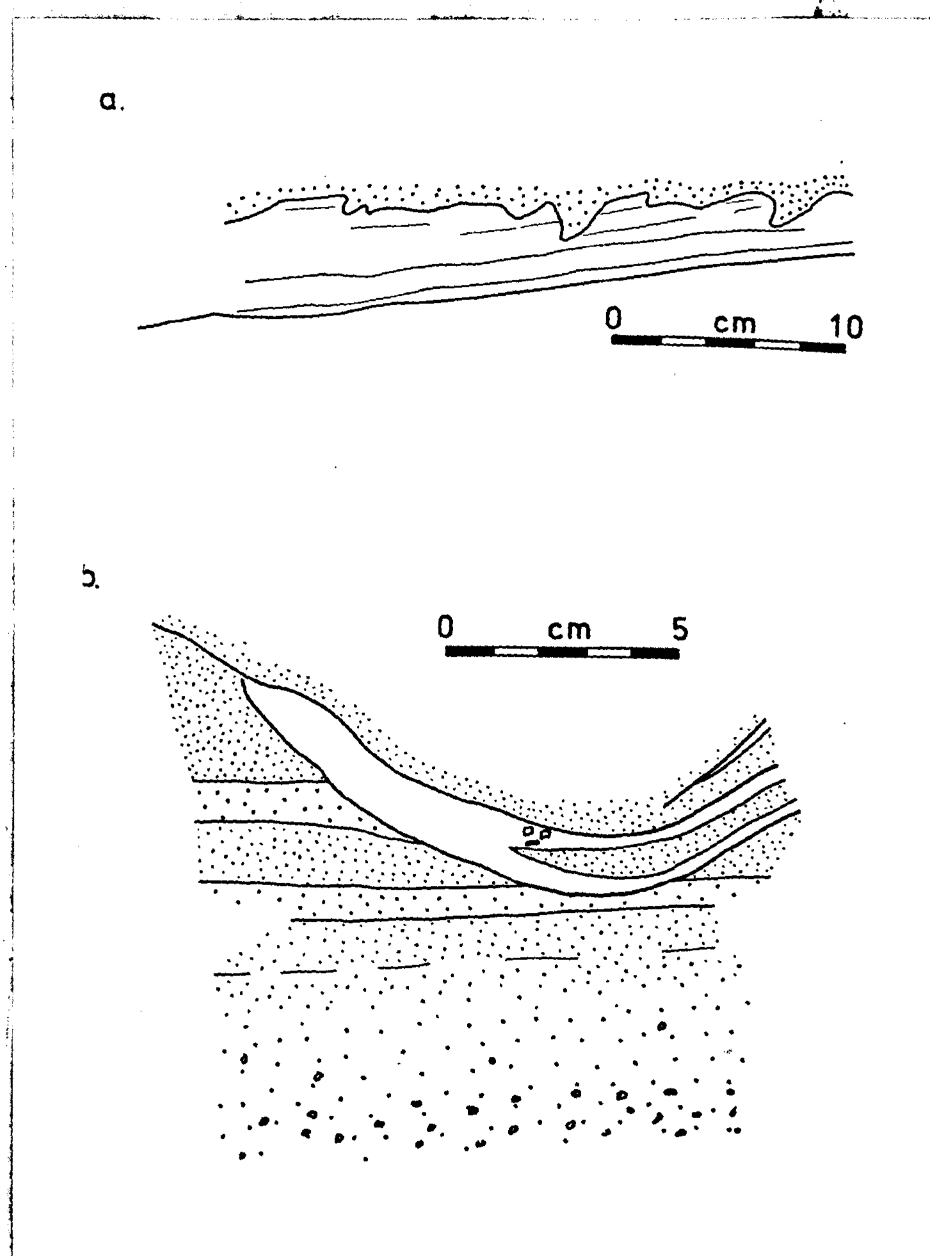

a.
0 cm 10
b.
0 cm 5

FIGURE 6.7

Soft sediment deformation structures in loose blocks, Thrang Quarry. Accurate tracings from specimens.

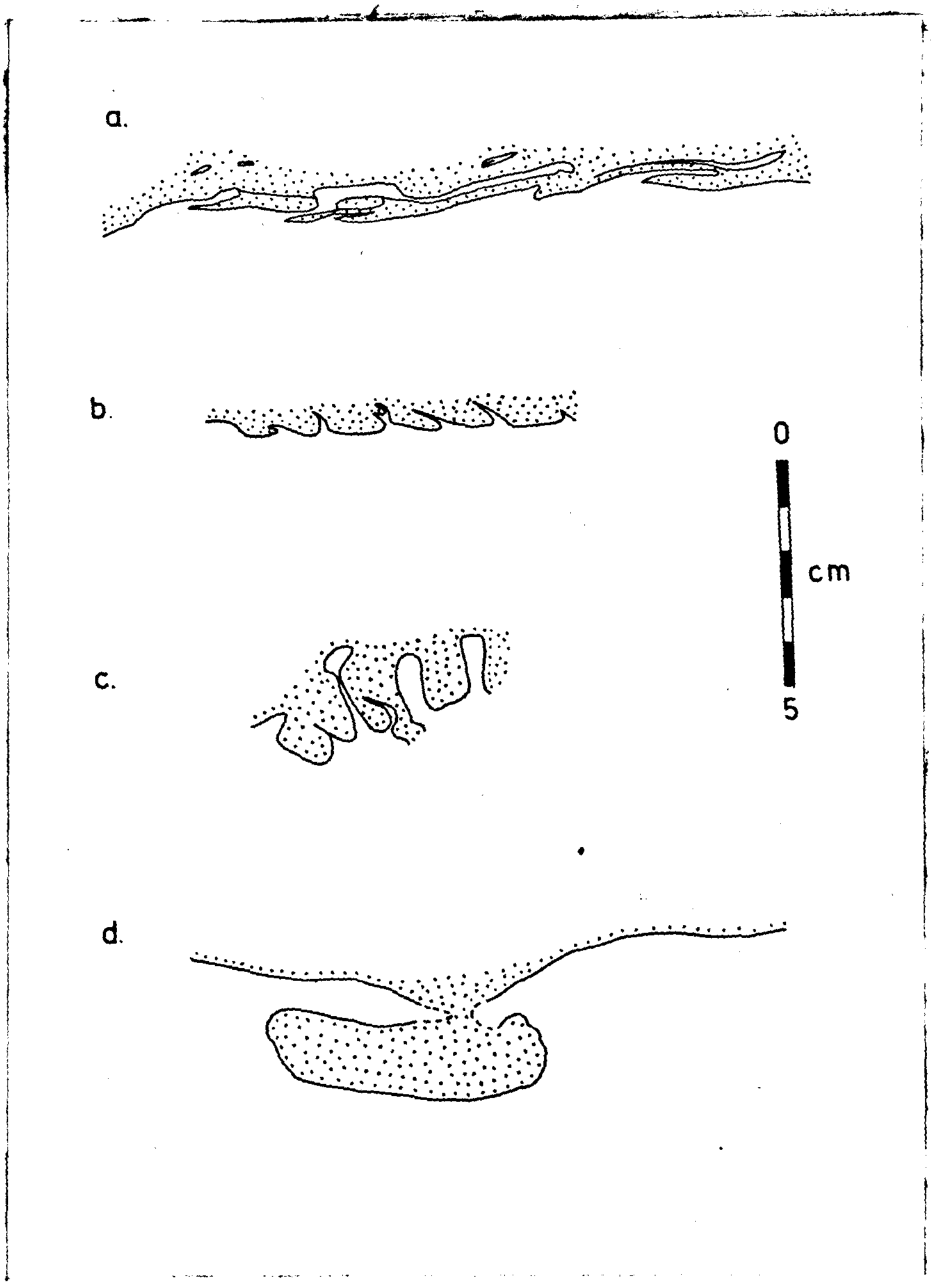
(a) Silt grade tuff overlain by very fine sand grade bed, the base of which has developed directional load structures.

(b) Load and flame structures at the contact of a clay grade bed with the overlying fine to very fine sand grade bed.

(c) Load and flame structures at the contact of a silt-clay grade bed with the overlying very fine sand grade bed.

(d) Fine to medium sand grade tuff loaded into very fine sand to silt. Dashed lines indicate points where the contact is obscured by mixing.

(e) Load and flame structures at the contact of sand grade tuff and the underlying silt-clay grade bed.


a.
b.
c.
d.
0
cm
5

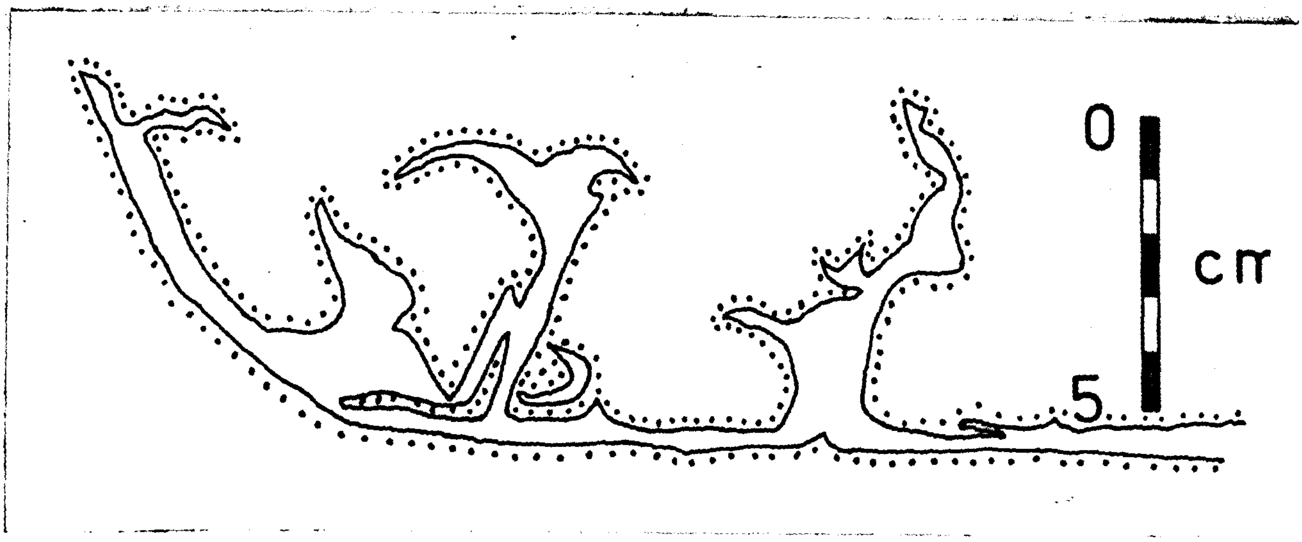

0
cm
5

FIGURE 6.8

Soft sediment deformation structures in Thrang Quarry, Langdale.

(a) Specimen showing both plastic and brittle deformation. Early plastic folds are cut by a later soft sediment fault. Note the presence of sand grade material along the fault plane. Loose block.

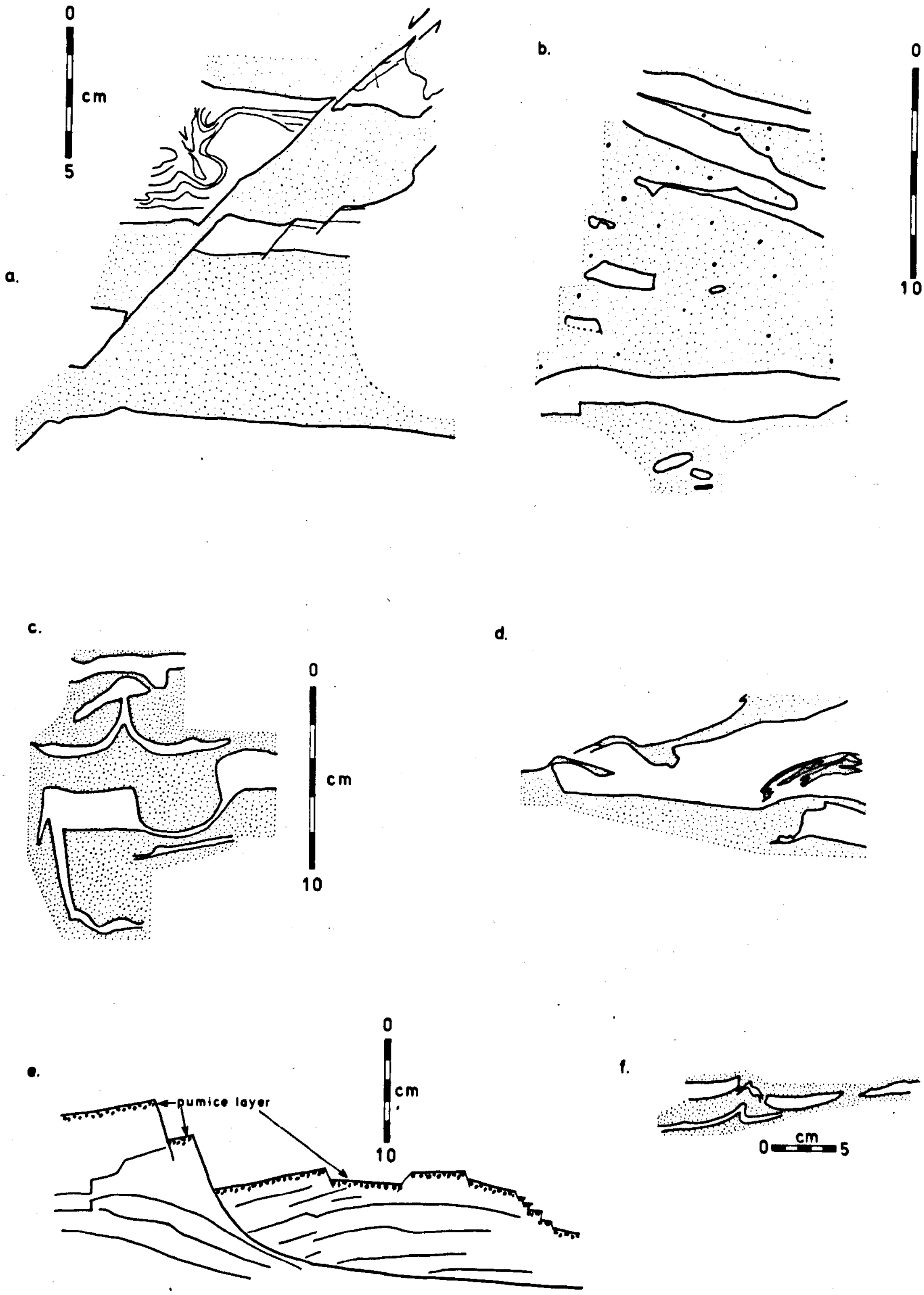
(b) Disruption of interbedded silt-clay grade and fine sand grade tuffs. The latter contain scattered pumice grains. Loose block.

(c) Plastically deformed sand and silt-clay grade beds. Loose block.

(d) Tongues of very fine sand grade tuff penetrating silt-clay grade beds. Loose block.

(e) Soft sediment faulting and rotational slump scar in fine sand to silt grade beds. To the right, the shear surface passes into a bedding plane. Near the top of Section 11.

(f) Disrupted find sand (stippled) and silt grade tuffs, demonstrating upward movement through a fracture in a silt grade bed. Near the base of Section 10.

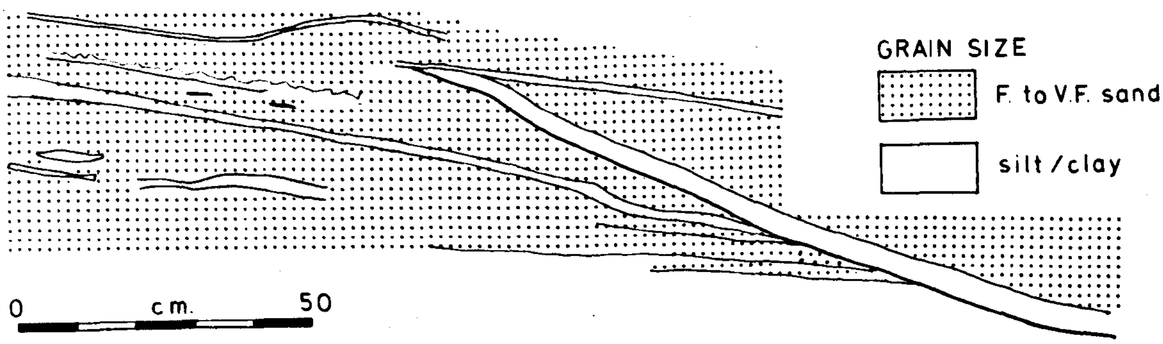


a.
0
cm
5
b.
0
cm
10
c.
0
cm
10
d.
0
cm
5
e.
pumice layer
0
cm
10
f.
0 cm 5

FIGURE 6.9

(a) Fine grained tuff beds cross cut by a probable slump scar. Note also the small scale disruption of tuff beds. Section 10. Sketch from photograph.

(b) Plastically deformed fragments of a disrupted silt-clay grade bed in a matrix of fine sand grade tuff. Sketch from photograph.


GRAIN SIZE
F. to V.F. sand
silt / clay
0 cm. 50

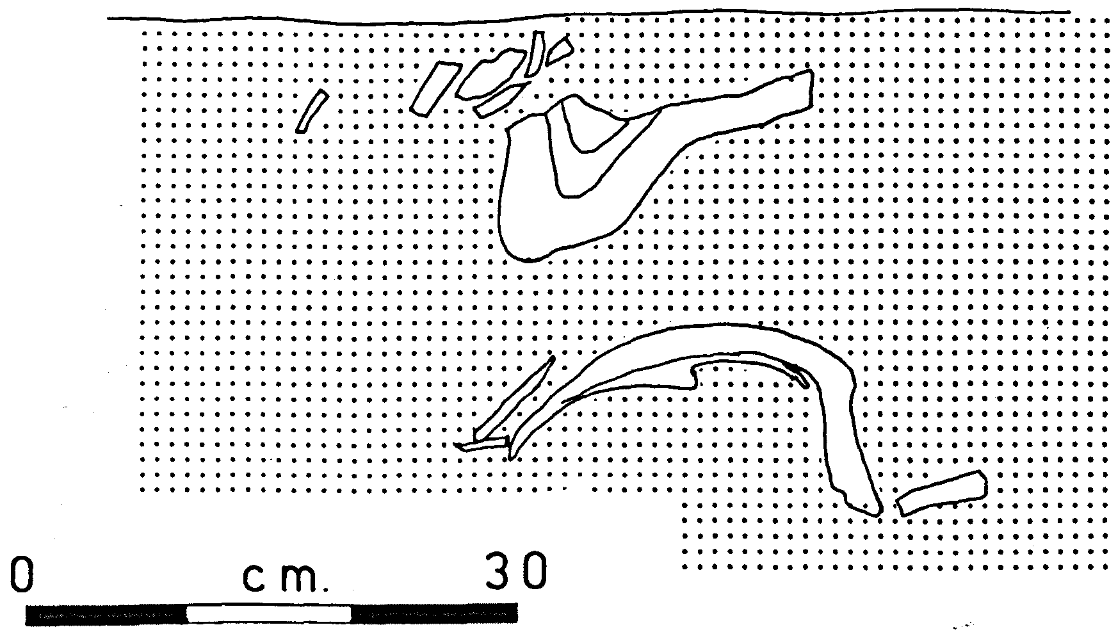
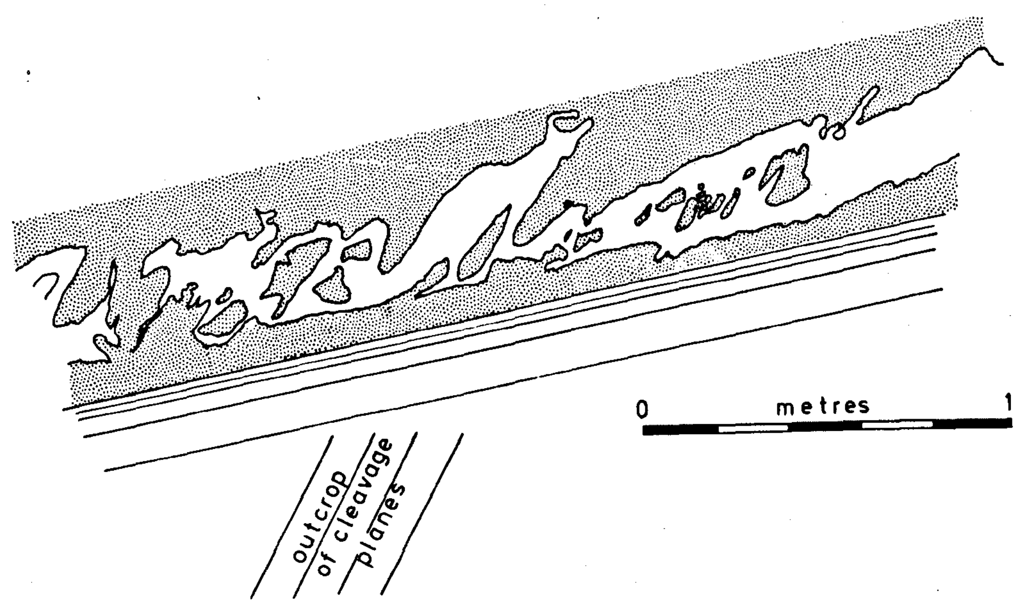

0 cm. 30

FIGURE 6.10

(a) Part of a laterally continuous plastically folded horizon. The structures are flattened in the plane of the cleavage. Sketch from photograph.

(b) Soft sediment faulting, brecciation and foundering of silt-clay grade beds. Sand grade material has entered the fractures between the blocks. Section 8. Field sketch.


0
metres
1
outcrop
of cleavage
planes

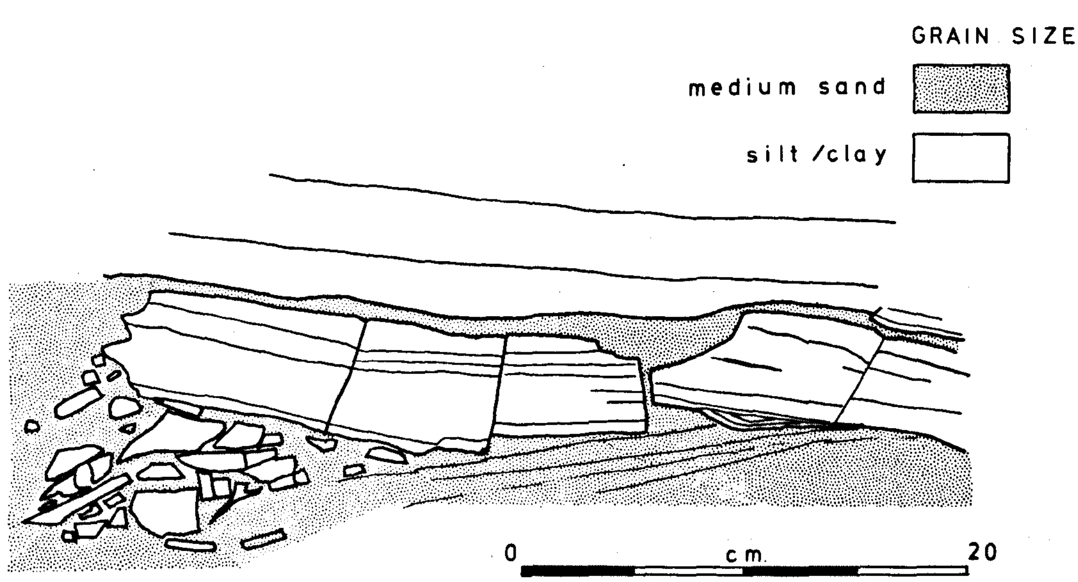
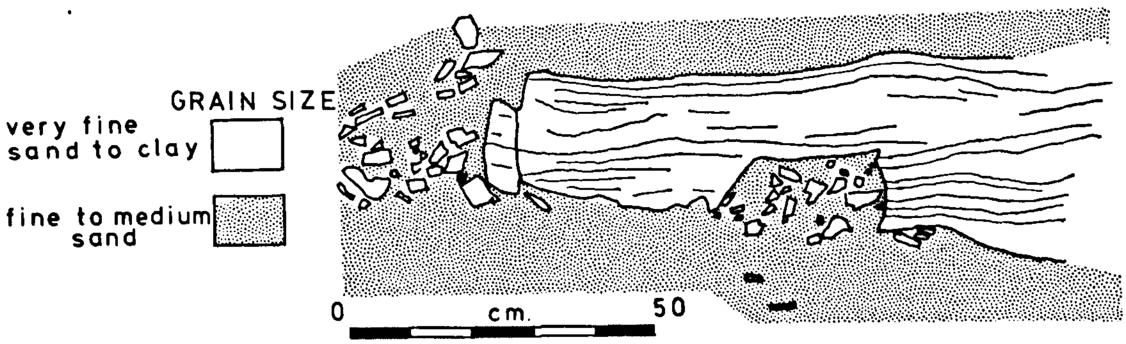

GRAIN SIZE
medium sand
silt /clay
0
cm.
20

FIGURE 6.11

(a) In situ brecciation of very fine sand to clay grade beds, with a fine to medium sand grade matrix. There is little vertical or lateral displacement of the fragments. Sketch from photograph.

(b) Detail of (a). Some of the bedded tuff fragments can be matched with the walls of the "intrusion". This is the structure figured by Parker (1966). Drawing from photograph.


GRAIN SIZE
very fine sand to clay
fine to medium sand
0
cm.
50

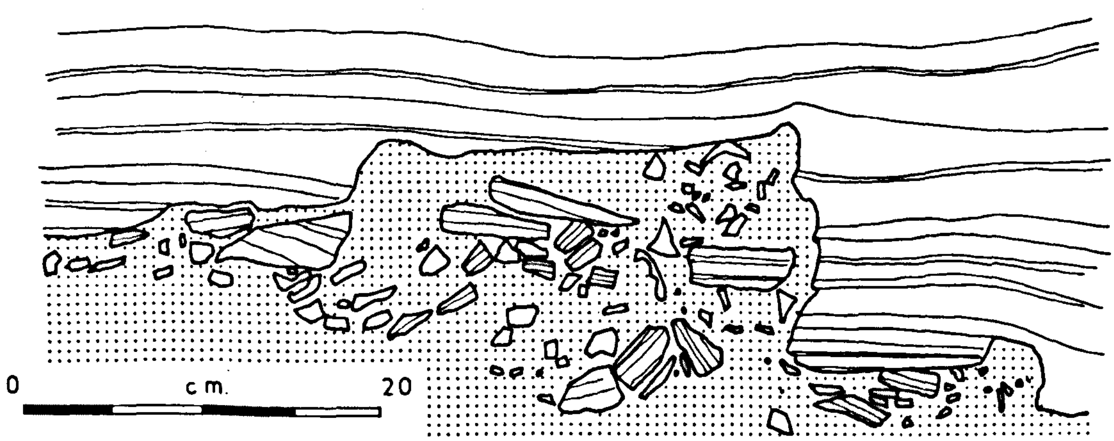

0
cm.
20

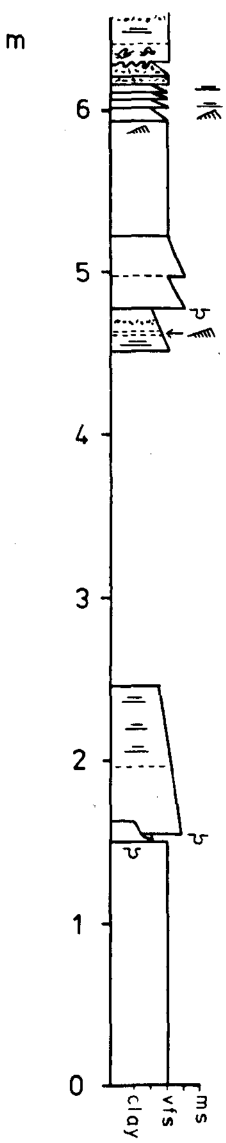
FIGURE 6.12

Sections in the Langdale Tuff Formation at Thrang Quarry.

See Figure 3.23 for key.

(a) Section 1

(b) Section 2


m
6
5
4
3
2
1
0
clay
vfs
ms

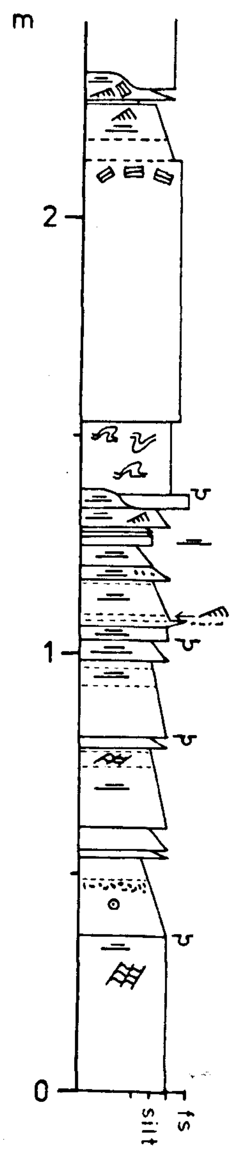

m
2
1
0
silt
fs

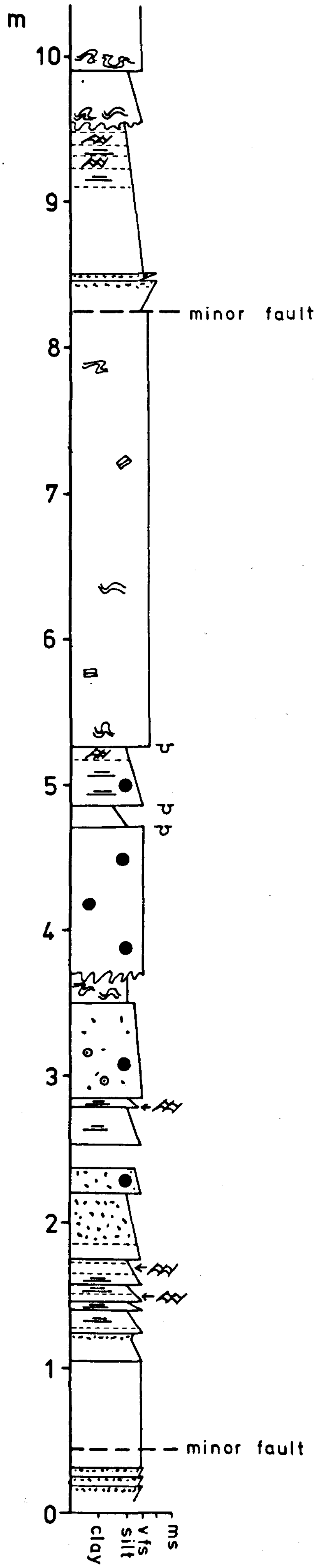
FIGURE 6.13

Sections in the Langdale Tuff Formation at Thrang Quarry.

See Figure 3.23 for key.

Sections 4 and 5 are separated by minor faults, but are believed to be at a similar level. Note the presence of beds with reverse size grading, due to concentration of pumice grains towards their tops.

(4)


m
10
9
minor fault
8
7
6
5
4
3
2
1
minor fault
0
clay
silt
vfs
ms

(5)

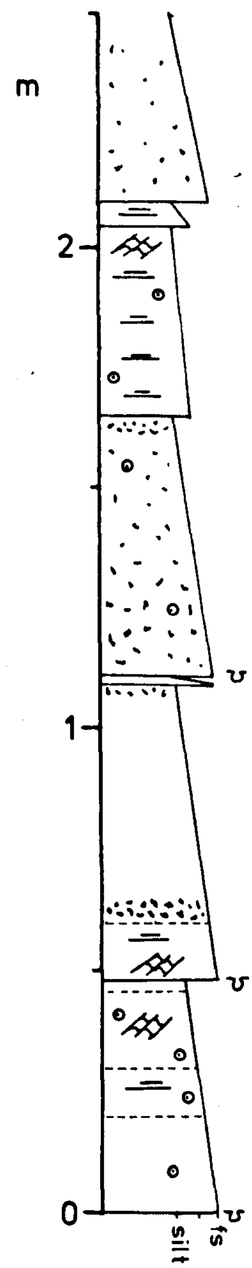
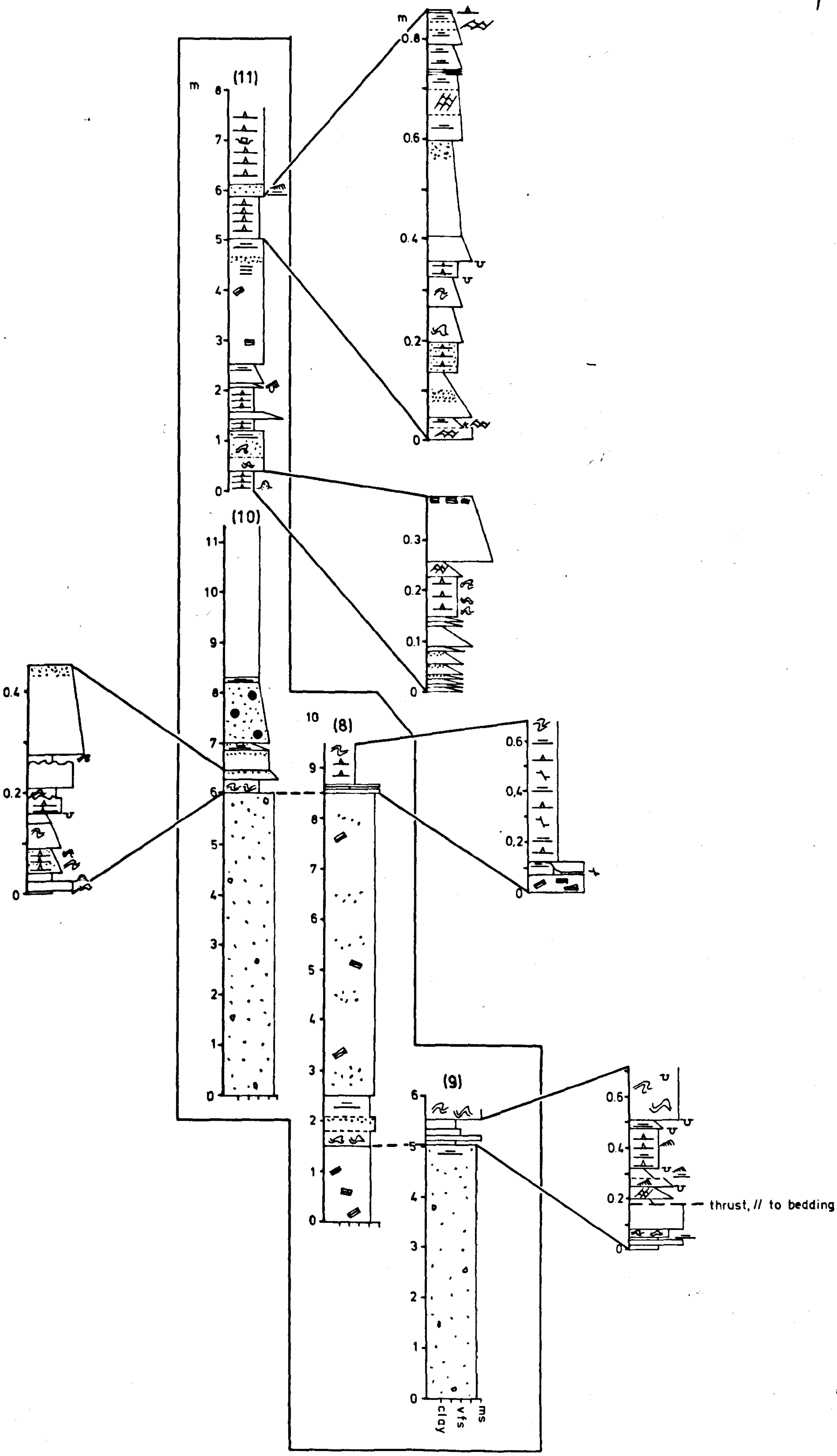

m
2
1
0
silt
fs

FIGURE 6.14

Sections 8 to 11, Thrang Quarry, showing the relative positions of the sections and details of some of the thin-bedded sequences. Key as for Figure 3.23.



(11)
(10)
(8)
(9)
m
thrust, // to bedding
clay
vfs
ms

FIGURE 6.15

Section through coarse bedded tuffs of the Langdale Tuff Formation. The junction with the underlying fine-grained bedded tuffs is at the Om level. Locality 13. See Figure 3.23 for key.

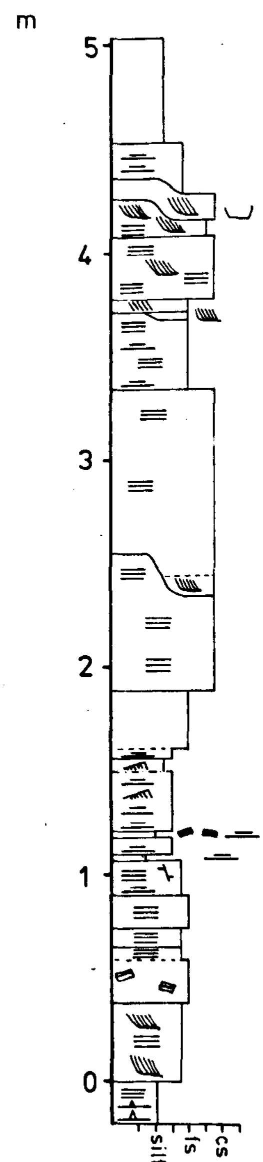
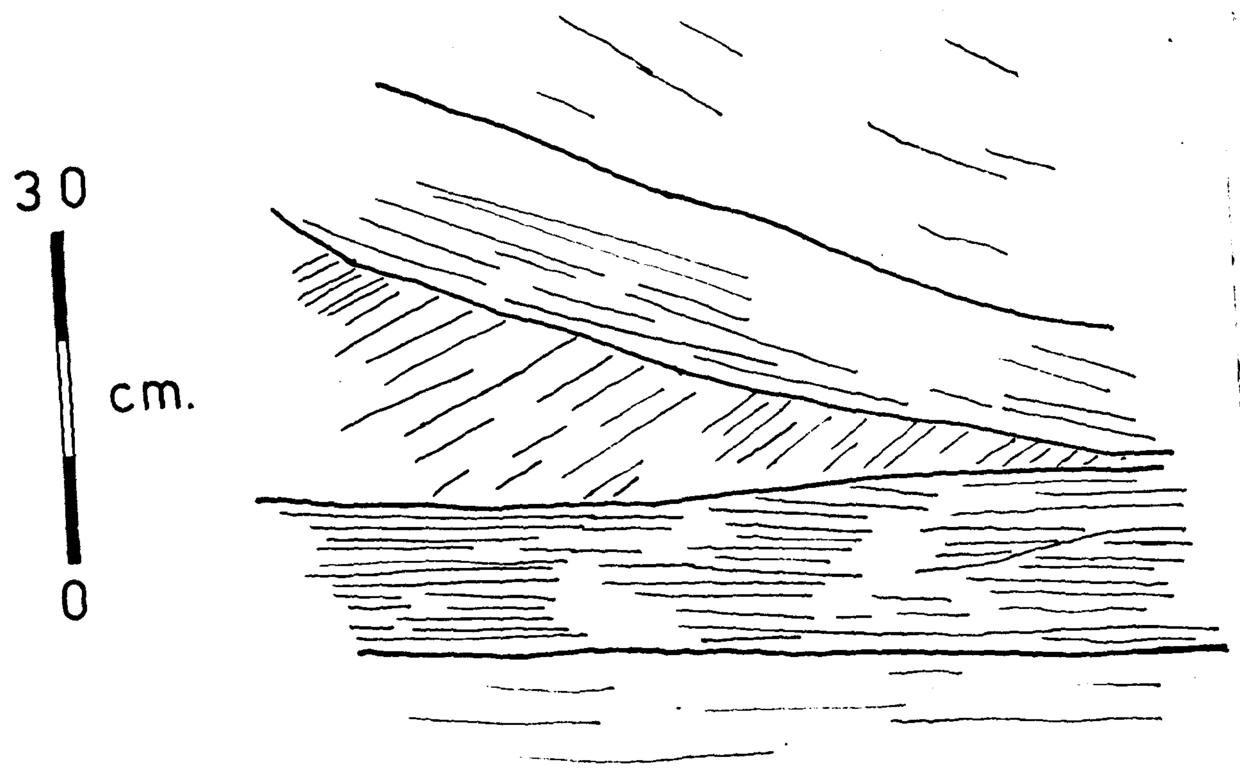
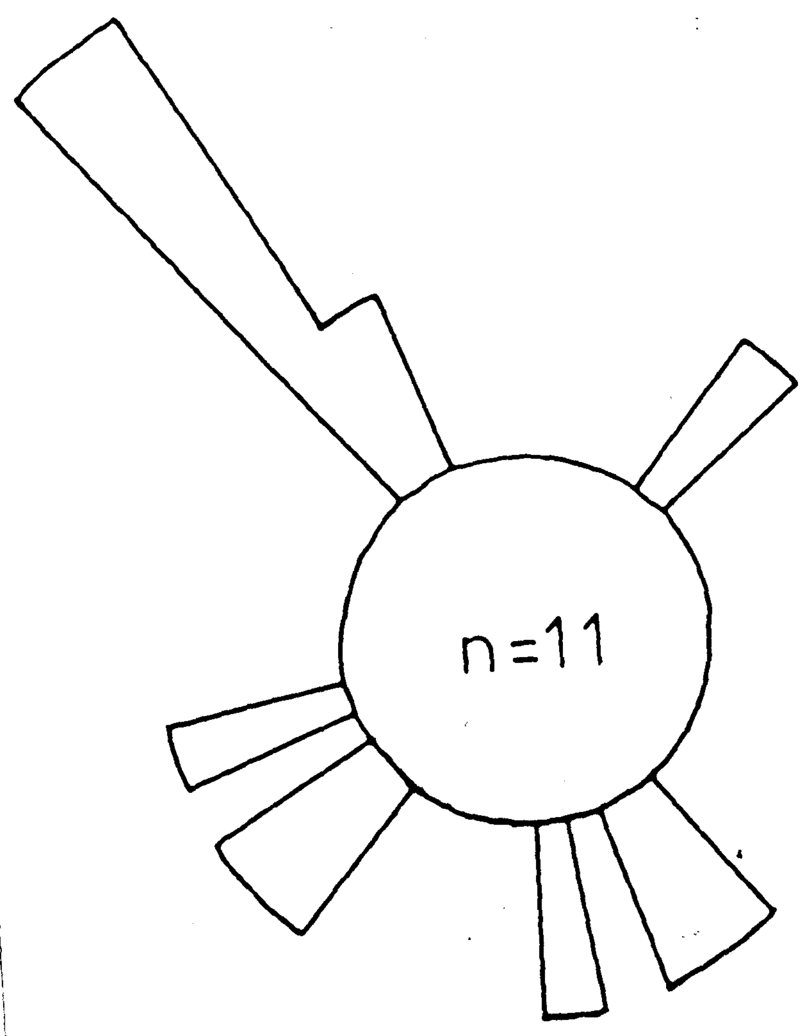

m
5
4
3
2
1
0
silt
fs
cs

FIGURE 6.16

(a) Wedge shaped cross-bedded set with steep foresets, underlain by low angle cross-bedded and flat-bedded tuffs, and overlain by flat-bedded tuffs. Locality 13. Field sketch; slight vertical exaggeration.

(b) Cross bedding direction from the coarse tuffs of the Langdale Tuff Formation in the Thrang area.


30
cm.
0


n=11

CHAPTER 7. CONCLUSIONS

I. THE VOLCANIC ENVIRONMENT

A. General Remarks

Previous authors (e.g. Green, 1919, Taylor et al, 1971) have suggested that the Borrowdale Volcanic Group is either entirely submarine or entirely subaerial. However, the present study shows that both subaerial and subaqueous environments may be represented, often in complex interrelationship. Many of the interpeetations are tentative, however. The environmental interpretation is hindered by the complete absence of fossils and non-volcanogenic sediments (apart from a thin mudstone low in the sequence) from the sections studied. Volcaniclastic sediments may often be more difficult to interpret than non- volcanic deposits: many more variables are involved, due to the action of both volcanic and sedimentary processes. A further problem is the lack of modern analogues for many of the facies found in ancient volcanic rocks. This applies particularly to subaqueous processes.

B. The Sequence of Environments in the Lower Part of the Borrowdale Volcanic Group

Detailed study of volcaniclastic facies has enabled recognition of several volcanic situations. The lowest part of the Borrowdale sequence (Chapter 3) was deposited in a subaqueous, and possibly submarine environment. During the deposition of the Brown Knotts and Ashness Gill members and the lower part of the Thirlmere Andesites, subaerial conditions predominated, with erosion and deposition by ephemeral streams in gently sloping areas of ashfall material. There is also evidence of lacustrine sedimentation here. A return to subaqueous conditions is indicated for at least part of the Thirlmere Andesites, and at their top, in the Sour Milk Gill section, clear evidence of a lacustrine environment is seen. The overlying thick ignimbrite sequence was deposited subaerially, but later, in the Langdale area, there was a return to lacustrine conditions.

C. Volcanic Topography and Volcano Type

One interesting observation arising from the present research is the lack of evidence for steep slopes and pronounced topography. In the lower, andesitic part of the sequence it appears that groups of lava flows of distinctive petrographic types can be traced over long distances. For example, massive, dark coloured aphyric andesites and basaltic andesites (including the present author's Cat Gill Member) are found at the base of the volcanic pile from Buttermere to Ullswater, a distance of over 20km (See Chapter 3, Section IE). It is not suggested that individual lava flows are continuous over this distance, nor that all the flows were erupted from the same vent, but they are clearly related. The overlying group of plagioclase-phyric lavas with tuffs is continuous over a similar distance.

Nutt (in discussion of Wadge, 1972) has suggested that shifting volcanic centres produced extensive diachronous units. The model of a monogenetic volcano field, proposed in Chapter 3, is broadly compatible with this. In one example of such a field (Bloomfield, 1975) andesitic lava flows and ashes cover a plateau 100 x 70km. This is only a small part of the 1000 km long Mexican Volcanic Belt, which includes thousands of monogenetic basaltic andesite volcanoes, and several large andesitic stratovolcanoes (Bloomfield, 1975).

The presence of such stratovolcanoes in the lower part of the Borrowdale Volcanic Group has been suggested (Suthren, 1977). This cannot be completely ruled out, but much evidence points to subdued topography in the lower part of the pile.

Higher in the section, a thick sequence of ignimbrites (the Airy's Bridge Formation and its correlatives) extends right across the Lake District. The earlier pyroclastic flows would tend to fill in any irregularities in the underlying topography, allowing the later ones to spread over large areas. The plateau thus formed allowed overlying andesitic units (e.g. Soper and Numan, 1974) to become widespread. This situation is broadly similar to the ignimbrite plateaux in New Zealand, the Andes and western U.S.A.

C. Alteration

The identification of the causes of alteration of the volcanic rocks is largely beyond the scope of the present research. The processes involved are part of a continuum including diagenesis, hydrothermal alteration and low grade regional metamorphism, and distinction of the processes is very difficult. However, the apparent relationship of alteration to a major fault at Thirlmere supports the importance of hydrothermal activity.A large system of convecting groundwater would very probably be associated with the underlying granite batholith.

D. Sources

The location and identification of possible sources for the rocks of the present study has proved very difficult, and previous authors have had similar problems. There is, however, no shortage of possible vents within, and close to the Group. All those identified from the literature are shown in Figure 7.2

II. THE TECTONIC ENVIRONMENT

In recent years many authors have tried to apply plate tectonic models to the Lower Palaeozoic volcanic rocks of Britain and Ireland (e.g. Dewey, 1969; Fitton and Hughes, 1970; Phillips et al, 1976). Most of these models involve a southward dipping subduction zone, where magmas were produced to feed island arc, and possibly back-arc, volcanoes. The present author broadly accepts this view.

The similarities with areas such as New Zealand and the western U.S.A. are discussed above. It is suggested that if a destructive margin is represented here, it was either an evolved island arc or a continental margin. The presence of a large granite batholith beneath the Lake

District (Bott, 1974) is consistent with such an environment. Although geochemical interpretations are largely outside the scope of the present work, it is interesting to note the similarity of the trace element contents of the Lake District Lavas to those of calc-alkaline basalts and andesites (Figure 7.1)

III. FURTHER RESEARCH

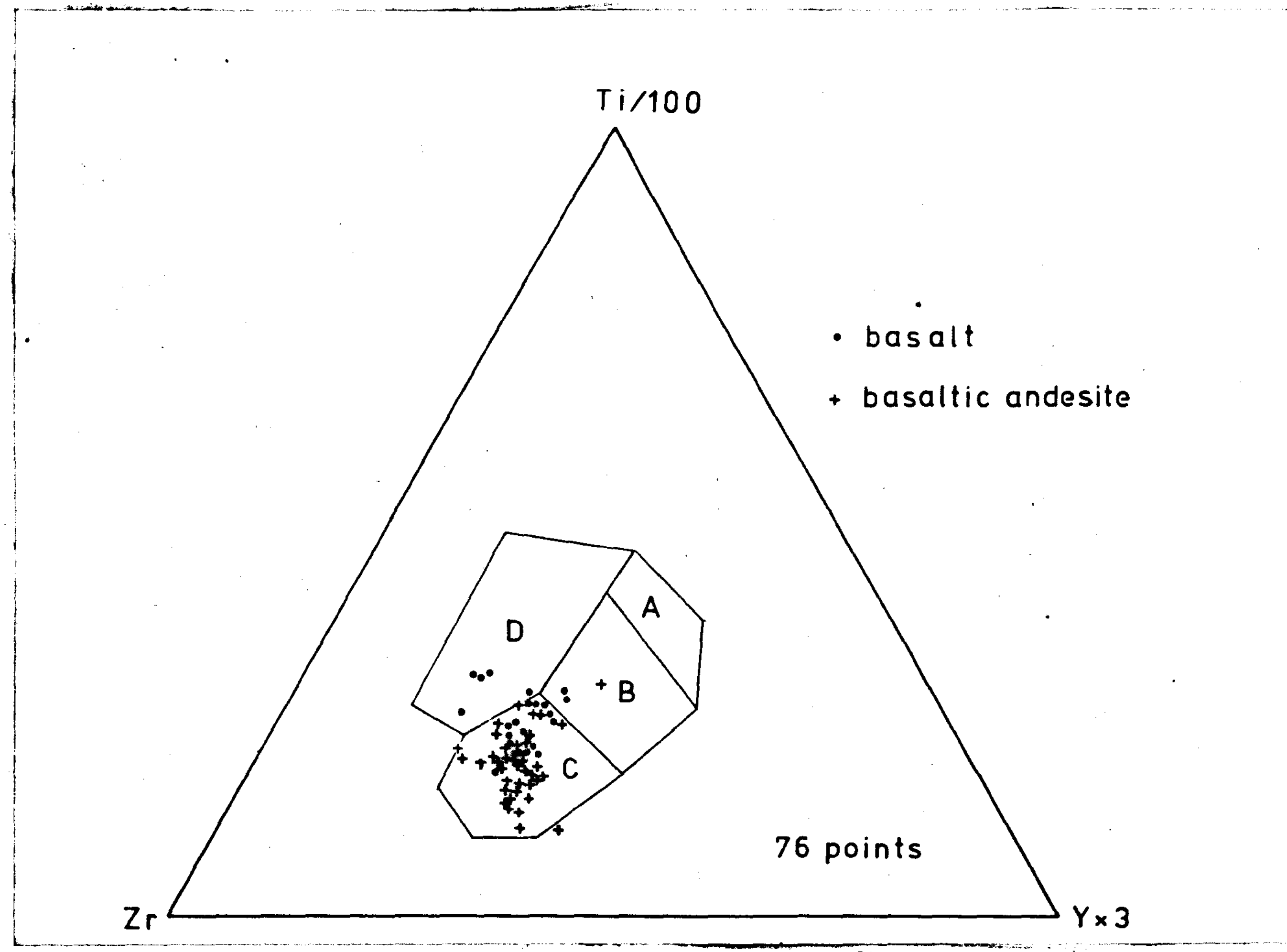
In order to obtain a deeper understanding of process and environment in the Borrowdale Volcanic Group, much more work on detailed volcanic sequences is required, in conjunction with remapping large parts of the volcanic pile. Areas which are likely to be particularly rewarding include the continuation of the Langdale Tuff Formation to the east and south, and the bedded tuffs at Honister and Kirkstone Passes. The rocks which Sedgwick described as 'out of all comparison the most remarkable physical group in the British Isles' have a great deal more information to yield.

FIGURE 7.1

Trace element data from lavas of the main outcrop of the Borrowdale Volcanic Group, analysed by Fitton (1971) and plotted by the present author on a diagram of the type devised by Pearce and Cann (1973):

Field A: low-potassium tholeiites
Field B: ocean-floor basalts and island arc volanics
Field C calc-alkaline basalts and andesites
Field D: within-plate basalts

Most of the samples analysed fall within the field of calc-alkaline basalts and andesites



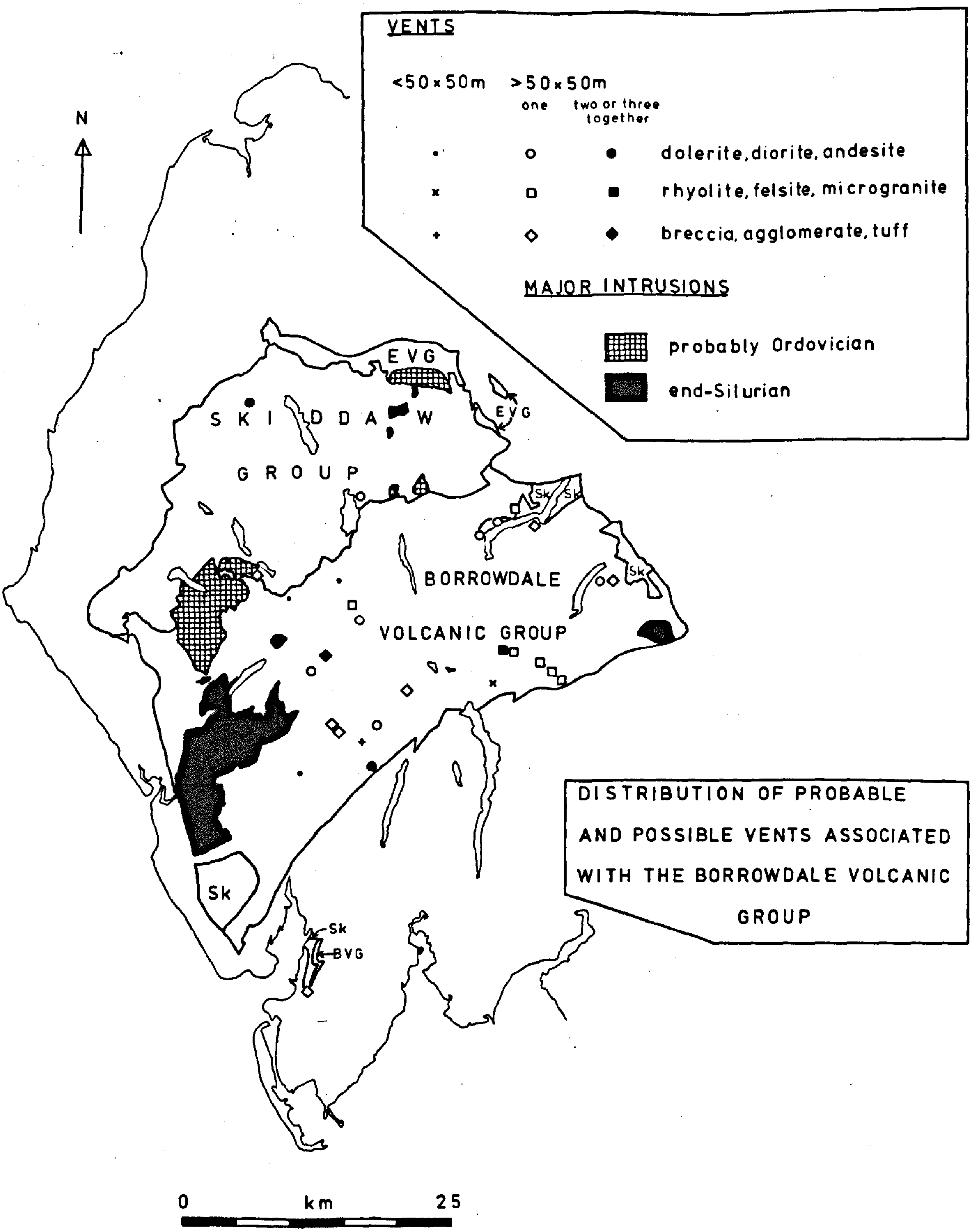
Ti/100
• basalt
+ basaltic andesite
D
A
B
C
76 points
Zr
Y×3

FIGURE 7.2

Map showing the distribution of minor intrusions which certainly or probably represent volcanic vents. Many dykes, some of which may be feeders for lava flows, are omitted.

BVG:	Borrowdale Volcanic Group
EVG:	Eycott Volcanic Group
Sk:	Skiddaw Group

Information from Clark (1964), Firman (1957), Fitton (1971), Hartley (1925), Mitchell (1929, 1940, 1963), Moseley (1960, 1964), Nutt (1966, 1970), Oliver (1953, 1961), S. M. Smith (personal communication), Soper (1970), Strens (1962), Suthren (1973), Wadge et al (1974), Ward (1876).



DISTRIBUTION OF PROBABLE AND POSSIBLE VENTS ASSOCIATED WITH THE BORROWDALE VOLCANIC GROUP

ACKNOWLEDGEMENTS

This work was financed by a University of Keele Research Studentship, for which I express my gratitude.

I would like to thank John Collinson and Bob Roach who supervised this project, and I am grateful for productive discussions with other members of staff and research students at the Department of Geology, University of Keele, in particular Richard Bevins. Much has been learnt about volcanic rocks in the field, and the hostelries of Wales, the Lake District and South East Ireland with members of the Lower Palaeozoic 'hard core' of the Volcanic Studies Group, in particular Richard Bevins, Bob Roach, Malcolm Howells, Peter Kokelaar, Peter Dunkeley, John Rea, Chris Stillman and Peter Strogen. A Volcanic Studies Group trip to Sicily and the Aeolian Islands, led by George Walker, gave a particularly valuable insight into volcanic processes, and I thank the University of Keele for paying my expenses for this excursion.

I am grateful to Ian Evans for providing a copy of his map of the Sour Milk Gill area, and to Mrs. S. M. Smith of the Royal Scottish Museum, Edinburgh, who sent me copies of two unpublished papers on the Langdale area. I would like to thank all my friends in the Lake District, particularly the wardens at the various Youth Hostels, for their help, and the North West Water Authority and the owners of Thrang Quarry , Langdale for allowing me access to their land.

The mammoth task of reproducing the photographs and diagrams for this thesis was undertaken by David Kelsall, and Peter Greatbatch and others cut over 300 thin sections for me.

Parts of the manuscript were read by John Collinson and Richard Bevins, and it was typed by Mrs. Norma Duckett, Mrs. Kaye Bell and my mother, who also mounted all the illustrations. I am very grateful to my parents and brother for their constant encouragement and support, without which this work would not have been possible.

BIBLIOGRAPHY

Allen, J. R. L. 1973. A classification of climbing ripple cross-lamination. J. Geol. Soc. Lond. 129 537-541

American Geological Institute. 1962. Dictionary of geological terms. Dolphin. New York. 545 pp.

Aramaki, S. and Yamasaki, S. 1963. Pyroclastic flows in Japan. Bull. volcanol. 26, 89-99.

Baker, B. M. 1976. Geology and Geochemistry of the Ol Doinyo Nyokie Trachyte Ignimbrite Vent Complex, South Kenya Rift Valley. Bull. volcanol. 39, 420-440.

Baker, P. E. 1963. The geology of Mount Misery Volcano, St. Kitts, B.W.I.
Unpublished D. Phil. thesis, University of Oxford.

Baker, P. E. 1972. Volcanism at destructive plate margins. J. Earth Sci., Leeds. 8 pt. 2, 183-195

Ballance, P. F. 1964. Streaked-out mud ripples below Miocene turbidites, Puriri Formation, New Zealand. J. Sedim. Petrol. 34 91-101

Ballance, P. F. 1974. An inter-arc flysch basin in northern New Zealand: Waitemata Group (Upper Oligocene to Lower Miocene). J. Geol. 82 439-471

Bassett, M. G. (Ed.) 1976. The Ordovician System: proceedings of a Palaeontological Association symposium, Birmingham, September 1974. 696 pp. Univ. Wales Press and Nat. Museum of Wales, Cardiff.

Beavon, R. V., Fitch, F.J. and Rast, N. 1961. Nomenclature and diagnostic characters of ignimbrites with reference to Snowdonia. Liverpool and Manchester Geol. J. 2, p.600

Bemmelen, R. W. van 1949. Geology of Indonesia, V.1A. General geology of Indonesia and adjacent archipelagos. The Hague, Govt. Printing Office. 732 pp.

Blake, D. H. Elwell, R. W. D., Gibson, I. L., Skelhorn R. R. and Walker, G.P. L. 1965. Some relationships resulting from intimate association of acid and basic magmas. Q. J. Geol. Soc. Lond. 121 31-49

Blatt, H. and Christie, J. M. 1963. Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks. J. Sedim. Petrol. 33, 559-579.

Bloomfield, K. 1975. A late-Quaternary monogenetic volcano field in Central Mexico. Geol. Rundschau 64, 476-497.

Blythe, F. G. H. 1940. The nomenclature of pyroclastic deposits.
Bull. volcanol. 6, 145-156

Bond, A. and Sparks, R.S. J. 1976. The Minoan eruption of Santorini, Greece.
J. Geol. Soc. Lond. 132, 1-16

Booth, B. 1973 The Granadilla Pumice Deposit of Southern Tenerife, Canary Islands.
Proc. Geol. Assoc. 84, 353-370

Bott, M. H. P. 1974. The geological interpretation of a gravity survey of the English Lake District and the Vale of Eden.
J. Geol. Soc. Lond. 130, 309-331

Brenchley, P. J. 1972. The Cwm Clwyd Tuff, North Wales. A Palaeogeographical interpretation of some Ordovician ash-shower deposits.
Proc. Yorks. Geol. Soc. 39, 199-224

Burton, M. F. 1969. Excursion to the Armboth Dyke, Fisher Crag, Thirlmere.
Proc. Cumb. Geol. Soc. 2 pt. 4, 175-177

Clark, L. 1964. The Borrowdale Volcanic series between Buttermere and Wasdale, Cumberland.
Proc. Yorks. Geol. Soc. 34, 343-356

Coats, R. R. 1968. The Circle Creek Rhyolite, a Volcanic Complex in Northern Elko County, Nevada.
Geol. Soc. Am. Mem. 116, p.69-106

Coats, R. R. Hay, R. L. and Anderson, C. A. (Eds.) 1968
Studies in Volcanology.
A memoir in honour of Howel Williams.
Geol. Soc. Am. Mem. 116

Cooke, R. V. and Warren, A. 1973. Geomorphology in deserts.
Batsford, London.

Crandell, D. R. 1957. Some features of mudflow deposits (abstract)
Bull. Geol. Soc. Am. 68, 1821

Cristofolini, R., di Girolamo, P. and Stanzione, D. 1973. Caratteri Genetici e mineralogici di ialoclastiti dell'Altopiano Ibleo (Sicilia) e dell'Isola di Procida (Campania)
Societa Italiana Mineralogia e Petrologia, Milano. 29 497-552
(Summary in English pp. 497-8)

Crowe, B. M. and Fisher, R. V. 1973. Sedimentary structures in base surge deposits with special reference to cross bedding, Ubehube Craters, Death Valley, California.
Bull. Geol. Soc. Am. 84, 663-684

Curtis, G. H. 1968. The stratigraphy of the ejecta from the 1912 eruption of Mount Katmai, Novarupta, Alaska.
Geol. Soc. Am. Mem. 116, 153-210 (Coats et al, 1968)

Dakyns, J. R. Tiddeman, R. H. and Goodchild, J. G. 1897.
The geology of the country between Appleby, Ullswater and Haweswater, (Explanation of quarter-sheet 102 SW, New Series Sheet 30)
Mem. Geol. Surv. G. B.

Daley, B. 1972 Diapiric and other deformational structures in an Oligocene argillaceous limestone.
Sedim. Geol. 6, 29-51

Debenham, F. 1962. Great World Atlas
Readers Digest, London.

Deer, W. A. Howie, R. A. and Zussman, J. 1966. An introduction to the rock-forming minerals.
Longman, London, 528 pp.

Denaeyer, M. E. 1963. Les hyaloclastites de la rive nord du lac Kivu (Congo).
Bull. volcanol. 25 201-216

Downie, C. and Soper, N. J. 1972 Age of the Eycott Volcanic Group and its conformable relationship to the Skiddaw Slates in the English Lake District.
Geol. Mag. 109 259-268

Dzulynski, S. and Walton, E. K. 1965. Sedimentary features of Flysch and Greywackes.
Developments in Sedimentology, 7. Elsevier, Amsterdam. 274 pp.

Eastwood, T. Hollingworth, S. E., Rose, W. C. C. and Trotter, F. M. 1968
Geology of the country round Cockermouth and Caldbeck.
Mem. Geol. Surv. U. K. 298 pp.

Firman, R. J. 1956. Garnets in the Borrowdale Volcanic Series.
Geol. Mag. 93, 435-436

Firman, R. J. 1957. The Borrowdale Volcanic Series between Wastwater and Duddon Valley, Cumberland.
Proc. Yorks. Geol. Soc. 31, 39-64

Fisher, R. V. 1960 Classification of Volcanic Breccias.
Bull. Geol. Soc. Am. 71, 973-982.

Fisher, R. V. 1961 Proposed classification of Volcaniclastic sediments and rocks.
Bull. Geol. Soc. Am. 72, 1409-1414

Fisher, R. V. 1966 Rocks composed of volcanic fragments and their classification.
Earth Sci. Rev. 1, 287-298.

Fisher, R. V. 1968. Puu Hou littoral cones.
Geol. Rundsch. 57, 837-864.

Fiske, R. S., 1963. Subaqueous pyroclastic flows in the Ohanepecosh Formation, Washington.
Bull. Geol. Soc. Am. 74, 391-406

Fiske, R. S. and Matsuda, T. 1964. Submarine equivalents of ash flows in the Tokiwa Formation, Japan.
Am. J. Sci. 262, 76-106.

Fitch, F. J. 1967. Ignimbrite volcanism in North Wales.
Bull. volcanol. 30, 199-219.

Fitch, F. J. 1971. The recognition of ignimbrites in North Wales.
Proc. Geol. Soc. Lond. 1664, 280-282.

Fitch, F. J., Forster, F. C. and Miller, J. A., 1976. The dating of the Ordovician.
p. 15-27
in M. G. Bassett (Ed.)

Fitton, J. G. 1971. The petrogenesis of the calc-alkaline Borrowdale Volcanic Group, Northern England.
Unpub. Ph.D. thesis. Univ. of Durham.

Fitton, J. G. 1972. The genetic significance of almandine-pyrope phenocrysts in the calc-alkaline Borrowdale Volcanic Group, Northern England.
Contr. Miner. Petrol. 36, 231-248

Fitton, J. G. and Hughes, D. J. 1970. Volcanism and plate tectonics in the British Ordovician.
Earth Planet. Sci. Lett. 8, 223-228.

Fitton, J. G. and Hughes, D.J. 1977. Ordovician volcanism in England and Wales - a review. (Extended abstract)
J. Geol. Soc. Lond. 133, 404-405.

Francis, P. W. 1976. Volcanoes.
368 pp Pelican. Lond.

Furnes, H. 1972. Metahyaloclastite Breccias associated with Ordovician pillow lavas in the Solund area, West Norway.
Norsk Geol. Tidsskr. 52, 385-407

Furnes, H. 1974. Volume relations between palagonite and authigenic minerals in hyaloclastites and its bearing on the rate of palagonitisation.
Bull. volcanol. 38, 173-186.

Gass, I. G. and Mallick, D. I. J. 1968 Jebel Khariz: an Upper Miocene Strato-volcano of comenditic affinity on the South Arabian Coast.
Bull, volcanol. 32-1, 33-88

Green, J. F. N. 1912. The Older Palaeozic succession of the Duddon Estuary.
23 pp. privately published.

Green, J. F. N. 1917. The age of the chief intrusions of the Lake District.
Proc. Geol. Assoc. 28, 1-30.

Green, J. F. N. 1919. The Vulcanicity of the Lake District. (presidential address)
Proc. Geol. Assoc. 30 153-182

Green, J. F. N. 1920. The Geological structure of the Lake District.
Proc. Geol. Assoc. 31 109-26.

Hadfield, G. S. and Whiteside H. M. C. 1936. The Borrowdale Volcanic Series and the adjoining Low Rigg Microgranite.
Proc. Geol. Assoc. 47, 42-64

Harker, A. 1902. Notes on the igneous rocks of the English Lake District.
Proc. Yorks. Geol. Soc. 14, 487-493.

Harker, A. 1906. A cordierite-bearing lava from the Lake District.
Geol. Mag. dec. V., 3, 176-177.

Harland, W. B. and Francis, E. H. 1971. The Phanerozoic Time Scale. A Supplement. Part 1. Supplementary papers and items.
Geol. Soc. Lond. Sp. Pub. No. 5.

Harland, W. B., Smith A. G. and Wilcock, B. (eds) 1964. The Phanerozoic Time Scale. A symposium.
Q. J. Geol. Soc. Lond. 120S Sp. Pub. No. 1

Harland W. B. et al. 1972. A concise guide to stratigraphical procedure.
J. Geol. Soc. Lond. 128, 295-305.

Hartley, J. J. 1925. The succession and structure of the Borrowdale Volcanic Series as developed in the area lying between the lakes of Grasmere, Windermere and Coniston.
Proc. Geol. Assoc. 36, 203-226

Hartley, J. J. 132. The volcanic and other igneous rocks of Great and Little Langdale, Westmorland.
Proc. Geol. Assoc. 43, 32-69

Hartley, J. J. 1941. The geology of Helvellyn and the southern part of Thirlmere.
Q. J. Geol. Soc. Lond. 97, 129-162.

Helm, D. G. and Roberts, B. 1971. The relationship between the Skiddaw and Borrowdale Volcanic Groups in the English Lake District.
Nature, Phys. Sci. 232, 181-183.

Honnorez, J. and Kirst, P. 1975. Submarine basaltic volcanism: morphometric parameters for discriminating hyaloclastites from hyalotuffs.
Bull. volcanol. 39, 441-465

Howells, M. F., Leveridge, B. E. and Evans, C. D. R. 1973. Ordovician ash-flow tuffs in eastern Snowdonia.
Rept. Inst. Geol. Sci. 73/3. 33 pp.

Ingham, J.K. and Wright, A. D. 1976. The North of England.
pp. 43-49 in A. Williams et al. 1976.

Jeans, P. J. F. 1972. The junction between the Skiddaw Slates and Borrowdale Volcanics in Newlands Beck, Cumberland. Geol. Mag. 109, 25-28.

Johnson, A. M. 1970 Physical processes in Geology. Chapters 12. 13. 14. Freeman, Cooper, San Francisco.

Johnston-Lavis, H. J. 1885. On the fragmentary ejectamenta of volcanoes. Proc. Geol. Assoc. 9, 421-432.

Kerr, P. F. 1959. Optical mineralogy. 3rd. Edn. McGrow Hill. 442 pp.

Konig J. M. 1964 A sedimentological, diagenetic and structural study in the Middle Tuffs, Borrowdale Volcanics, English Lake District. Unpublished Ph. D. thesis, Univ. of London.

Krauskopf, K. B. 1948. Lava movement at Paricutin Volcano, Mexico. Bull. Geol. Soc. Am. 59, 1267-1284

Kuenen, Ph. H. 1965. Value of experiments in geology. Geologie en Mijnb. 44, 22-36

Lomas, J. 1904. On a piece of faulted slate from the Volcanic Slates of Ulpha (Cumberland). Q. J. Geol. Soc. Lond. 60, iv-v

Lowe, D. R. 1975. Water escape structures in coarse grained sediments. Sedimentology, 22, 157-204

Lowe, D. R. 1976. Subaqueous liquified and fluidised sediment flows and their deposits. Sedimentology 23, 285-308

Macdonald, G. A. 1972. Volcanoes. 510 pp. Brentice-Hall.

Marr, J. E. 1916 The Geology of the Lake District. Cambridge University Press

Marshall, P. 1935. Acid rocks of the Taupo-Rotorua volcanic district. Trans. Roy. Soc. N. Z. 64, pt. 3, 323-366

Mattson, P. M. and Alvarez. W. 1973. Base surge deposits in Pleistocene volcanic ash near Rome. Bull. volcanol. 37, 553-572.

Middleton, G.V. and Hampton, M. A. 1973. Sediment gravity flows: mechanics of flow and deposition. Part I of S.E.P.M. Pacific section short course: Turbidites and deep water sedimentation. Anaheim.

Mitchell, A. H. G. 1970. Facies of an Early Miocene Volcanic Arc, Malekula Island, New Hebrides. Sedimentalogy. 14, 201-243.

Mitchell, G. H. 1929. The succession and structure of the Borrowdale Volcanic Series in Troutbeck, Kentmere and the western part of Long Sleddale (Westmorland).
Q. J. Geol. Soc. Lond. 85, 9-44

Mitchell, G. H. 1930. Notes on the Petrography of the Borrowdale Volcanic series of Kentmere (Westmorland).
Q. J. Geol. Soc. Lond. 86, 1-8.

Mitchell, G. H. 1934. The Borrowdale Volcanic Series and associated rocks in the country between Long Sleddale and Shap.
Q. J. Geol. Soc. Lond. 90, 418-444

Mitchell, G. H. 1940. The Borrowdale Volcanic Series of Coniston, Lancashire.
Q. J. Geol. Soc. Lond. 96, 301-319

Mitchell, G. H. 1954. The Borrowdale Volcanic Series of the Dunnerdale Fells, Lancashire.
Liverpool and Manchester Geol. J. 1, 428-449.

Mitchell, G. H. 1956. The Geological History of the Lake District.
Proc. Yorks. Geol. Soc. 30, 407-463.

Mitchell, G. H. 1957. Ordovician volcanoes.
Adv. of Sci. 14, 34-37.

Mitchell, G. H. 1963. The Borrowdale Volcanic Rocks of the Seathwaite Fells, Lancashire.
Liverpool and Manchester. Geol. J. 3, 289-300.

Moore, J. G. 1967. Base surge in recent volcanic eruptions.
Bull. volcanol. 30, 337-363.

Moore, J. G. and Melson, W. G. 1969. Nuees ardentes of the 1968 eruption of Mayon volcano, Phillipines.
Bull. volcanol. 33, 600-620.

Moore, J. G. and Peck, D. L. 1962. Accretionary lapilli in volcanic rocks of the western continental United States.
J. Geol. 70, 182-193.

Morton, D. M. and Campbell, R. M. 1974. Spring mudflows at Wrightwood, Southern California.
Q. J. Eng. Geol. 7, 377-384

Moseley, F. 1960. The succession and structure of the Borrowdale Volcanic Rocks, S. E. of Ullswater.
Q. J. Geol. Soc. Lond. 116, 55-84

Moseley, F. 1964. The succession and structure of the Borrowdale Volcanic Rocks, N.W. of Ullswater
Geol. J. 4, 127-142

Moseley, F. 1972. A tectonic history of North West England.
J. Geol. Soc. Lond. 128, 561-598.

Moseley, F. 1975. Structural relations between the Skiddaw Slates and the Borrowdale Volcanics.
Proc. Cumberland Geol. Soc. 3, 127-145

Mullineaux, D. R. and Crandell, D. R. 1962. Recent lahars from Mount St. Helens Washington.
Bull. Geol. Soc. Am. 73 855-870

Nicholls, G.D. 1959. Autometasomatism in the Lower Spilites of the Builth Volcanic Series.
Q. J. Geol. Soc. Lond. 114, 137-162

Nicholson, H. A. 1870. On the correlation of the Silurian deposits of the North of England with those of the South of Scotland.
Trans. Edinburgh Geol. Soc. 2, 105-113

Nutt, M. J. C. 1966. Field meeting: Haweswater.
Proc. Yorks. Geol. Soc. 35, 429-433

Nutt, M. J. C. 1968. Borrowdale Volcanic Series and associated rocks around Haweswater, Westmorland.
Proc. Geol. Soc. Lond. 1649, 112-113.

Nutt, M. J. C. 1970. The Borrowdale Volcanic Series and associated rocks around Haweswater, Westmorland.
Unpublished Ph.D. thesis. Q.M.C. Univ. of London.

Oliver, R. L. 1953. The Borrowdale Volcanic and associated rocks of the Scafell area, Lake District (England).
Unpublished Ph. D. thesis, No. 2485, Cambridge Univ.

Oliver, R. L. 1954a. Welded Tuff in the Borrowdale Volcanic Series, English Lake District, with a note on similar rocks in Wales.
Geol. Mag. 91, 473-483

Oliver, R. L. 1954b. Note on the succession in the region around the head of Borrowdale, Cumberland.
Proc. Geol. Assoc. 65, 407-411

Oliver, R.L. 1956. The origin of garnets in the Borrowdale Volcanic Series and associated rocks, English Lake District.
Geol. Mag. 93, 121-139

Oliver, R. L. 1961. The Borrowdale volcanic and associated rocks of the Scafell area, English Lake District.
Q. J. Geol. Soc. Lond. 117, 377-417

Otley, J. 1820. Remarks on the succession of rocks in the District of the Lakes. Phil. Mag. 56, 257-261.

Otley, J. 1827. A concise description of the English Lakes and adjacent mountains.
The Geology of the Lake District, 107-122. 3rd. Edn. Keswick.

Parker, W. R. 1966. Quicksand structures in the bedded tuffs of Great Langdale, Westmorland.
Nature. 210, 1247-1248

Pearce, J. A. and Cann, J. R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis.
Earth Planet Sci. Lett. 12 290-300.

Pearce, T. H. 1971. Short distance fluvial rounding of volcanic detritus.
J. Sedim. Petrol. 41, 1069-1072.

Pettijohn, F. J. Potter, P. E. and Siever, R. 1973. Sand and sandstone.
618 pp. Springer Verlag. Heidelberg.

Phillips, J. 1865. An essay on the geology of the District in 'Black's Picturesque Guide to the English Lakes.'
A. and C. Black, Edinburgh. 13th. edn.

Phillips, W. E. A., Stillman, C. J. and Murphy, T. 1976. A Caledonian plate tectonic model.
J. Geol. Soc. Lond. 132, 579-609

Picard, M. D. and High, L. R. 1973. Sedimentary structures of ephemeral streams.
Developments in Sedimentology, 17. Elsevier, Amsterdam.

Postlethwaite, J. 1913. Mines and mining in the English Lake District.
3rd. edn. Whitehaven. 164 pp.

Rast, N. 1962. Textural evidence for the origin of ignimbrites.
Liverpool and Manchester Geol. J. 3, 97-109

Reineck, H. E. and Singh, I. B. 1975. Depositional sedimentary environments.
439 pp. Springer Verlag. Berlin.

Rittmann. A. 1962. Volcanoes and their activity. (trans. E. A. Vincent).
Wiley.

Roobol, M. J. and Smith, A. L. 1976. A comparison of the recent eruptions of Mount Pelee, Martinique, and Soufriere, St. Vincent.
Bull. volcanol. 39, 214-240.

Ross, C. S. and Smith R. L. 1961. Ash-flow tuffs - their origin, geologic relations and identification.
U. S. Geol. Surv. Prof. Pap. 366. 81 pp.

Schmincke, H. U. 1967. Graded lahars in the type section of the Ellensburg Formation, South Central Washington.
J. Sedim. Petrol. 37, 438-448.

Schmincke, H. U. 1967a. Fused tuff and peperites in South Central Washington.
Bull. Geol. Soc. Am. 78, 319-330

Schmincke, H. U. 1974, Pyroclastic rocks. Ch. 4 in Fuchtbauer, H. Sediments and sedimentary rocks, 1.
Stuttgart.

Schmincke, H. U., Fisher, R. L. and Waters, A. C. 1973. Antidune and chute and pool structures in the base surge deposits of the Laacher See Area, Germany.
Sedimentology 20, 553-574.

Sedgwick, A. 1832. On the geological relations of the stratified and unstratified groups of rocks comprising the Cumbrian mountains.
Proc. Geol. Soc. Lond. 1, No. 27, 399-401

Sedgwick, A. 1848. On the organic remains found in the Skiddaw Slate with some remarks on the classification of the older rocks of Cumberland and Westmorland and c.
Q. J. Geol. Soc. Lond. 4, 216-225

Sedgwick, A. 1852. On the classification and nomenclature of the Lower Palaeozoic Rocks of England and Wales.
Q. J. Geol. Soc. Lond. 8, 136-168

Sedgwick A. 1853. Five letters on the Geology of the Lake District in W. Wordsworth "A complete guide to the Lakes."
4th Edn. J. Hudson, Kendal.

Segerstrom, K. 1950. Erosion studies at Paricutin, State of Michoacan, Mexico.
Bull. U. S. Geol. Surv. 965 A, 1-164

Shackleton, E. H. 1971. Lakeland Geology, Where to go: what to see. Dalesman, Clapham. 136 pp.

Sheridan, M. F. and Updike, R. G. 1974. Phreatomagmatic deposits of the Sugarloaf Tephra, San Francisco Mountains, Northern Arizona.
in T.N.V. Karlstrom et al. (eds.) Geology of Northern Arizona with notes on archaeology and paleoclimate, part II: G.S.A. Rocky Mountain Sect. Meeting Guidebook. 580-591.

Sheridan, M. F. and Updike R. G. 1975. Sugarloaf Mountain Tephra - a Pleistocene Rhyolitic deposit of base surge origin in Northern Arizona.
Bull. Geol. Soc. Am. 86, 571-581.

Shibata, T. 1962. Pyroclastic rubble flow in the Yumoto tuff member, Miyagi prefecture.
Tohoku Univ. Sci. Repts. 2nd. series (Geology sp. vol. no. 5, 293-302).

Simpson, A. 1967. The stratigraphy and tectonics of the Skiddaw Slates and the relationship of the overlying Borrowdale Volcanic Series in part of the Lake District.
Geol. J. 5, 391-418.

Smedes, H. W. 1956. Peperites as contact phenomena of sills in the Elkhorn Mountains, Montana (abstract).
Bull. Geol. Soc. Am. 67, 1783.

Smith, A. G. Briden, J. L. and Drewry, G. E. 1973
Phanerozoic World Maps.
p. 1-42 in "Organisms and continents through time." Pal. Assoc. Sp. papers in Palaeontology No. 12.

Smith, B. 1924. The unconformable base of the Coniston Limestone Series in the Lake District.
Geol. Mag. 61, p.163.

Smith, R. A. 1975. A bibliography of the geology and geomorphology of Cumbria.
Cumb. Geol. Soc. 32 pp.

Smith, R. L. 1960. Ash Flows.
Bull. Geol. Soc. Am. 71, 795-842.

Smith, S. M. Note on the geological structure of Langdale and Tilberthwaite, English Lake District.
Unpublished manuscript.

Smith, S. M. The succession and volcanic history of the Borrowdale volcanic rocks of Langdale, English Lake District.
Unpublished manuscript.

Snyder, G. L. and Fraser, G. D. 1963. Pillowed lavas I: Intrusive layered lava pods and pillowed lavas, Unalaska Is., Alaska.
Bull. U. S. Geol. Surv. Prof. Pap. 454B, 1-23

Solomon, N. 1969. The nature and possible origin of the pillow lava and hyaloclastite breccias of King Island, Australia.
Q. J. Geol. Soc. Lond. 124 153-169

Soper, N. J. 1970. Three critical localities on the junction of the Borrowdale Volcanic Rocks with the Skiddaw Slates in the Lake District.
Proc. Yorks. Geol. Soc. 37 461-493.

Soper, N. J. and Numan, N. M. S. 1974. Structure and stratigraphy of the Borrowdale volcanic rocks of the Kentmere area, English Lake District.
Geol. J. 9, 147-166

Sorby, H. C. 1880. Slates of the English Lake District (part of the Presidential Address).
Q. J. Geol. Soc. Lond. 36 74-75

Sorby, H. C. 1908. On the application of quantitative methods to the study of the structure and history of rocks.
Q. J. Geol. Soc. Lond. LXIV, 171-233

Sparks, R. S. J. 1975. Stratigraphy and Geology of the ignimbrites of Vulsini Volcano, Central Italy.
Geol. Rundsch. 64, 497-523

Sparks, R. S. J. 1976. Grain size variations in ignimbrites and implications for the transport of pyroclastic flows.
Sedimentology 23, 147-188

Sparks, R. S. J., Self, S. and Walker, G. P. L. 1973.
Products of ignimbrite eruptions.
Geology. Nov. 1973, 115-118.

Sparks, R. S. J. and Walker, G. P. L. 1973. The ground surge deposit: a third type of pyroclastic rock.
Nature (Phys. Sci.) 241, 62-64

Spjeldnaes, N. 1976. Ordovician climates (abstract).
P. 67-69 in M. G. Bassett (ed.), 1976.

Stillman, C. J. 1976. A field guide to the Ordovician volcanic rocks of south-east County Waterford.
Geology Department, Trinity College, Dublin.

Strens, R. G. J. 1962. The Geology of the Borrowdale-Honister District of Cumberland with special reference to the mineralisation.
Unpublished Ph. D. thesis, University of Nottingham.

Strens, R. G. J. 1964. Epidotes of the Borrowdale Volcanic Rocks of Central Borrowdale.
Mineralog. Mag. 33, 868-886.

Suthren, R. J. 1973. The Geology of the area north west of Coniston, Lancashire.
Unpublished B.A. thesis. University of Oxford.

Suthren, R. J. 1976. Volcaniclastic rocks of the Borrowdale Volcanic Group (abstract)
J. Geol. Soc. Lond. 132, p. 120 (Part I, Jan. '76)

Suthren, R. J. 1977 Sedimentary processes in the Borrowdale Volcanic Group (extended abstract)
J. Geol. Soc. Lond. 133, 410-411 (pt. 4)

Taylor, B. J., Burgess, I. C., Land, D. H. Mills, D. A. C., Smith, D. B. and Warren, P. T. 1971. British Regional Geology: Northern England.
H.M.S.O. London.

Thorarinsson, S. 1954. The tephra fall from Hekla on March 29th, 1947. in The eruption of Hekla 1947-48. Visindafelag islendinga and Mus. Nat. Hist, Reykjavik, Pt. 2 No. 3, 68 pp.

Thorpe, R. S. and Francis, P. W. 1976. Volcan Ceboruco: a major composite volcano of the Mexican volcanic belt.
Bull. volcanol. 39, 201-213.

Vlodavetz, V. I. et al. 1963. Draft of the proposal submitted to the commission of the classification of pyroclastic rocks elected at the First All Union Volcanology Conference.
Intern. Geol. Rev. 5, 516-524.

Wachendorf, H. 1973. The Rhyolitic lava flows of the Lebombos, S. E. Africa.
Bull. volcanol. 37, 515-529.

Wadge, A. J. 1972. Sections through the Skiddaw-Borrowdale Unconformity in Eastern Lakeland. Proc. Yorks. Geol. Soc. 39, 179-198.

Wadge, A. J., Harding, R. R. and Darbyshire, D. P. F. 1974. The rubidium strontium age and field relations of the Threlkeld microgranite. Proc. Yorks. Geol. Soc. 40, 211-222.

Wadge, A. J. Nutt, M. J. C. and Skevington, D. 1972. Geology of the Tarn Moor Tunnel in the Lake District. Bull. Geol. Surv. Gt. Britain, No. 41, 55-73.

Waldron, H. M. 1967. Debris flow and erosion control problems caused by the ash eruptions of Irazu Volcano, Costa Rica. Bull. U. S. Geol. Surv. 1241-I, 37 pp.

Walker, E. E. 1904 Notes on the garnet-bearing and associated rocks of the Borrowdale Volcanic series. (detailed petrography) Q. J. Geol. Soc. Lond. 60, 70-105.

Walker, G. P. L. 1959. Geology of the Reydarfjordur Area, Eastern Iceland. Q. J. Geol. Soc. Lond. 114, 367-393.

Walker, G. P. L. 1971. Compound and simple lava flows and flood basalts. Bull. volcanol. 35, 579-590.

Walker, G. P. L. 1973. Explosive volcanic eruptions - a new classification scheme. Geol. Rundschau 62 431-446

Walker, G. P. L. 1974. Volcanic mudflows (abstract of talk) Q. J. Eng. Geol. Vol. 7, 351.

Walker, R. G. 1975. Conglomerate: sedimentary structures and facies models. Chapter 7 in "Depositional Environments as interpreted from primary sedimentary structures and stratification sequences." S.E.P.M. Short Course No. 2 Dallas, 1975.

Walker, R. G. and Mutti, E. 1973. Turbidite facies and facies associations. Part IV of S.E.P.M. Pacific Section Short Course "Turbidites and deep water sedimentation" Anaheim.

Ward, J. C. 1875. Notes on the comparative microscopic rock structure of some ancient and modern volcanic rocks. Q. J. Geol. Soc. Lond. 31, 388-422.

Ward, J. C. 1876. The Geology of the Northern Part of the English Lake District. Quarter Sheet 101 S.E. Mem. Geol. Surv. G. B.

Ward, J. C. 1876-77. Jonathan Otley, the Geologist and Guide. Trans. Cumb. Assoc. Adv. Lit. and Sci. Pt. II 125-169.

Wentworth, C. K. 1922. A scale of grade and class terms for clastic sediments.
J. Geol. 30, 377-392.

Wentworth, C. K. and Williams, H. 1932. The classification and terminology of the pyroclastic rocks.
Nat. Res. Coun. Bull. 89, 19-53.

Westercamp, D. 1976. Petrology of the Volcanic Rocks of Martinique, West Indies.
Bull. volcanol. 39, 175-200.

Whitford-Stark, J. L. 1973. Vesicles and related structures in lavas
Geol. J. 8, 317-332.

Wilcox, R. E. 1950. Petrology of Paricutin Volcano, Mexico.
Bull. U. S. Geol. Surv. 965C, 281-354.

Williams, A. Strachan, I. Bassett, D. A., Dean, W. T. Ingham, J. K., Wright, A. D. and Whittington, M. B. 1976.
A correlation of Ordovician Rocks in the British Isles.
Geol. Soc. Lond. Sp. Rpt. No. 3.

Williams, H. 1942. The Geology of Crater Lake National Park, Oregon, with a reconaissance of the Cascade Range southward to Mt. Shasta.
C.I.W. Pub. 540, 162 pp.

Wright, A. E. and Bowes, D. R. 1963. Classification of volcanic breccias: a discussion.
Bull. Geol. Soc. Am. 74, 79-86

Dewey, J. F. 1969. Evolution of the Appalachian/Caledonian orogen. Nature 222, 124 -129

Francis, E. H. and Howells, M. F. 1973. Transgressive welded ashflow tuffs among the Ordovician sediments of NE Snowdonia, North Wales. J. Geol. Soc. Lond. 129, 621-641

Friedman, I. I., Smith, R. L. and Long, W.D. 1966. Hydration of natural glass and formation of perlite. Bull. Geol. Soc. Am. 77, 323-327

Marshall, R.R. 1961. Devitrification of natural glass. Bull. Geol. Soc. Am. 72, 1493-1520

Mutti, E.1965. Submarine flood tuffs (Ignimbrites) associated with turbidites in Oligocene deposits of Rhode Island (Greece). Sedimentology 5, 265-288

Myers, J. S., 1975. Cauldron subsidence and fluidization: mechanisms of intrusion of the Coastal Batholith of Peru into its own Volcanic ejecta. Bull. Geol. Soc. Am. 86, 1209-1220

Sims, J. D. 1975. Determining earthquake recurrence intervals from deformational structures in young lacustrine sedimants. Tectonophysics 29, 141-152.

Sparks, R.S.J. and Wilson, L. 1976. A model for the formation of ignimbrite by gravitational column collapse. J. Geol. Soc. Lond. 132, 441 - 451