CHAPTER 1

INTRODUCTION

1.1 PURPOSE AND SCOPE OF THE STUDY

A number of large volume silicic ignimbrites (Appendix I) are present in the Lower Carboniferous terrestrial sedimentary succession in the Hunter Valley of New South Wales, at the southern end of the New England Orogen. These ignimbrites have been described in many stratigraphic- and sedimentary-based studies and some of them have been chemically analysed in regional studies of the petrogenesis of the Hunter Valley volcanics. But a detailed study of individual ignimbrites, including their mineralogy and petrology remained to be done.

Stratigraphers and sedimentologists have postulated that the ignimbrites originated from a 'volcanic arc' located west of the main ignimbrite outcrop, as the ignimbrites increase in thickness and the interbedded sedimentary rocks coarsen in that direction. The 'arc' is not exposed and its exact nature and position is still a matter of debate. Volcanological aspects of the arc such as the type of volcanoes, their location, and spacing, have been largely ignored and this thesis researches these unknowns.

Six ignimbrites units, in different parts of the Hunter Valley in the southern part of the New England Orogen, are far more widespread than others within the Lower Carboniferous succession. They overlap each other at their margins and consequently, crop out almost continuously along the entire length of the Hunter Valley. In this study, these six ignimbrites are extensively sampled and analysed, both mineralogically and geochemically, and flow lineations and directions have been determined from orientated slabs of the ignimbrites they were then used to locate the source volcanoes.

Once the location of the source volcanoes had been determined, the available geophysical data of the region (gravity and magnetics) was investigated to determine if this data could be used in support of the determined locations of the source volcanoes.

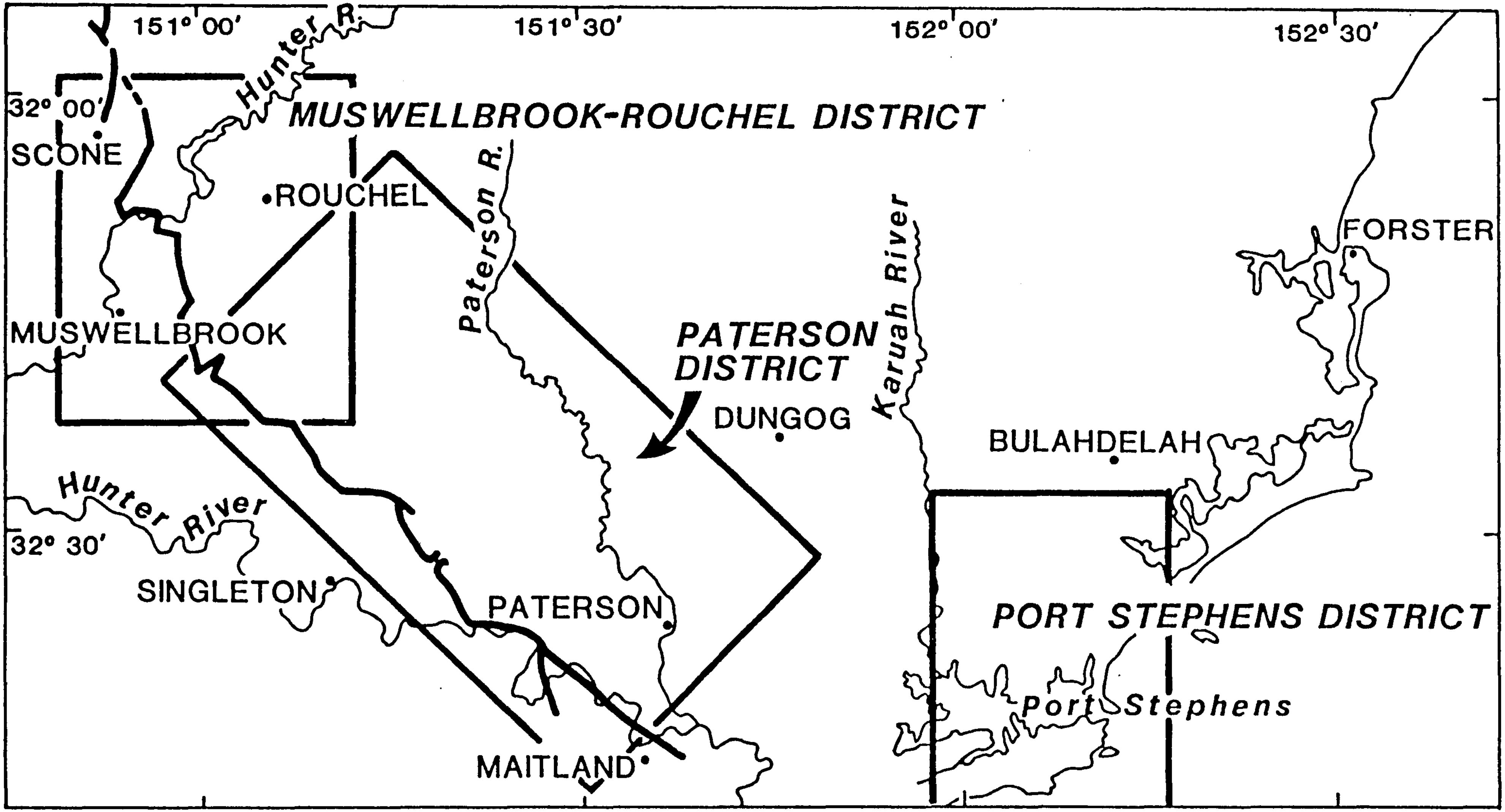
1.2 THESIS FORMAT

The format of this thesis departs slightly from a normal thesis. The aim here, in preparing and presenting this research, is to have it ready for publication at the same time as having it ready for binding in the thesis. As a consequence, the general layout of the thesis is as Macquarie University regulations demand, but the main body of the thesis is not in true thesis format. i.e. the body of the thesis is in chapters, as the regulations require, but each chapter, as a distinct part of the study, is written in the accepted form of research papers.

This first introductory chapter consists largely of previously published material to provide the necessary background information on which this study is based. This includes a description of the aims and scope of the study, the location of the study area, and the tectonic and geological setting of the study area. Following this introduction, are four chapters (papers) that all relate to the central aim and theme of the thesis as explained in Chapter 1.1. Each paper (chapter) contains its own introduction, summary of previous work, results, discussion, conclusions, and bibliography. The papers are planned to be submitted to different journals but at this time all of the papers are written in the format of the *Australian Journal of Earth Sciences*. Paper 1 (Chapter 2) is to be submitted to the *Australian Journal of Earth Sciences*, and Paper 2 (Chapter 3) to the *Bulletin of Volcanology*. Paper 2 duplicates a little of the data presented in Paper 1 but two different reader audiences are reached by these two journals.

FIGURE 1.1

The three map areas of study in this thesis.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Paterson R.
Karuah River
FORSTER
MUSWELLBROOK
PATERSON
DISTRICT
DUNGOG
BULAHDELAH
Hunter River
SINGLETON
PATERSON
PORT STEPHENS DISTRICT
Port Stephens
MAITLAND

Paper 3 (Chapter 4) is planned to be sent to the *Journal of Volcanology and Geothermal Research* and Paper 4 (Chapter 5), to the *Australian Journal of Earth Sciences* as well.

Following a concluding chapter, the final part of this thesis consists of extended appendices which contain all of the data gathered or used in this research. This includes sample localities, flow lineation data (methods, statistics and rose diagrams), previous chemical analyses, computer programs, and some lithological and mineralogical notes.

1.3 THE STUDY AREA

The study area is bounded by longitudes 150° 25'E and 152° 30'E and latitudes 32° 00'S and 32° 45'S and it is situated on the eastern and northern side of the Hunter River Valley in New South Wales, Australia. Three map districts are considered in detail and they have been termed the Muswellbrook-Rouchel District, the Paterson District, and the Port Stephens District (Fig 1.1). These areas extend for a combined distance of about 170 km, from approximately 10 km north of the township of Scone, south to Port Stephens.

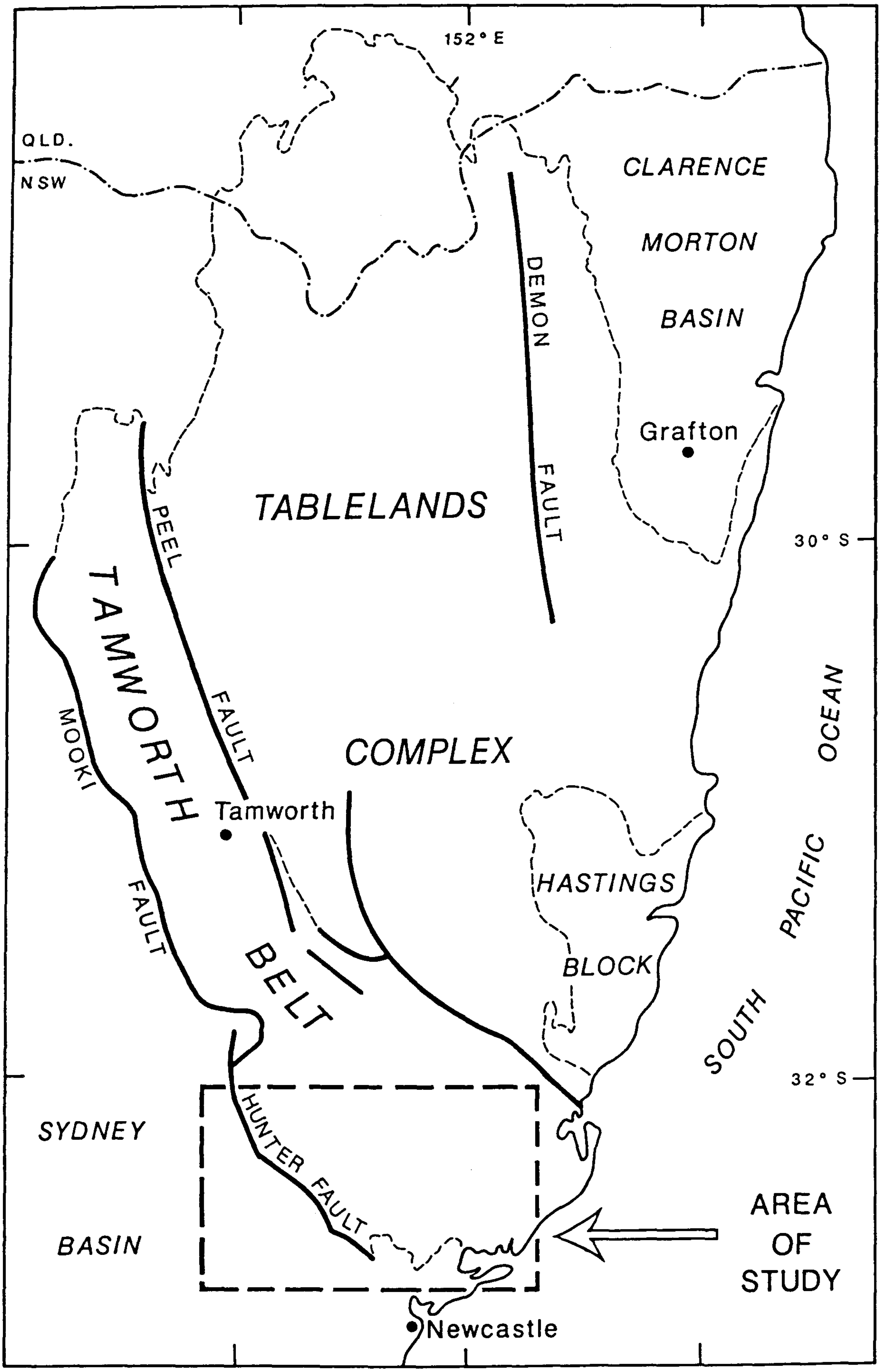
1.4 GEOLOGICAL SETTING

A detailed 1:50,000 geology map of the Rouchel District has been presented by Roberts and Oversby (1974) and 1:100,000 geology maps of the Hunter-Myall region are soon to be published (Roberts and Engel, In press). These cover the Paterson District and northern part of the Port Stephens District. I thank Professor John Roberts, from the University of New South Wales, who made preliminary copies of these maps available to me as it was the availability of these maps that made this area most suitable for this study.

The study area lies at the southern end of the Tamworth Belt along the eastern side of the New England Orogen (Fig

FIGURE 1.2

The study area with respect to the major tectonic elements of the New England Orogen.


152° E
QLD.
NSW
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MORTON
BASIN
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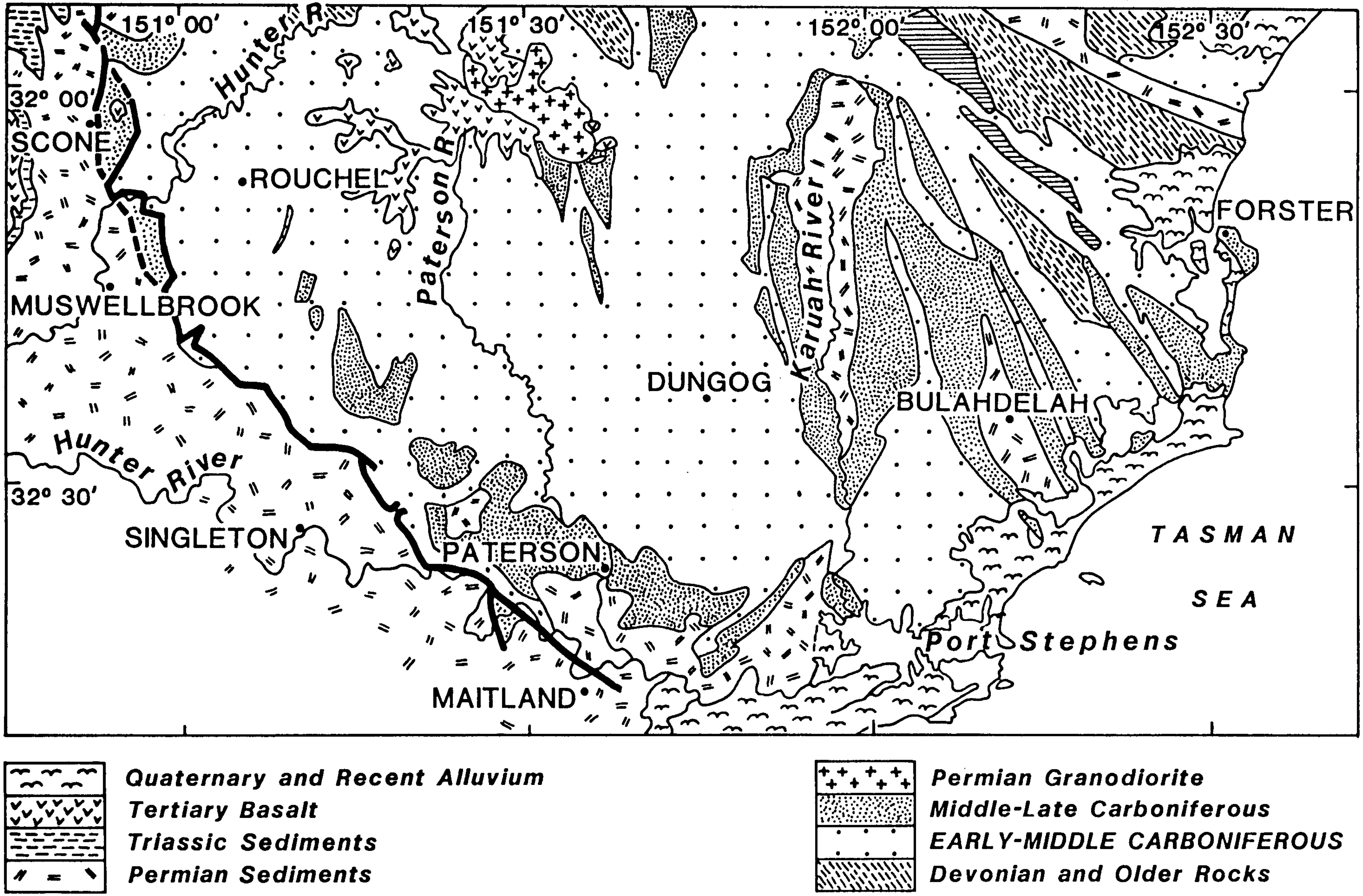
Grafton
TABLELANDS
PEEL
FAULT
30° S
TAMWORTH
BELT
MOOKI
FAULT
COMPLEX
Tamworth
HASTINGS
BLOCK
OCEAN
PACIFIC
SOUTH
32° S
SYDNEY
BASIN
HUNTER FAULT
AREA
OF
STUDY
Newcastle

FIGURE 1.3

Generalised geological map of the southern part of the Tamworth Belt (after Roberts 1985b). The thick black line is the Hunter Fault System.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Hunter R.
Hunter River
Paterson R.
Karuah River
SCONE
ROUCHEL
MUSWELLBROOK
DUNGOG
BULAHDELAH
FORSTER
SINGLETON
PATERSON
MAITLAND
Port Stephens
TASMAN
SEA
Quaternary and Recent Alluvium
Tertiary Basalt
Triassic Sediments
Permian Sediments
Permian Granodiorite
Middle-Late Carboniferous
EARLY-MIDDLE CARBONIFEROUS
Devonian and Older Rocks

1.2). The Tamworth Belt, is bounded by the Hunter Fault System (including the Mooki Fault), and the Permo-Triassic Sydney Basin sequence, to the west and south, and by the Peel Fault System to the east (Fig. 1.2). The Hunter Fault System consists of several sub-parallel, NW-SE trending faults which occur mainly in the Carboniferous strata, although some faults also displace parts of the adjacent Permian Sydney Basin strata. Roberts and Engel (1987) describe about 40 km of the "Hunter Fault" between Muswellbrook and Singleton as a low angle (13^{o}), northeast dipping thrust, with the Carboniferous succession being thrust over the Sydney Basin strata. But east of this low angle thrust area, the "Hunter Fault" diminishes in importance and dies out completely near Maitland.

Although the Hunter Fault System consists of a set of sub-parallel, connecting faults, in <u>all</u> figures in this thesis it is simply depicted by a line at the position that the Carboniferous succession and the Permian Sydney Basin sediments are juxtaposed.

The rock succession in the study area consists of stratified Devonian to Upper Permian sedimentary (marine and continental) and volcanic sequences which are intruded by small Lower Permian granitoids (Fig.1.3). This broad statement, and the generalised geological map (Fig.1.3) hide the actual complexities of the outcrop and stratigraphic relations of more than 40 Carboniferous formations defined in the southern part of the Tamworth Belt (Fig.1.4). However, these complexities have little bearing on this study and are therefore not described here. Roberts and Oversby (1974) and Roberts and Engel (In press) describe these details at length.

The Lower Carboniferous succession in the southern part of the New England Fold Belt is essentially a regressive sedimentary sequence which has a number of ignimbrites inter-bedded throughout it (Fig 1.4). The outcrop map of these ignimbrites (Fig 1.5) shows that they are largely confined to the western edge of the Tamworth Belt, close to the Hunter

FIGURE 1.4

Time-stratigraphic diagram of the Lower Carboniferous facies in the Tamworth Belt (after Roberts and Engel, 1987). Ignimbrites of this study (and shown on Fig. 1.6) are coloured red.

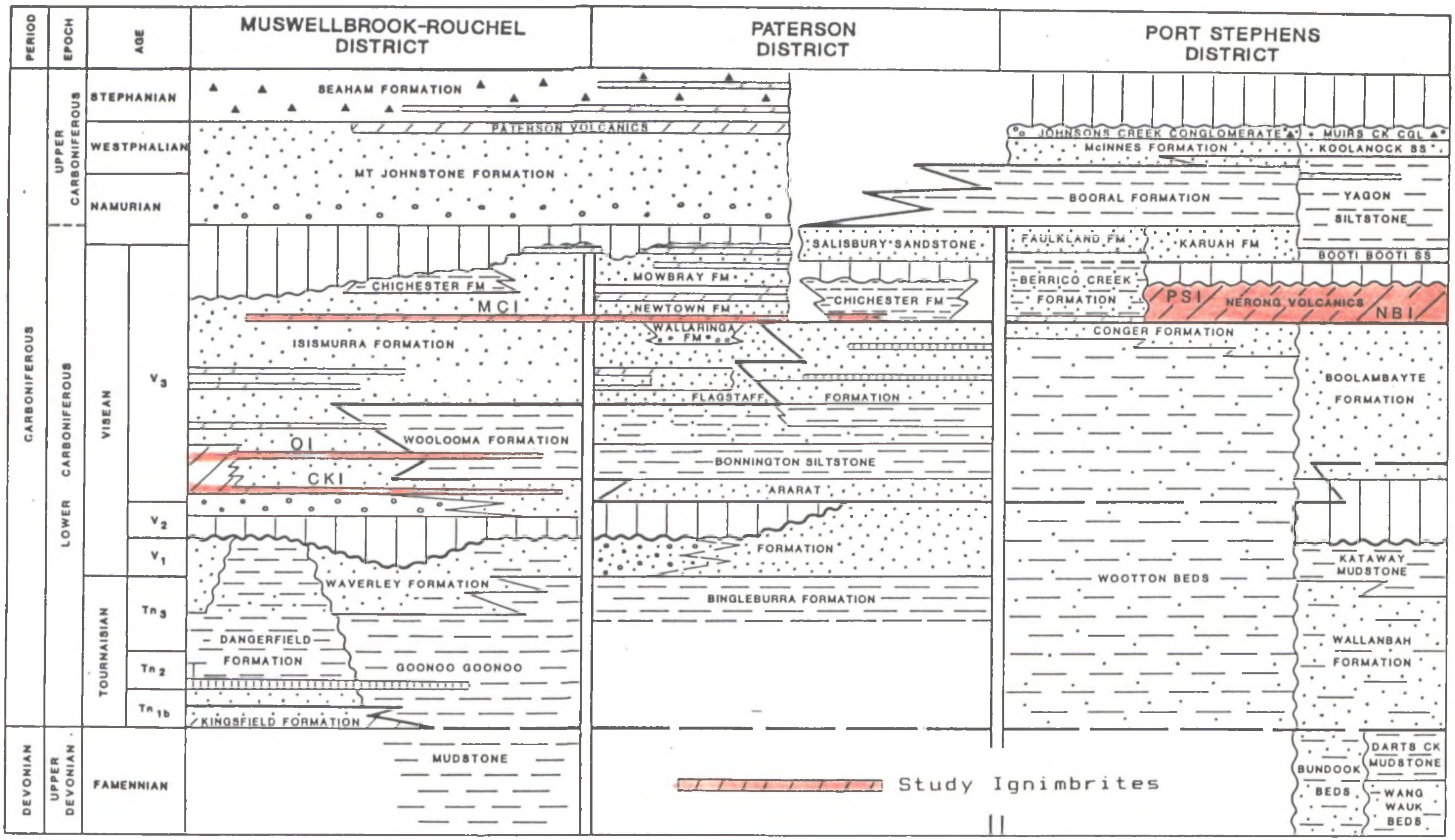
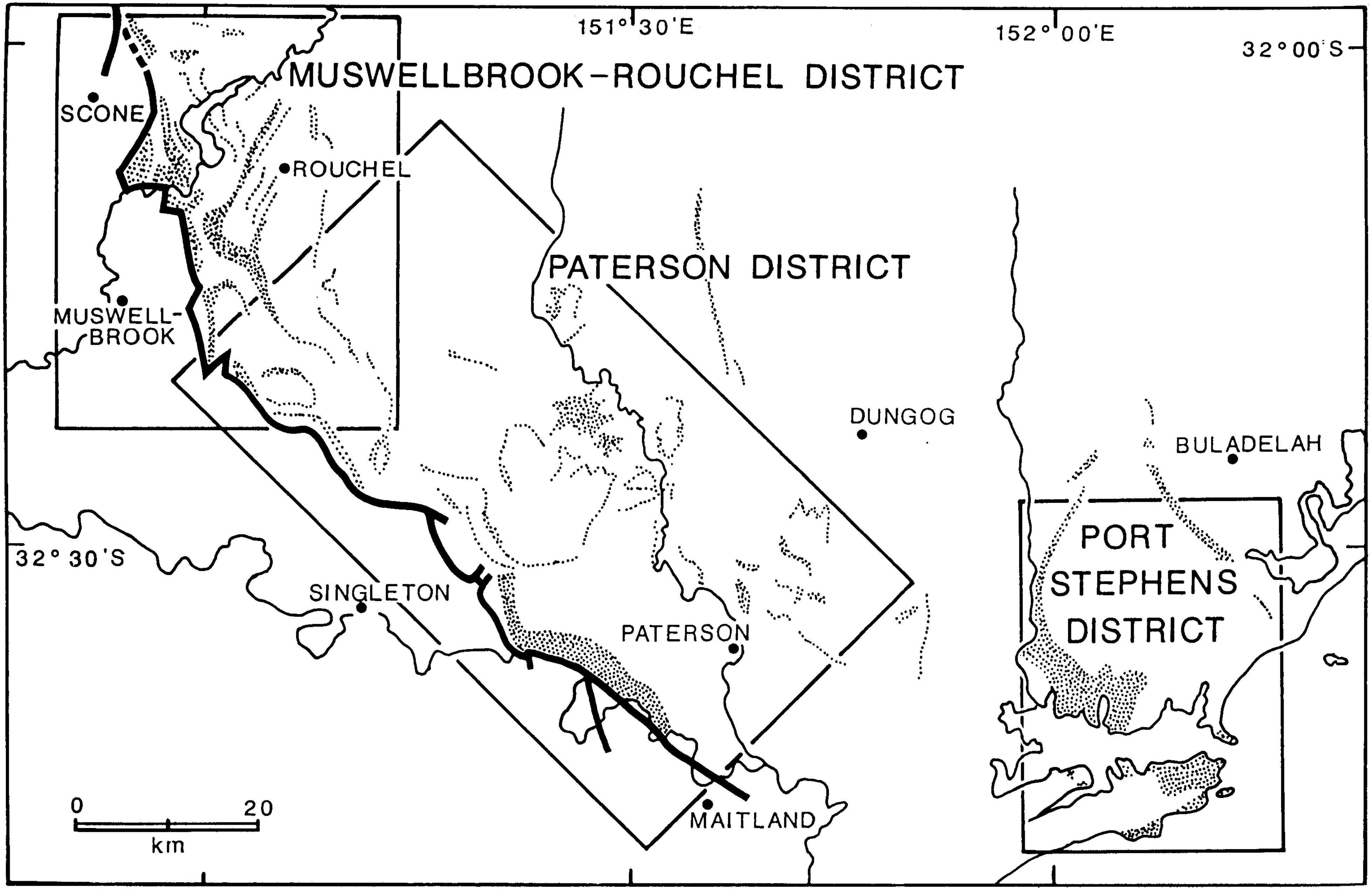

PERIOD
EPOCH
AGE
MUSWELLBROOK-ROUCHEL DISTRICT
PATERSON DISTRICT
PORT STEPHENS DISTRICT
CARBONIFEROUS
UPPER CARBONIFEROUS
LOWER CARBONIFEROUS
DEVONIAN
UPPER DEVONIAN
STEPHANIAN
WESTPHALIAN
NAMURIAN
VISEAN
TOURNAISIAN
FAMENNIAN
V3
V2
V1
Tn3
Tn2
Tn1b
SEAHAM FORMATION
PATERSON VOLCANICS
MT JOHNSTONE FORMATION
CHICHESTER FM
MCI
ISISMURRA FORMATION
OI
CKI
WOOLOOMA FORMATION
WAVERLEY FORMATION
DANGERFIELD FORMATION
GOONOO GOONOO
KINGSFIELD FORMATION
MUDSTONE
MOWBRAY FM
NEWTOWN FM
WALLARINGA FM
FLAGSTAFF FORMATION
BONNINGTON SILTSTONE
ARARAT
FORMATION
BINGLEBURRA FORMATION
SALISBURY SANDSTONE
CHICHESTER FM
JOHNSONS CREEK CONGLOMERATE
MUIRS CK CGL
McINNES FORMATION
KOOLANOCK SS
BOORAL FORMATION
YAGON SILTSTONE
FAULKLAND FM
KARUAH FM
BOOTI BOOTI SS
BERRICO CREEK FORMATION
PSI
NERONG VOLCANICS
NBI
CONGER FORMATION
BOOLAMBAYTE FORMATION
WOOTTON BEDS
KATAWAY MUDSTONE
WALLANBAH FORMATION
BUNDOOK BEDS
DARTS CK MUDSTONE
WANG WAUK BEDS
Study Ignimbrites

FIGURE 1.5

Map showing the outcrops of the Lower Carboniferous ignimbrites (stipple). Thick black line is the Hunter Fault System.



151° 30'E
152° 00'E
32° 00'S
MUSWELLBROOK-ROUCHEL DISTRICT
SCONE
ROUCHEL
PATERSON DISTRICT
MUSWELL-BROOK
DUNGOG
BULADELAH
32° 30'S
PORT STEPHENS DISTRICT
SINGLETON
PATERSON
MAITLAND
0
20
km

Fault System.

A study of the six most widespread silicic ignimbrites form the basis of this thesis and their position in the regional stratigraphy is shown in Fig. 1.4. The oldest of the ignimbrites are early Viséan in age and they occur within the Isismurra Formation in the Muswellbrook-Rouchel District. They have been named herein the Curra Keith ignimbrite, Oakfields ignimbrite, and M^{c}Cullys Gap ignimbrite. The Martins Creek ignimbrite, of Late Viséan age, crops out mostly in the Paterson District within the Newtown Formation although it also extends into the Muswellbrook-Rouchel District where it is the uppermost ignimbrite in the Isismurra Formation. The base of the Nerong Volcanics, in the Port Stephens District, is regarded as equivalent in age with the Martins Creek ignimbrite (Roberts and Engel, In press) and within the Nerong Volcanics are two very widespread ignimbrites, interbedded with volcaniclastic sediments, which have been named herein the Port Stephens ignimbrite and Nelson Bay ignimbrite.

Descriptions of these six ignimbrites and their enclosing epiclastic rocks are given at appropriate places in the thesis.

1.5 TECTONIC SETTING

In the accepted terminology of the tectonics of eastern Australia the study area lies in the southern part of the Tamworth Belt of the New England Orogen (Fig 1.2), the easternmost and youngest part of the Palaeozoic Tasman Fold Belt.

From the 1920's approximately 400 research papers and theses have been written on aspects of the New England Fold Belt and, as a consequence of this profusion of literature, the terminology and names of individual tectonic components have changed repeatedly. As a general rule, most of these publications expound a slightly different view of the Fold Belt's development and it is therefore difficult for the

TECTONIC ELEMENT	YARROL OROGEN	NEW ENGLAND OROGEN
VOLCANIC REGION	Connors-Auburn Arch	Kuttung Volcanic Chain
SHELF	Yarrol Shelf	Tamworth Shelf
SLOPE AND SUB-DUCTION COMPLEX	Wandilla Slope and Basin	Woolomin Slope and Basin

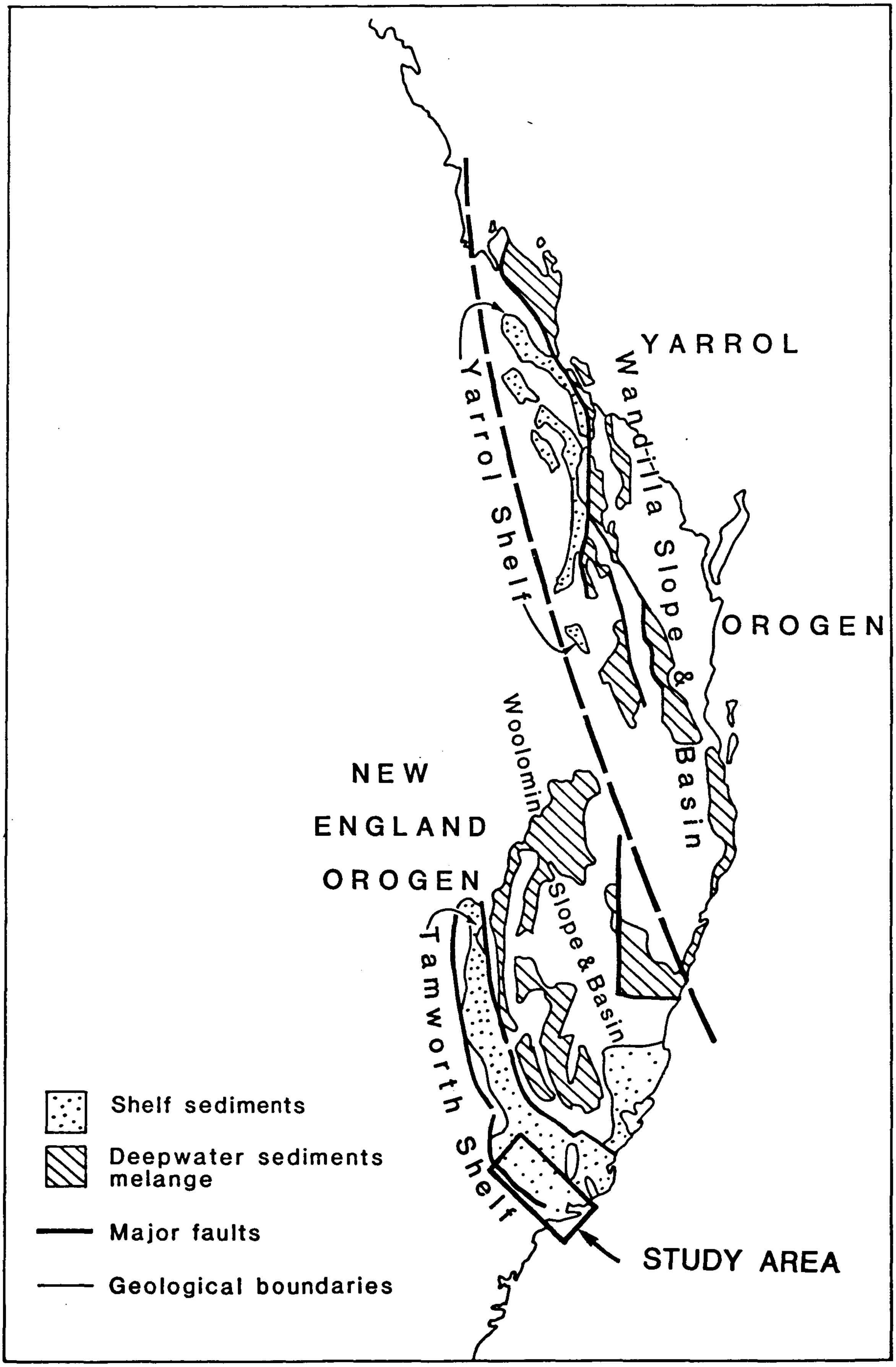
TABLE 1.1
Palaeogeographic names given to the major tectonic elements of the Yarrol and New England Orogens in the New England Fold Belt as recorded in Roberts and Engel (1980), except the Kuttung Volcanic Chain is defined in this thesis.

outsider to learn any details of the tectonics of the New England Fold Belt quickly. The most recent publications concerning the tectonic development of the New England Orogen (Harrington and Korsch 1985; Murray *et al* 1987; Roberts and Engel 1987) summarize much of the earlier work and included extensive reference lists. The aim here therefore, is to give to the outsider a brief synopsis of the New England Fold Belt and cite the most significant contributions to the understanding of the Fold Belt that have been published within the last decade or so.

The New England Fold Belt is usually transversely divided into two main components, Day *et al* (1978) naming the southern part, the New England Orogen, and the northern part, the Yarrol Orogen (Fig.1.6). The naming of these two parts of the fold belt as orogens has held favour for over a decade, but recently (Murray *et al* 1987) considered them as provinces in a single orogenic unit since according to them, both of the orogens "have a similar stratotectonic and structural history". These similarities were first examined by Day *et al.* (1978), who stated that both orogens consisted of essentially three stratotectonic elements: a western volcanic arc, a central narrow continental shelf or unstable forearc basin; (Murray *et al.* 1987), and an eastern continental slope and ocean basin

FIGURE 1.6

The study area with respect to the major palaeo-enviromental provinces in the Tasman Fold Belt and the distribution of Carboniferous rocks in the New England and Yarrol Orogens (after Roberts 1985a). Note, the Woolomin Slope and Basin is referred to as the Tablelands Complex, and the Tamworth Shelf as the Tamworth Belt in this thesis.


YARROL
OROGEN
Wandilla Slope & Basin
Yarrol Shelf
Woolomin Slope & Basin
NEW
ENGLAND
OROGEN
Tamworth Shelf
STUDY AREA
Shelf sediments
Deepwater sediments melange
Major faults
Geological boundaries

REFERENCE	TECTONIC UNIT	
Korsch (1977)	Tamworth Belt	Tablelands Complex
Leitch (1974)	Zone A	Zone B
Depositional Environment	Terrestrial and shallow Marine	Deep Marine
Deformation	Moderate	Severe
Metamorphism	Burial	Regional
Granite Intrusions	Uncommon	Widespread

TABLE 1.2
The principal differences between the two major subdivisions in the New England Orogen (after Leitch, 1974).

presumably with a trench and related to a west dipping subduction zone (Table 1.1). Murray *et al.* (1987) postulated that the present 200 km of dextral displacement of the Yarrol Orogen from the New England Orogen (Fig 1.6) is best explained by large-scale transform faulting in the Middle and Late Carboniferous. The Yarrol Orogen has no bearing on this thesis so that it is considered no further.

The volcanic region that formed along the western edge of the New England Orogen, was active during much of the Carboniferous, and it was called a volcanic chain by Leitch (1975) However, more recently it has been named the Kuttung Arc by Harrington and Korsch (1985). This thesis, examines the concept of a volcanic chain versus a volcanic arc and it finds that in the soutern part of the New England Orogen, at least, is best called a volcanic chain. It is thus named herein as the Kuttung Volcanic Chain (Table 1.1).

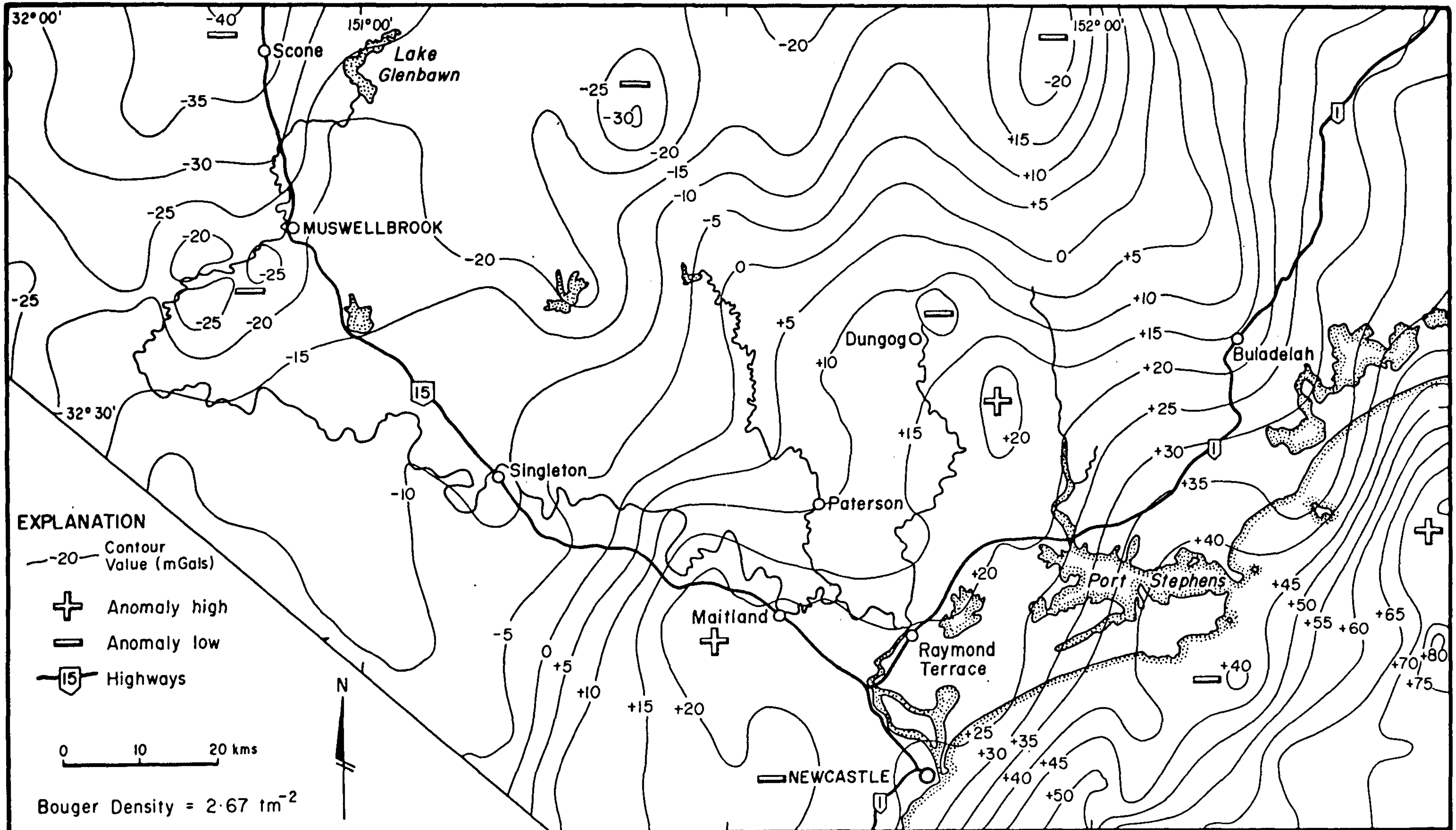
Korsch (1977) named the continental shelf [or forearc basin? (Murray *et al* 1987)] the Tamworth Belt, and the slope and basin and subduction unit the Tablelands Complex (Fig. 1.2). These are the preferred names used throughout this thesis. Note, however, that the Tamworth Belt has been termed the Tamworth Shelf (Fig. 1.6) in palaeogeographic studies (Day *et al* 1978; Roberts and Engel 1980), and the Tablelands Complex has had many names, including Woolomin-Texas Block (Scheibner 1973), Woolomin Slope and Basin (Day *et al* 1978), Central Complex (Roberts and Engel 1980), the Central and Southern Tablelands (Korsch and Harrington 1981), and the Texas-Woolomin Block (Murray *et al* 1987). Leitch (1974) first detailed the differences between the Tamworth Belt and the Tablelands Complex (Table 1.2) although, at that time, he simply referred to them as Zone A and B respectively.

The Tamworth Belt existed from the Late Devonian to the Early Permian (McPhie 1982; Roberts and Engel 1987) with the Kuttung Volcanic Chain lying along its western edge. It was a region of shelfal sedimentation and it received both fluvial and shallow marine sediments in the west, and it deepened towards the bounding Peel Fault in the east. The Tablelands Complex, on the other hand, was originally a continental slope and basin province (Day *et al* 1978; Roberts and Engel 1980) which received deep oceanic sediments that were accreted in a stack of thrust sheets (Murray *et al* 1987) as part of a subduction complex (Cawood 1982; Flood and Fergusson 1982; Fergusson 1984; Fergusson and Flood 1984)

A recent contribution to the tectonic history of the Tamworth Fold Belt was provided by Klootwijk (1985). He indicated that (palaeo)magnetism in the Lower Carboniferous (Viséan) volcanics in the Muswellbrook-Rouchel District (in the study area), had low inclination and this disclosed that these rocks were initially magnetised close to the equator. On the other hand, rocks of similar age within the Australian Craton in North Queensland, were shown to have been magnetised (initially) at about 30^{o} south. If this palaeomagnetic data from altered Carboniferous rocks is accepted as being accurate, then the Yarrol-New England Orogen was, during the Carboniferous, a separate terrane that was located north of the Australian continent (craton). This terrane is suggested to have "docked" with the craton prior to the end of the Carboniferous, before deposition of the Namurian Spion Kop

FIGURE 1.7

Bouger gravity map of the southern part of the New England Orogen. The Hunter Fault is not shown but it virtually runs parallel to, and slightly east of Highway 15. Drawn from the preliminary, unpublished 1:50,000 Bouger Gravity map (based on the Singleton and Newcastle 1:25,000 topographic sheets) compiled by the Australian Bureau of Mineral Resources, Geology and Geophysics, Canberra.


32° 00'
151° 00'
152° 00'
32° 30'
Scone
Lake Glenbawn
MUSWELLBROOK
Singleton
Dungog
Paterson
Buladelah
Maitland
Raymond Terrace
NEWCASTLE
Port Stephens
15
1
-40
-35
-30
-25
-20
-15
-10
-5
0
+5
+10
+15
+20
+25
+30
+35
+40
+45
+50
+55
+60
+65
+70
+75
+80
EXPLANATION
-20- Contour Value (mGals)
Anomaly high
Anomaly low
Highways
0 10 20 kms
N
Bouger Density = 2·67 tm^-2

Conglomerate (in the northern New England Orogen) (Klootwijk 1985). The Spion Kop Conglomerate is the first sedimentary unit in the New England Orogen succession to contain cratonic sediments (Leitch and Willis 1982).

The most recent tectonic interpretations of the tectonic development of the New England Fold Belt have been in terms of tectonostratigraphic terranes (Scheibner 1985; Leitch and Scheibner 1987; Blake and Murchey 1988). The Tamworth Belt is considered as a single terrane of fore-arc (sediment) accumulation whereas the Tablelands Complex is divided into several fault-bounded terranes. Murray *et al* (1987) elaborated the views of many previous authors on the remarkable similarity between the New England Fold Belt (Fig. 1.2) and the convergent margin in western California. They modeled the development of the Fold Belt on the Californian example and Blake and Murchey (1988) developed the idea further and showed the likeness of the terranes in the 'Tablelands Complex' with terranes in the Californian Franciscan Complex. They conclude with the statement that "the late Palaeozoic New England Fold Belt .... had a tectonic history similar to that recently proposed for the late Mesozoic and early Cainozoic of California".

1.6 REGIONAL GRAVITY SETTING

Figure 1.7 is the Bouger Gravity map of the study area. There is an obvious regional slope to the gravity values, from a maximum of +80 mGals off shore of Port Stephens to a minimum of -40 mGal near Scone. This relates to the gradual thickening of the Australian continent crust westwards from the edge of the continental shelf.

A number of anomalies in the regional trend are present spaced throughout the region and attention is drawn here to negative anomalies, immediately southwest of Muswellbrook and southeast of Port Stephens, and the positive anomaly at Maitland. These anomalies have relevance with the locations of the ignimbrite sources determined in this study.

1.7 GRID REFERENCES

All grid references cited in this thesis refer to the 1,000 metre interval Australian Map Grid on the Australian 1:100,00 (and 1:25,000) topographic map series.

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CHAPTER 2

FLOW DIRECTION INDICATORS IN IGNIMBRITES DELINEATE AN LOWER CARBONIFEROUS VOLCANIC CENTRE IN THE UPPER HUNTER VALLEY, NEW SOUTH WALES, AUSTRALIA

2.1 ABSTRACT

Flow lineations and limited flow azimuths were determined for three extensive Lower Carboniferous outflow ignimbrite sheets (Curra Keith ignimbrite, M^{c}Cullys Gap ignimbrite and Oakfields ignimbrite), to determine the position of their eruptive centre. These ignimbrites are present within the Native Dog Member of the Isismurra Formation, and they crop out on the easternside of the Hunter Fault in the Muswellbrook-Rouchel District in the Hunter Valley, New South Wales. Flow lineations are determined by the statistical analysis of flow aligned crystal and pumice clasts on slabs of the ignimbrites that have been cut from the bedding plane (parallel to the foliation).

The determined flow lineations were projected until they intersected and distinct clustering of the intersection points occurs with each of the ignimbrites. The source area of the Curra Keith and M^{c}Cullys Gap ignimbrites was determined to have been located approximately 4 kms north of Muswellbrook and the source of the Oakfields ignimbrite to be about 12 kms south of Muswellbrook. These source areas lie on the western side of the Hunter Fault, where Permian strata of the Sydney Basin are now exposed at the surface. The source areas have been displaced relative to the outcropping ignimbrites by the Hunter Fault. However, the source areas lie on the eastern periphery of a nearly circular, mostly negative gravity anomaly which is inferred to outline a 15 - 20 kms diameter caldera. The caldera is likely filled with low density

pyroclastics and/or is underlain by low density 'granitic' rock, and it is now buried below the Sydney Basin strata. The coincidence of the gravity anomaly with the determined position of the sources of the ignimbrites suggests that displacement along the Hunter Fault, in this area, is either essentially vertical or that the lateral and thrust displacement, that occurs on the northern parts of the fault, is absent.

2.2 INTRODUCTION

Initial stimulus for this study began with the (production of the) detailed map of the Rouchel District (Roberts and Oversby 1974) which showed the Lower Carboniferous rock succession to contain several large-volume ignimbrites. The ignimbrites occur within a regressive sedimentary succession, where they are interbedded with terrestrial fluviatile and shallow-marine volcaniclastic sediments. Twelve or more ignimbrite units are present in the succession, which is predominantly composed of conglomeratic sands (that were) deposited on an alluvial fan or piedmont plain, from braided rivers (Isismurra Formation, Roberts and Oversby 1974). Three ignimbrite units were found to be far more extensive than any of the others and they crop out over almost the entire Rouchel District, and extend further south into the Muswellbrook area. These three ignimbrites, named the Curra Keith, Oakfields and McCullys Gap ignimbrites, were chosen to find their source as their extensive and consistent outcrop indicated that their flow were not influenced by a pre-existing topography and they were likely emplaced on a flat alluvial surface. Thus, modifications to the primary flow direction by secondary, post-emplacement flowage (rheomorphism) (which can occur on steep slopes after the ignimbrite comes to rest) (Wolff and Wright 1981: Suzuki and Ui 1982), was deemed to have been unlikely.

Roberts and Oversby (1974) argued, on the basis of south- and southwest-wards increases in both the degree of welding and thickness of the ignimbrites, that the source vent of the ignimbrites lay in that direction. Furthermore, it is now a generally accepted concept that the source of these ignimbrites were located on a volcanic chain which lay somewhere west of the outcropping ignimbrites (Harrington and Korsch 1985, Roberts and Engel 1987). But, the actual location of the volcanoes (vent sites), and the nature of the volcanic centres are unknown and this research aimed to qualify determine these unknowns.

This paper first describes the methods devised to determine the flow directions of the ignimbrites in the Muswellbrook-Rouchel District, and then discusses the way in which, and where the source volcano(es) of the ignimbrites were located.

2.3 PREVIOUS WORK

The determination of primary flow directions of pyroclastic flows has been successfully achieved in the past by the study of the primary fluidal textures in ignimbrites. Schmincke and Swanson (1967) first documented flow structures in ignimbrites after their study of the Miocene ignimbrites on Gran Canaria. Soon after, Elston and Smith (1970) developed a technique for statistically determining the flow directions of pyroclastic flows by measuring the preferred orientation of crystals and clasts in thin sections of the Pleistocene ignimbrites from the Valles Caldera. The methods of Elston and Smith were subsequently used by Rhodes and Smith (1972) and Aldrich (1976) to identify the flow directions of Oligocene ignimbrites on the Mogollon Plateau, New Mexico, by Sides (1981) for the Grassy Mountain ignimbrite in Missouri, U.S.A., by Suzuki and Ui (1981, 1982, 1983) for the Holocene Ata pyroclastic flow deposit, and Ui *et al.* (1983) for the Koya ignimbrite, both in southern Kyushu, Japan. Minmura (1984) and Potter and Oberthal (1987) have used the imbrication of pumice clasts to determine the flow directions of the Pleistocene pumice-flow tuffs near Bend, Oregon and the Otowi ash flows in the Jemez Mountains, New Mexico, respectively. Ellwood (1982) determined flow directions of Oligocene ignimbrites in the San Juan Mountains, Colorado by measuring magnetic susceptibility fabrics in the ignimbrites which were produced by the flow alignment of magnetic grains in the ignimbrites.

All of these previous studies of flow directions in ignimbrites deal with geologically 'young' ignimbrites, in that the oldest is Tertiary. Moreover, in each of these areas of study the actual source caldera of the ignimbrite was previously known or it actually cropped out. In contrast, the Lower Carboniferous ignimbrites in the Muswellbrook-Rouchel District are distinctly 'old' and they cannot be related to any exposed volcanic structure. Their eruptive centres is assumed to be displaced, relative to the present outcrop of the ignimbrites, by the Hunter Fault System and are assumed to be buried beneath the Permian sedimentary succession of the Sydney Basin.

2.4 REGIONAL GEOLOGY

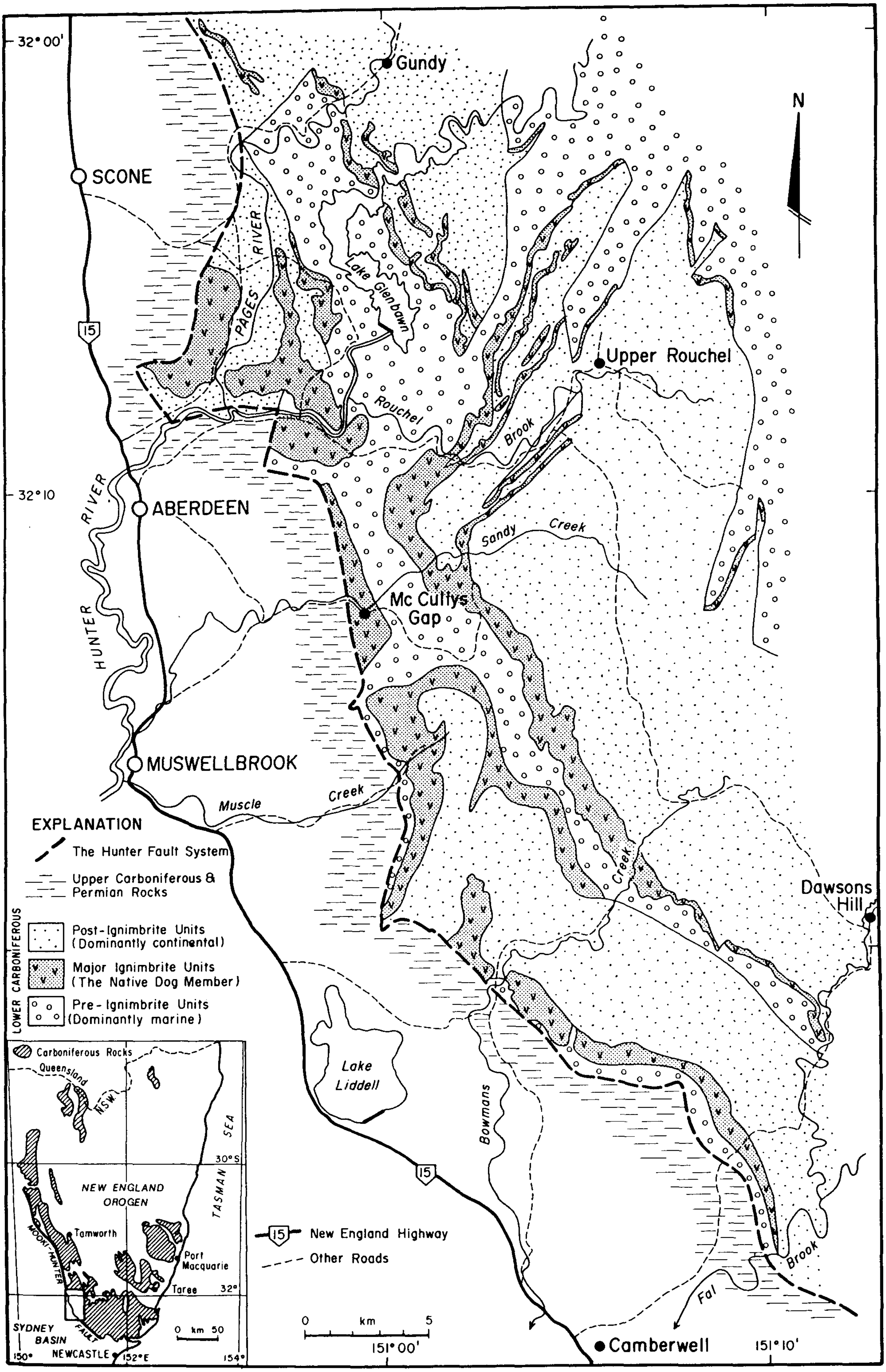
The Muswellbrook-Rouchel District (Fig. 2.1), in central eastern New South Wales, lies (essentially) within the southern part of the Tamworth Belt of the New England Orogen (Fig. 2.1, Inset). The western margin of the New England Orogen is the Hunter Fault System, which passes through the district in a arcuate north-northwest trend, just east of the townships of Scone, Aberdeen and Muswellbrook. It separates the Devonian-Carboniferous succession (Fig. 2.1) of the Tamworth Belt from the Permo-Triassic Sydney Basin succession.

Detailed mapping of the Muswellbrook-Rouchel District (Roberts and Oversby 1974; Roberts and Engel, In press) shows that the pre-ignimbrite succession is predominantly marine, consisting of sandstone, mudstone and limestone. Then, just prior to the volcanism the area was uplifted and terrestrial

FIGURE 2.1

Generalised geology map of the Muswellbrook-Rouchel District. The post-ignimbrite units also includes the syn-ignimbrite sediments.

Inset shows the position of the study area with respect to the outcrops of the Carboniferous succession in the New England Orogen in Eastern Australia.



32°00'
32°10
Gundy
N
SCONE
ABERDEEN
MUSWELLBROOK
Upper Rouchel
Mc Cullys Gap
Dawsons Hill
Camberwell
PAGES RIVER
HUNTER RIVER
Lake Glenbawn
Rouchel Brook
Sandy Creek
Muscle Creek
Creek
Bowmans
Fal Brook
Lake Liddell
15
EXPLANATION
The Hunter Fault System
Upper Carboniferous & Permian Rocks
LOWER CARBONIFEROUS
Post-Ignimbrite Units (Dominantly continental)
Major Ignimbrite Units (The Native Dog Member)
Pre-Ignimbrite Units (Dominantly marine)
Carboniferous Rocks
Queensland
N.S.W.
NEW ENGLAND OROGEN
TASMAN SEA
30°S
Tamworth
MOOKI-HUNTER FAULT
Port Macquarie
Taree
32°
SYDNEY BASIN
NEWCASTLE
150°
152°E
154°
0 km 50
New England Highway
Other Roads
0 km 5
151°00'
151°10'

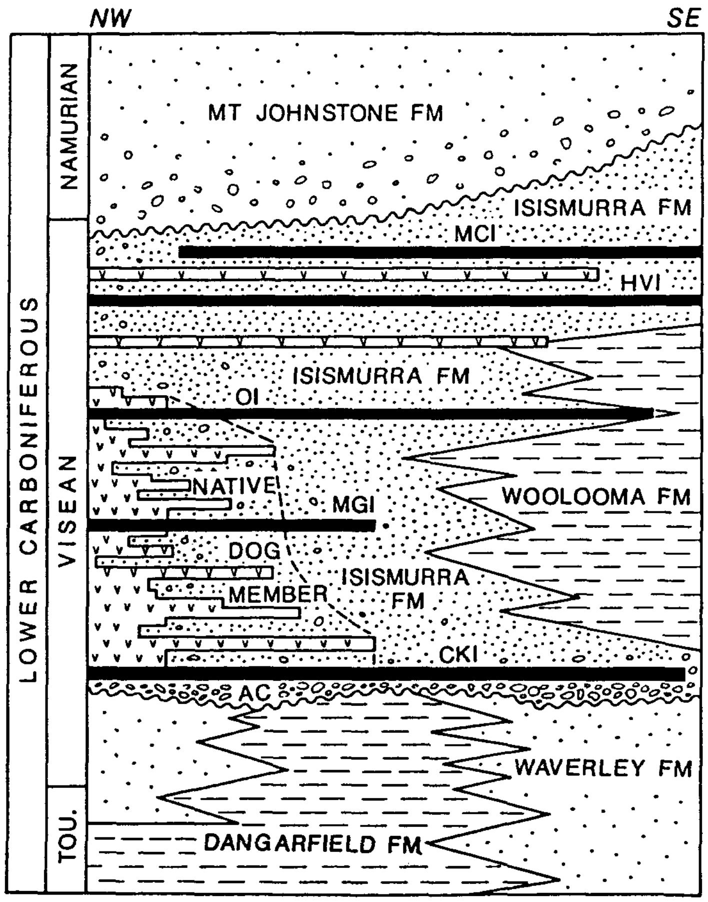


FIGURE 2.2

Time-space diagram of the stratigraphy in the Muswellbrook-Rouchel District (after Roberts and Oversby, 1974). AC = Ayr Conglomerate, CKI = Curra Keith ignimbrite, MGI = McCullys Gap ignimbrite, OI = Oakfields ignimbrite, HVI = Happy Valley ignimbrite, MCI = Martins Creek ignimbrite.

sedimentation and intermittent eruptions of ignimbrite, with incursions of marine sediments from the east, continued in the area until the end of Lower Carboniferous (Fig. 2.2). The generalised geology map of the Muswellbrook-Rouchel District (Fig. 2.1) omits the complexities of the stratigraphy shown in Fig. 2.2 and it simply shows the distribution of the pre-, syn- and post- ignimbrite strata in the area.

2.4.1 Stratigraphy

A time-space diagram (Fig. 2.2) of the district based on the work of Roberts and Oversby (1974) shows an essentially regressive sequence through the Lower Carboniferous.

The pre-ignimbrite strata include the Dangarfield (Roberts and Oversby 1974) and Waverley (Manser 1968) Formations which are laterally equivalent units that transgress from one to the other in the central parts of the District around Upper Rouchel. The Dangarfield Formation consists of marine sandstones, shales and limestones whereas the Waverley Formation is essentially non-marine, to paralic sandstones and conglomerates.

The Isismurra Formation, named by Manser (1968), disconformably overlies the Waverley and Dangarfield Formations and it is the equivalent of, and the modern name of the Kuttung Series (Sussmilch and David 1919) that Osborne (1928a & b, 1950) mapped in the Rouchel district. The lowest member of the Isismurra Formation, and the unit upon which the ignimbrites were emplaced is a coarse polymictic conglomerate named the Ayr Conglomerate (Roberts and Oversby 1974) . It contains abundant granite (up to 80%), ignimbrite, volcanic breccia and lithic sandstone clasts and it is assumed to be the product of initial uplift (and erosion) of the basement with the conception of volcanism in the west.

Conformably overlying the Ayr Conglomerate is the Native Dog Member (Roberts and Oversby 1974) which contains the most, and the greatest thickness of ignimbrites in the Isismurra Formation. Sandstone, pebbly sandstone and conglomerate are interbedded with the ignimbrites in the Native Dog Member and these sediments are little different from the underlying Ayr Conglomerate except that they contain more clasts of volcanic rocks and fewer of plutonic rocks. The Ayr Conglomerate and the Native Dog Member are both terrestrial units containing only rare plant fossils.

The Woolooma Formation (Roberts and Oversby 1974) is a sequence of shallow marine siltstone, mudstone and minor limestone which interfingers with the Isismurra Formation in the east. (The transition zone between the Woolooma Formation and the Isismurra Formation marks the position of the palaeo-shoreline in the Muswellbrook-Rouchel District in the Lower Carboniferous (Roberts and Oversby 1974; Roberts and Engel 1980)). The interfingering of the two formations indicates that there were fluctuating incursions of the sea into this area from the east at the same time as the volcanism in the west. Thin (20-30 cm) shard-rich tephra horizons, some of which can be mineralogically correlated to the Native Dog Member ignimbrites, occur throughout the Woolooma Formation. The most distal parts of the larger ignimbrites seem to transgress into the marine sediments and a 3 metre thick, planar bedded (reworked) volcaniclastic unit in the Woolooma Formation in the Upper Rouchel region is probably the marine equivalent of the Curra Keith ignimbrite. There is no evidence of any of the ignimbrites having been emplaced intact in a marine environment.

The Mount Johnstone Formation, first described by Sussmilch and David (1919), disconformably overlies the Isismurra Formation to the south of the Muswellbrook-Rouchel District. The basal disconformity occurs at about the Viséan-Namurian boundary and it marks the end of volcanism in the Muswellbrook-Rouchel District. A conglomerate layer at the base of the Mount Johnson Formation grades upwards into lithic sandstone, pebble conglomerate, and siltstone and Roberts and Engel (1987) stated

"....the lower part of the Mount Johnstone Formation contains clastic material that was derived from the Australian continent west of the volcanic arc, which suggests that the arc by this time was no longer an eroding high area".

2.4.2 Structure

The Muswellbrook-Rouchel District has imposed upon it an intricate fault pattern which overprints a terrain of broad open folds that, according to Roberts and Oversby (1974) "occur within several geometrically interdependent blocks". Leitch (1974) described the Tamworth Belt, including the Muswellbrook-Rouchel District, as "mildly folded but intensely faulted". Figure 2.1 omits the complexities of structure since a detailed discussion of the faults and their inception is included in Roberts and Engel (in press). Only the elements of structure that have relevance to this study are discussed here.

FIGURE 2.3

Logans Mountain, viewed west from Rouchel Road. This cuesta-type landscape is typical of the Muswellbrook-Rouchel District which reflects the strong geological control on the topography. Scarp faces are normally fault scarps and the low-angle dip slopes form on resistant beds of sandstone/conglomerate and ignimbrite.

The Hunter Fault is more appropriately called the Hunter Fault System since it is a network of several NW-SE trending, sub-parallel faults which occur mainly in the Carboniferous strata although several also displace parts of the adjacent Permian Sydney Basin strata (Summerhayes 1982). The relative sense of movement on most of the faults has been west or south side down. Roberts and Engel (1987) described the Hunter Fault in the Lake Liddell area (Fig. 2.1) as a low angle (13°), northeast dipping thrust, with the Carboniferous rocks thrust over the Sydney Basin strata. The line shown as the Hunter Fault on Figs. 2.1, 2.8, 2.9 and 2.10 is in detail several interconnecting faults that juxtapose the Carboniferous rocks and the Permian Sydney Basin sediments. This fault line is taken to be the western margin of the New England Orogen.

The Muswellbrook-Rouchel District is also characterised by extensive faults that have a north-northeast orientation which normally trend perpendicular to strike of the beds, and they terminate against the "Hunter Fault". Most of the faults contain, sometimes quartz-hardened, fault breccias, and rare slickensides show vertical movements only. No evidence has been found for strike-slip movement on the Hunter Fault System in this district nor on the many other faults that occur throughout the district. Roberts and Engel (1987) state that there is "little stratigraphic displacement between adjacent fault blocks" .

Many of the faults have decreasing throw along strike and this has broken the terrain into tilted fault-blocks where dips rarely exceed 30o, except where beds have been steepened immediately adjacent to some faults. These tilted fault blocks, with resistant ignimbrite and conglomerate units within them, exert control on the topography of the district and produce a cuesta-type landscape (Fig. 2.3).

The outcrop pattern of the Carboniferous strata in the Muswellbrook-Rouchel District (Fig. 2.1) is principally controlled folds. Fold axes, and strata, essentially trend parallel to the Hunter Fault, although in the Upper Rouchel area fold axes trend NE-SW. Roberts and Oversby (1974) describe the folds as plunging "gently to both the north and south at angles that do not exceed 10 degrees".

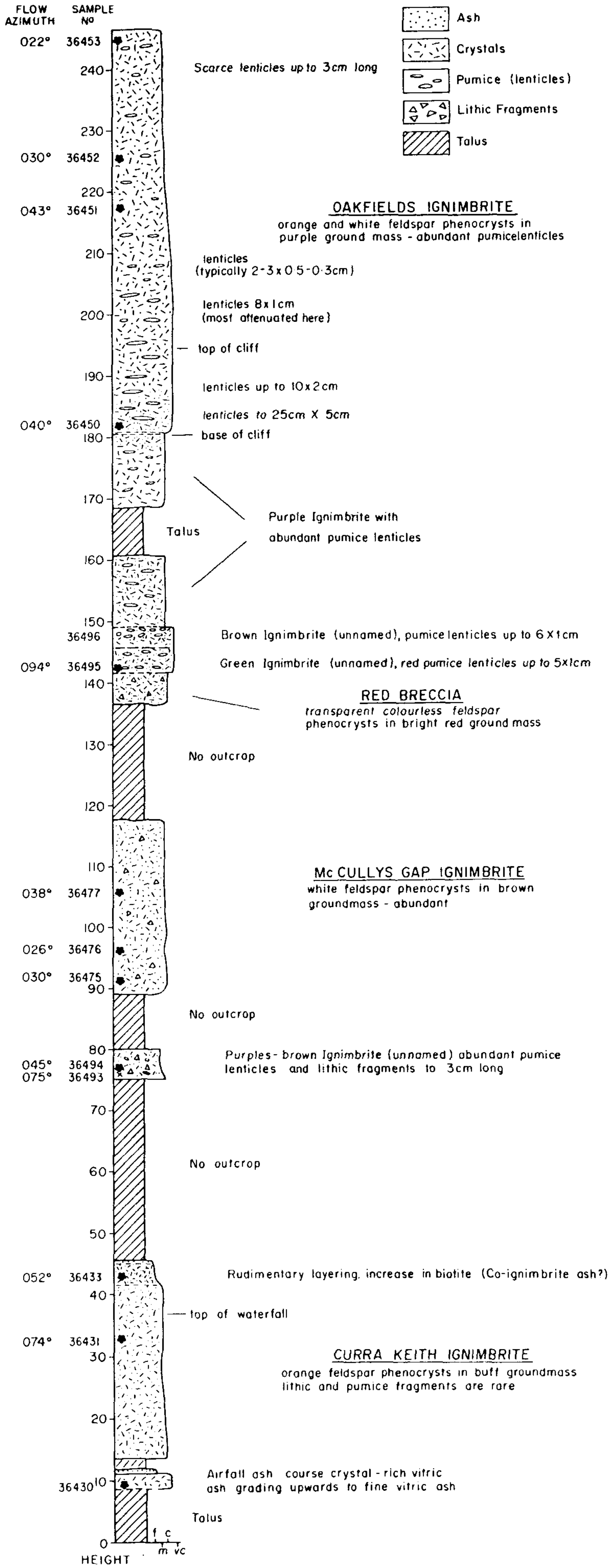
Folding in this part of the New England Orogen is considered by most workers to have taken place during the Late Palaeozoic Hunter-Bowen Orogeny and the faulting to have occurred both during and after that orogeny.

2.4.3 Metamorphism and Alteration

The Carboniferous succession in the Muswellbrook-Rouchel District is only mildly metamorphosed, so that the original rock structures are still largely intact. Immediately southwest of the Muswellbrook-Rouchel District, Offler and Diesel (1976) delineated three zones of metamorphism in the Carboniferous

Figure 2.4

Measured section through the Native Dog Member at Summer Hill, McCullys Gap (G.R. Rouchel Brook 123320-122316). Sample locations (*) and the flow azimuths determined from the samples are shown.


FLOW AZIMUTH
SAMPLE No
Ash
Crystals
Pumice (lenticles)
Lithic Fragments
Talus
022° 36453
Scarce lenticles up to 3cm long
030° 36452
043° 36451
OAKFIELDS IGNIMBRITE
orange and white feldspar phenocrysts in purple ground mass - abundant pumicelenticles
lenticles (typically 2-3 x 0.5-0.3cm)
lenticles 8x1cm (most attenuated here)
top of cliff
lenticles up to 10x2cm
lenticles to 25cm X 5cm
040° 36450
base of cliff
Talus
Purple Ignimbrite with abundant pumice lenticles
36496
Brown Ignimbrite (unnamed), pumice lenticles up to 6 X 1cm
094° 36495
Green Ignimbrite (unnamed), red pumice lenticles up to 5x1cm
RED BRECCIA
transparent colourless feldspar phenocrysts in bright red ground mass
No outcrop
McCULLYS GAP IGNIMBRITE
white feldspar phenocrysts in brown groundmass - abundant
038° 36477
026° 36476
030° 36475
No outcrop
045° 36494
075° 36493
Purples - brown Ignimbrite (unnamed) abundant pumice lenticles and lithic fragments to 3cm long
No outcrop
052° 36433
Rudimentary layering, increase in biotite (Co-ignimbrite ash?)
top of waterfall
074° 36431
CURRA KEITH IGNIMBRITE
orange feldspar phenocrysts in buff groundmass lithic and pumice fragments are rare
36430
Airfall ash course crystal - rich vitric ash grading upwards to fine vitric ash
Talus
f c m vc
HEIGHT
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240

rocks on the basis of zeolite mineralisation and variations in the reflectance of phytoclasts. In order of increasing grade the zones are 1. Clinoptilolite-heulandite, 2. Laumontite and 3. Prehnite. Following this zonation the rocks in the Muswellbrook-Rouchel District are in the clinoptilolite-heulandite zone.

In thin section the original vitreous components of the ignimbrites (shards and pumice) are usually wholly devitrified and often pseudomorphed by zeolites. Both the devitrification minerals and the original crystals of plagioclase are partially altered to sericite and zeolite, and hornblende and biotite are both altered to chlorite. In contrast, the same vitreous material in the interbedded sedimentary rocks and airfall tephras show only some replacement by zeolites, no devitrification and much less alteration, and both feldspar and mafic minerals appear 'fresh'. This indicates that devitrification (recrystallisation) of the ignimbrites probably occurred during or soon after their emplacement, probably as a result of slow cooling and vapour phase activity. The zeolites appear to have formed both during the later metamorphism and alteration. The tephras and epiclastic sediments have not undergone devitrification, probabaly due to their 'cool' emplacement, and have only been affected by metamorphism and alteration.

The main secondary minerals observed in the rocks of the Muswellbrook-Rouchel District are quartz (chalcedony), albite, sericite, illite, chlorite, rarely cela-donite, heulandite and probably mordenite.

2.5 <u>MAJOR IGNIMBRITE UNITS</u>

The Native Dog Member is a 300 metre thick volcanic sequence consisting largely of ignimbrites with thin interbeds of conglomerate, sandstone and ash-fall deposits. A measured section through the Native Dog Member in the McCullys Gap Area

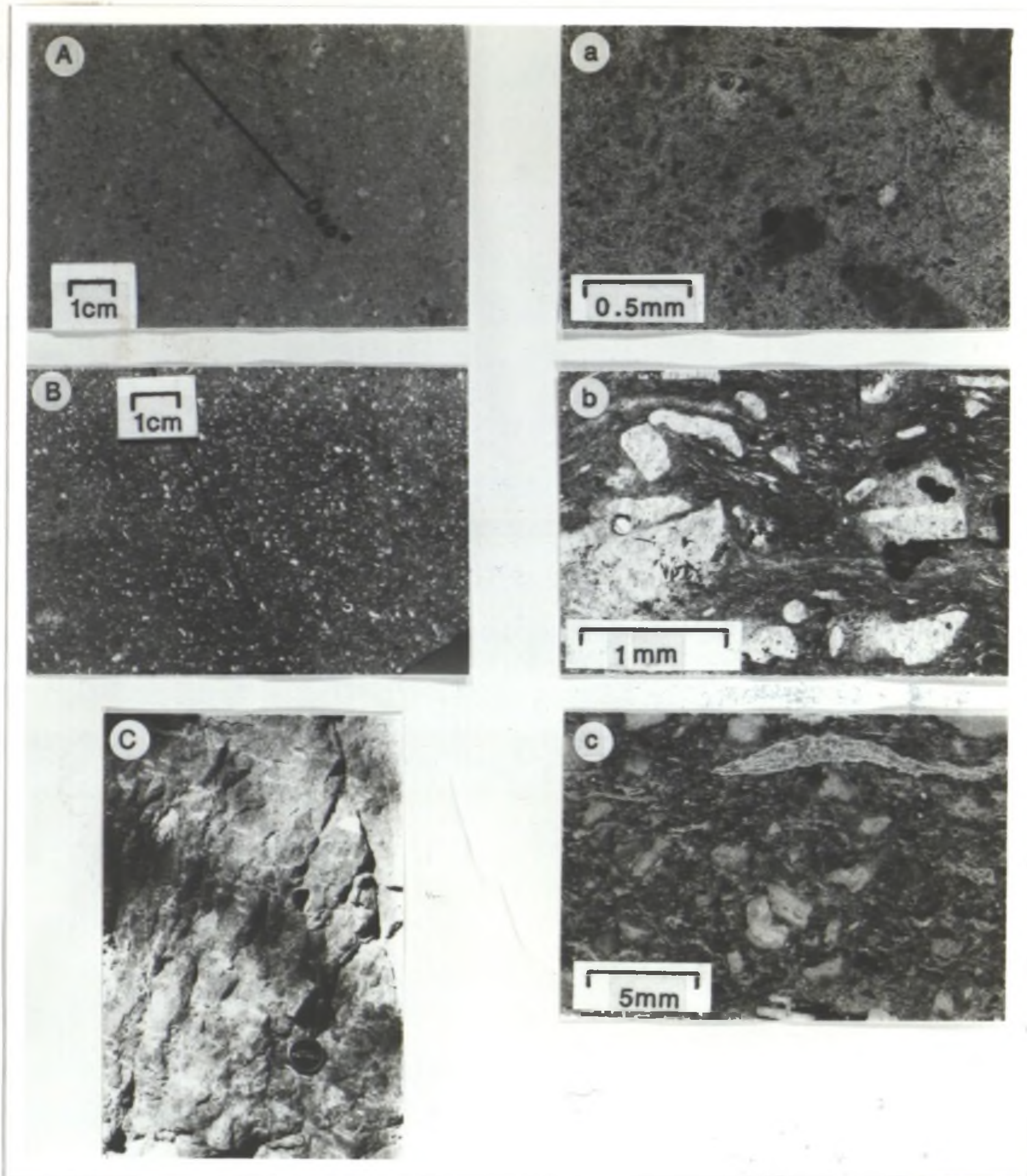


FIGURE 2.5

(A,a) Curra Keith Ignimbrite

(A) Bedding-parallel surface. Arrow shows the flow lineation and azimuth determined for this sample (MU 36417, G.R. Singleton 097552).

(a) Photomicrograph of bedding-parallel section, taken slightly out of focus to reveal the shard-rich matrix. Note the Y-shaped shards with long prongs in direction of flow. (MU 36411, G.R. Singleton 088462, Plane Polarised Light).

(B,b) McCullys Gap Ignimbrite

(B) Bedding-parallel surface. Flow lineation and azimuth is shown. (MU 36475, G.R. Rouchel Brook 122318).

(b) Photomicrograph of bedding-perpendicular section shows the ignimbrite to be densely welded, with the matrix shards deformed around the crystals. Determined flow direction is from right to left. (MU 36476, G.R. Rouchel Brook 122318, Plane Polarised Light).

(C,c) Oakfields Ignimbrite

(C) Cliff section at the base of the unit at the locality of Figure 2.4 showing the large pumice lenticles that are a feature of this ignimbrite (G.R. Rouchel Brook 122317).

(c) Photomicrograph of bedding-perpendicular section, shows the ignimbrite to be moderately welded with devitrified glass shards and flattened pumice. (MU 36443, G.R. Aberdeen 083410).

(Fig. 2.4) shows the relative positions of the ignimbrites in the member.

2.5.1 Curra Keith Ignimbrite (CKI)

The Curra Keith ignimbrite is the lowermost 'quartz-free' ignimbrite of the Curra Keith Tongue (Roberts and Oversby,1974) and it is the basal unit of the Native Dog Member.

Outcrops of the Curra Keith ignimbrite abut against the Hunter Fault northeast of the township of Muswellbrook and the unit extends to the northern and eastern edge of the Muswellbrook-Rouchel District (see Fig. 2.8). It is thickest adjacent to the Hunter Fault, where it has a measured thickness of 80 metres in the McCullys Gap area and it thins to a minimum of about 8 to 10 metres at Upper Rouchel. The Curra Keith ignimbrite is a rhyodacite (Chapter 4) and it characteristically contains up to 25 modal % orange (and sometimes white), highly sericitised andesine (An_{30}-An_{36}) crystals and crystal fragments set in a normally beige-coloured matrix (Fig. 2.5.A). Biotite crystals were originally present but they are now replaced (pseudomorphed) by chlorite and opaque oxides. The matrix of the ignimbrite is wholly devitrified to a finely crystalline mosaic of sericitised feldspar and opaque dust which partly masks an original partial to densely welded vitroclastic microstructure (Fig. 2.5.a).

A distinctive feature of the Curra Keith ignimbrite, besides a lacking of quartz crystals, is its fine grain-size, as it contains only rare lapilli-sized pumice and lithic fragments.

A fine grained and now cherty co-ignimbrite ash, enriched in vitric components, rests on top of the Curra Keith ignimbrite, in a quarry in this ignimbrite near Glenbawn Dam (Fig. 2.6).

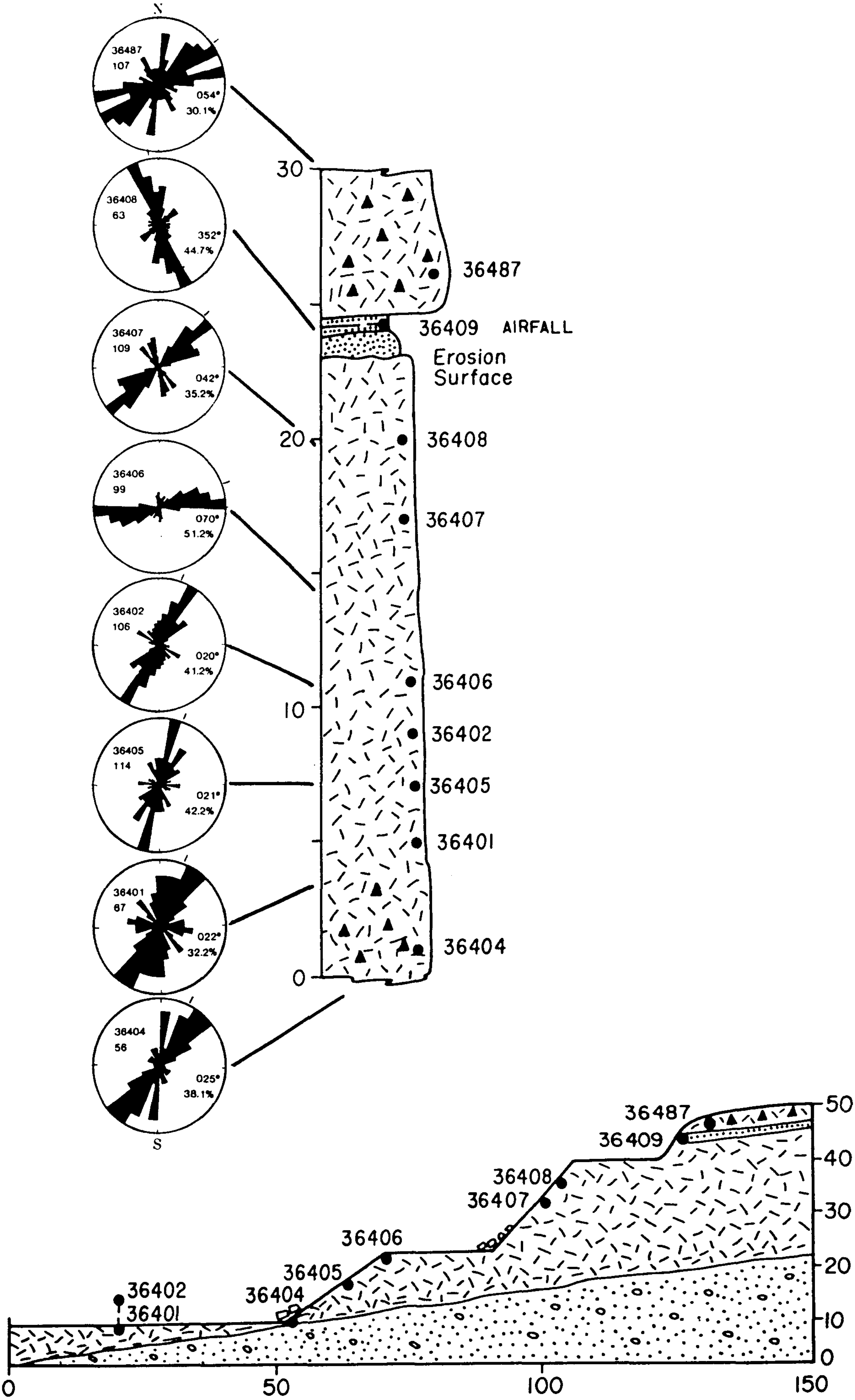
2.5.2 Oakfields Ignimbrite (OI)

The Oakfields ignimbrite is the uppermost ignimbrite of

Figure 2.6

Section through the now disused quarry in the Curra Keith Ignimbrite about 2kms west of Glenbawn Dam (GR Scone 086476). Lower diagram is a cross section of the quarry and the upper diagram shows a vertical column through the quarry. Solid circles denote sample locations, triangles represent lithic fragments. Scale is in metres.

The rose diagrams show the flow lineation detail determined for each sample; top left number is the sample number, bottom left number is the number of measurements, top right is the vector azimuth, and bottom left is the vector strength as a percentage. Small ticks outside the rose diagrams show the vector mean for the rose.


N
36487
107
054°
30.1%
36408
63
352°
44.7%
36407
109
042°
35.2%
36406
99
070°
51.2%
36402
106
020°
41.2%
36405
114
021°
42.2%
36401
67
022°
32.2%
36404
56
025°
38.1%
S
30
20
10
0
36487
36409 AIRFALL
Erosion
Surface
36408
36407
36406
36402
36405
36401
36404
36487
36409
36408
36407
36406
36405
36404
36402
36401
50
40
30
20
10
0
0
50
100
150

the Oakfields Tongue of Roberts and Oversby (1974) and it is the uppermost ignimbrite unit in the Native Dog Member.

The Oakfields ignimbrite is a purple, cliff-forming unit that crops out with a similar distribution to the Curra Keith ignimbrite, but it is more extensive in the southern parts of the Muswellbrook-Rouchel District (see Fig. 2.9). Its maximum thickness is at least 70 metres in the McCullys Gap Area (Fig. 2.4), and not 20 metres as recorded by Roberts and Oversby (1974). This ignimbrite is also a rhyodacite, very similar in chemistry to the Curra Keith ignimbrite (see Chapter 4). It has a distinctive purple coloured matrix, which contains abundant orange crystals and abundant lenticular pumice clasts (Fig. 2.5.C). In thin section, it has a slightly welded (deformed) eutaxitic texture (Fig. 2.5.c), and up to 20 modal % of the rock mass consists of orange zeolitised-sericitised andesine crystals, and biotite now largely altered to chlorite and opaque oxides. The lenticular pumice clasts form up to 35% of the ignimbrite and accidental lithic fragments constitute up to 15% of the rock mass in the lower parts of the flow in the McCullys Gap area (Fig. 2.4).

Welding in the Oakfields ignimbrite accords with the welding model described by Smith (1960) in that the greatest degree of welding (flattening) of pumice occurs about 10 metres above the base of the ignimbrite in the McCullys Gap section (Fig. 2.4), and welding decreases towards both top and bottom of the flow. It is invariably welded to some degree at the base of the unit but the upper few metres are essentially unwelded.

Sparks *et al* (1973) and Fisher (1979) interpreted inverse grading of pumice clasts in ignimbrites as a consequence of the added buoyancy of the larger pumice clasts, in a moving flow. The more dense lithic clasts, on the other hand, are normally graded as the larger denser clasts sink through the flow the most. The Oakfields ignimbrite exhibits normal grading of both pumice and lithic clasts. The pumices from zones of the ignimbrite where welding is almost absent, in thin section, have a dense fibrous appearance and low vesicularity, with narrow hair-like tubes that open at both ends to the exterior of the clasts. Thus, these features suggest that the pumice was probably abnormally "dense" (heavy) which caused it to behave in a similar manner to the lithic fragments.

2.5.3 McCullys Gap Ignimbrite (MCI)

Previously undifferentiated as a major outflow sheet in the Rouchel District, the McCullys Gap ignimbrite (new name) (Fig. 2.5.B) is also much more extensive than other ignimbrites in the Native Dog Member (Fig. 2.2). It is thickest at McCullys Gap, where it is at least 30 metres thick, and throughout the area of its outcrop (see Fig. 2.8) it shows little variation in thickness.

The McCullys Gap ignimbrite is a trachyte (see Chapter 4). It is conspicuous, in hand specimen, by having a brown matrix, which is invariably densely welded (Fig. 2.5.b). It contains up to 45 modal % yellowish-white andesine crystals and less than 5 % biotite crystals that are now replaced by chlorite and opaque oxides. Normally graded lithic fragments of a similar composition to the ignimbrite are abundant throughout the unit. Top and bottom contacts of this ignimbrite, similar to all of the ignimbrites in the Muswellbrook-Rouchel District, are rarely exposed, which made it impossible to determine meaningful lateral variations in the size of lithic fragments.

2.6 INVESTIGATION TECHNIQUES AND METHODOLOGY

2.6.1 Determination of Flow Lineations

Flow directions of ignimbrites have mostly been determined by employing the same methods of Elston and Smith (1970), who measured the preferred orientation of elongated crystals and pumice clasts (the flow lineation), resulting from primary flow, in oriented petrographic thin sections. However, it was found that the same crystal orientation measurements could be made on sawn slabs of the ignimbrites, using a specially adapted binocular microscope which reduced both sample preparation time and cost. As a consequence, the accuracy of the data obtained in this study, compared with the earlier work, was significantly increased. A description of methods used are in Appendix III.

Oriented samples of the ignimbrite were collected from the field and the flow lineation vectors were determined from the "bedding" plane in each sample. The bedding plane, in most samples, is also a flattening plane.

A tally of alignments of crystals and elongated pumice clasts was made directly from the cut bedding plane surface, using a specially modified binocular microscope (Appendix III). In the previous studies of flow lineations in ignimbrites only crystals with elongation ratios (length:width) greater than 2:1 were measured (e.g. Elston and Smith 1970; Rhodes and Smith 1972; Suzuki and Ui 1982). However, the large surface area of the slabs used in this study exposed significantly larger crystal populations to survey than those that can be obtained from thin sections, and it was thus possible to be more discriminating in the objects measured. Consequently, only "pencil-like", euhedral, prismatic crystals were measured, since they are the most affected and aligned by flow and no crystal was measured if it did not have at least a 3:1 length:breadth ratio. Elongated pumice lenticles were also measured. A new flow-alignment phenomenon that can be measured was discovered, as a consequence of the larger surface area of the ignimbrites being viewed,. A *crystal train* is a string of aligned crystals, which in themselves have no elongation, but the string has, and they are normally isolated within the matrix (Fig. 2.7). Each crystal string and pumice fragment measurement was considered equal to a single crystal measurement.

The vector mean, a statistically determined average of the

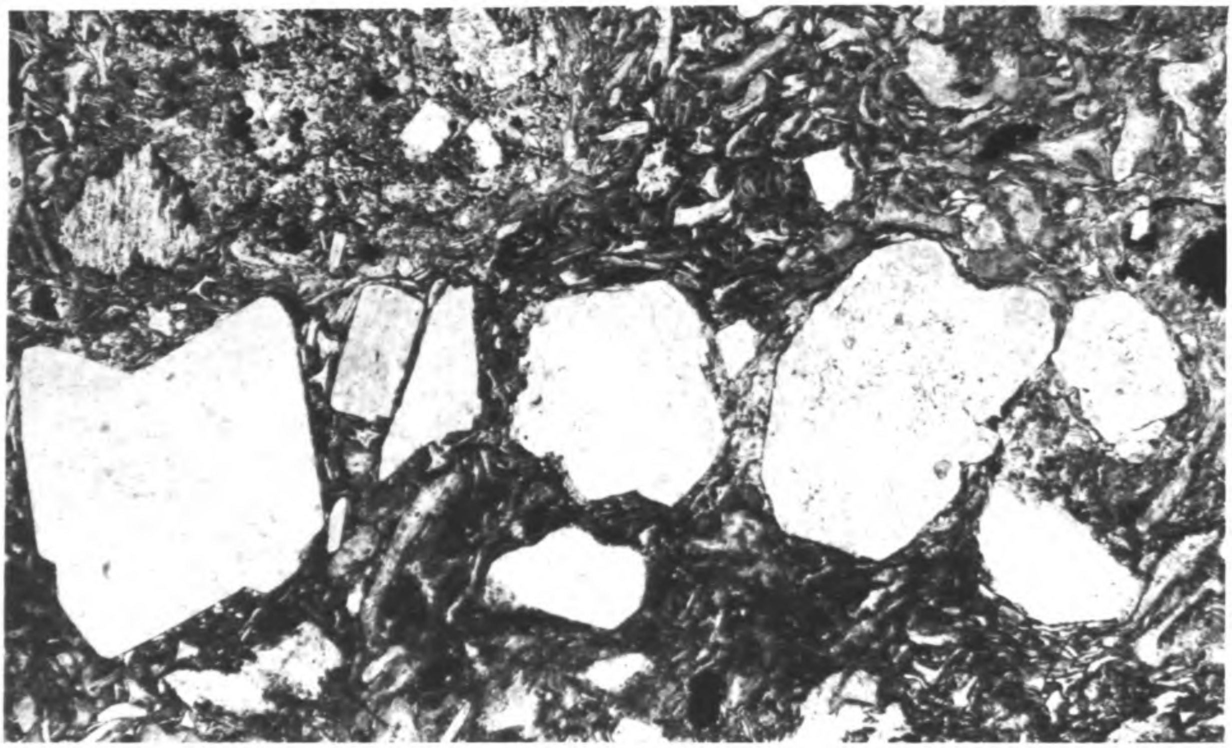


FIGURE 2.7

Photomicrograph of a crystal train, a measurable flow lineation structure in ignimbrites. (MU 36450, G.R. Rouchel Brook 122313, Image length 5.5 mm)

crystal orientations, was calculated for each sample. They were then corrected to account for tectonic tilt by stereographically rotating the bedding surface, back to the horizontal, about the fold axis. The corrected vector means are deemed the flow lineation and it is these that are shown on Figs. 2.4, 2.5, 2.6, 2.8 and 2.9.

2.6.2 Determination of Flow (Azimuths) Directions

While flow lineations could be obtained from all samples taken, it was not as easy to determine flow azimuths due to the alteration of the Muswellbrook-Rouchel District ignimbrites, which often obliterated any flow fabrics in the matrix. Elston and Smith (1970) defined six criteria that can be used to determine the direction of flow, namely (1) *Forked-shaped glass shards*, where one prong, longer than the others, points away from the source; (2) *Penetration effects*, where pumice fragments are deformed by more rapidly moving crystals orientated in the direction of flow; (3) *Blocking effects*, where small particles pile up behind larger, slower-moving fragments: (4) *Spindle-shaped objects*, which are aligned parallel to the flow lineation with their blunt ends facing toward the source; (5) *Eddy effects* similar to those reported by Cummings (1964) in rhyolite lavas, where large fragments develop eddy currents on their leeward sides; (6) *Imbrication of crystals and clasts*, where they dip back towards the source.

The first five of these criteria were successfully used to determine flow azimuths in this study but imbrication could not be used as post-emplacement compaction (induration) of the ignimbrites has flattened any imbrication that may have been present.

2.7 STATISTICAL TREATMENT

To compare the results of this study to those of Elston and Smith (1970) and others, the crystal-lineation data obtained in this study were analysed, using their Fortran IV program, provided to me by Professor Elston. This program, first, requires each set of data to be grouped into 10-degree class intervals and using the vector method (Krumbein 1939; Pincus 1956) it determines, for the set of data, the vector mean (flow lineation) and vector magnitude. It also carries out the Tukey Chi-Square test (Tukey 1954, in Middleton 1965) as well as a standard Chi-Square test.

The same sets of data were also analysed using a second program, which has evolved over a number of years, though various workers, at Macquarie University. This program treated the data individually without having to first group them in class intervals. It calculates vector mean and magnitude and it plots a rose diagram to illustrate the data set. Examples of the rose diagrams produced by this program are shown on Fig. 2.6, and the rose diagrams of all of the flow lineation data determined in the Muswellbrook-Rouchel District are presented in Appendix V.

Vector magnitude is a measure of dispersion about the vector mean and it is expressed as a value ranging between 0 and 100%. The statistical strength of the vector mean increases as the value increases, such that 100% indicates a perfect orientation and 0% indicates an entirely random orientation. The Chi-Square values denote the departures of the observed data from a completely random distribution and their significance is assessed at the 90% probability level. For 2 degrees of freedom and 90% probability, Chi-square equals 4.61 and any data sets with Chi-square values less than 4.61 are rejected.

2.7.1 Accuracy of the Data Obtained

Before accepting that flow lineations could be obtained and used to determine the flow directions of the Carboniferous ignimbrites in the Muswellbrook-Rouchel District, some preliminary tests were carried out, to determine the consistency and strength of the flow lineations that could be obtained.

The first test was to determine if a flow lineation could be duplicated from different slabs of the same sample. Two or sometimes three bedding-parallel planes were cut in 5 different samples of the Curra Keith ignimbrite and 5 samples of the Oakfields ignimbrite. Measurements of crystal lineations were made on all of the cut surfaces so that some samples had flow lineations determined from 6 different surfaces. It was found that the flow lineations determined on the surfaces on either side of the same cut were within 5^{o} of each other and those determined from all of the surfaces of a single sample were within 8^{o} of each other.

A second test was carried out to determine the variation of the flow lineations in several samples of the ignimbrite, from different vertical positions, in the same outcrop. This was considered to be of critical importance for further

Ignimbrite	No of Samples	Av Tukey Chi-Sq	Av Vector Strength (%)	Total Area (cm2)	Av Grain Counts
<u>Muswellbrook-Rouchel District</u>					
CKI	34 (1)	37.72	45	2952	88
MCI	10	24.89	36	1027	80
OI	28 (1)	41.87	48	2485	86
<u>Mogollon Plateau</u>					
RCR	18 (4)	17.91	23	?	91
ASQL	29 (4)	21.16	24	?	130

(4) = number of samples not significant at 90% confidence level

TABLE 2.1
Comparison of the flow lineation data obtained from the Carboniferous ignimbrites in the Muswellbrook-Rouchel District (CKI = Curra Keith ignimbrite, MCI = McCullys Gap ignimbrite, OI = Oakfields ignimbrite) with that from the Tertiary ignimbrites on the Mogollon Plateau, New Mexico (Rhodes and Smith 1972: RCR = Railroad Canyon Rhyolite, ASQL = Apache Springs Quartz Latite).

sampling, since Suzuki and Ui (1982) had shown that flow lineations in the lower parts of the Ata Pyroclastic Flow Deposit tended to lie parallel to the slope of the underlying topography, whereas in the upper parts of that flow they were aligned in the direction of flow.

Seven samples were collected from different levels of the Curra Keith ignimbrite in a disused quarry (Fig. 2.6) just west of Glenbawn Dam (which provides the only near complete section through an ignimbrite in the Muswellbrook-Rouchel District). The flow-lineations obtained from these samples agreed within 5° of each other in the lowest half of the flow unit but in the upper half of the flow, where the crystal sizes are smaller, the flow-lineations varied significantly and seemingly unsystematically (Fig. 2.6). A similar trend was found in four samples of the Oakfields ignimbrite, where the upper third of unit produced flow lineations that are askew from the lower two thirds (Fig.2.4). However this trend was not found in the McCullys Gap ignimbrite as it gave flow directions within 14°

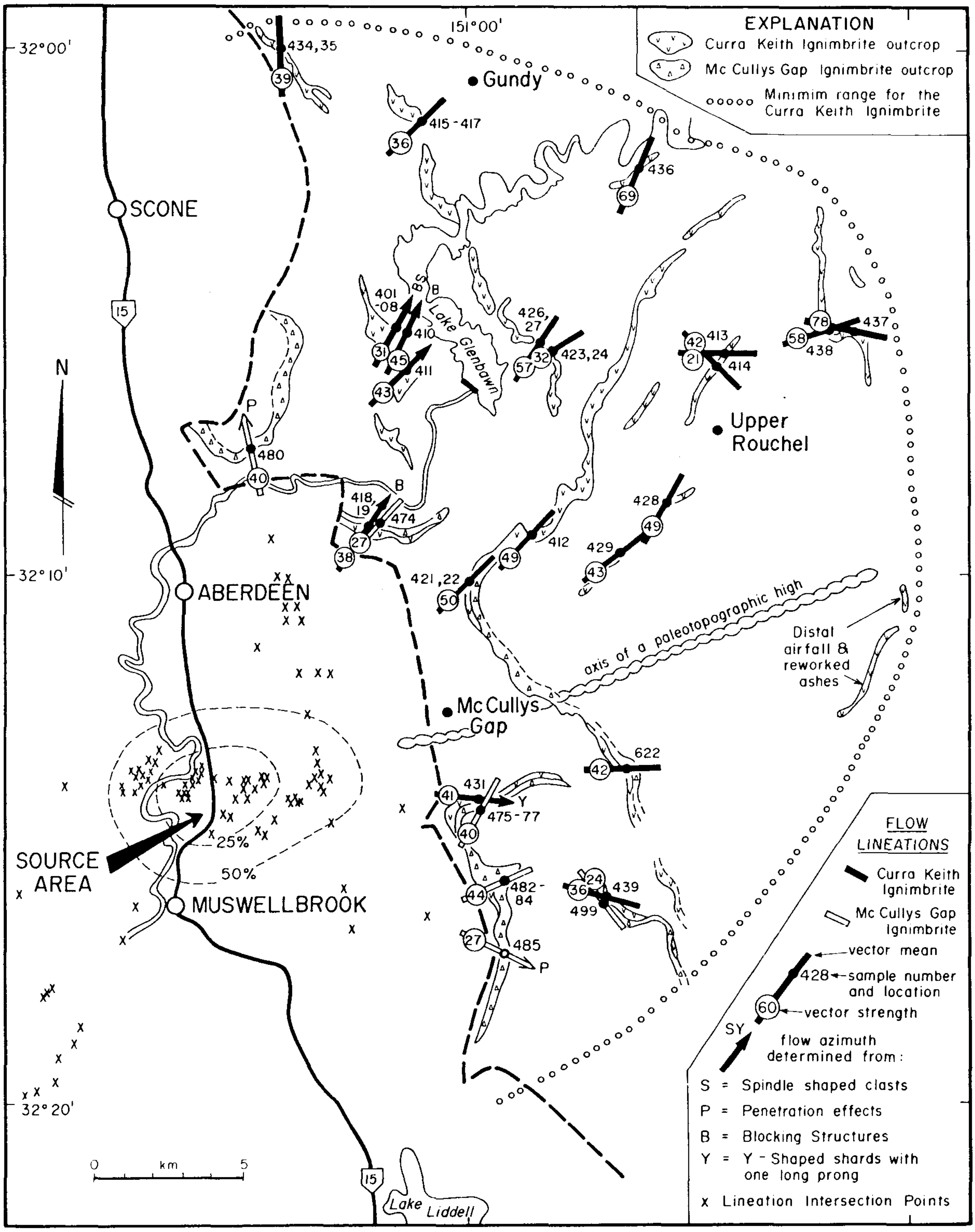


FIGURE 2.8

Palaeo-flow directions measured in the Curra Keith and McCullys Gap Ignimbrites. The source area of the ignimbrites has been determined by the intersections of the lineation vector means (see text).

of each other throughout its entire preserved thickness (Fig. 2.4).

Varga (1983) calculated that approximately 100 measurements of crystal orientations are needed to calculate a statistically significant flow lineation vector in ignimbrites, if the data are determined from thin sections. But the results presented here show that it is not the amount of data collected that determines the strength of the flow-lineation vectors obtained, but it is determined by the quality (the degree of spread) of the data . At least 100 measurements were aimed for in this study but even on some large slabs this was not always possible and the data were not rejected because of it. Smaller data sets were commonly obtained from samples of the distal parts of the flow units, where the crystal tend to be smaller and less abundant, as compared with the more proximal parts of the ignimbrites.

To show the relative strength of the results obtained in this study, where slabs rather than thin sections were used, Table 2.1 presents a summary of results obtained here and those obtained by Rhodes and Smith (1972) in their study of the Tertiary-aged ignimbrites on the Mogollon Plateau, New Mexico. There is no way of comparing the strength of individual lineations obtained in the two areas, without measuring a sample from each area using the same method, but it is noticeable from data in Table 2.1 that the 'slab' data has much greater statistical significance. This is demonstrated by the higher average vector strengths and Chi-square values of the Muswellbrook-Rouchel data, and the lower number of data sets rejected due to the calculated statistical parameters falling below the 90% confidence level.

2.8 RESULTS

2.8.1 Flow Lineation Patterns

Statistically acceptable flow lineations were determined

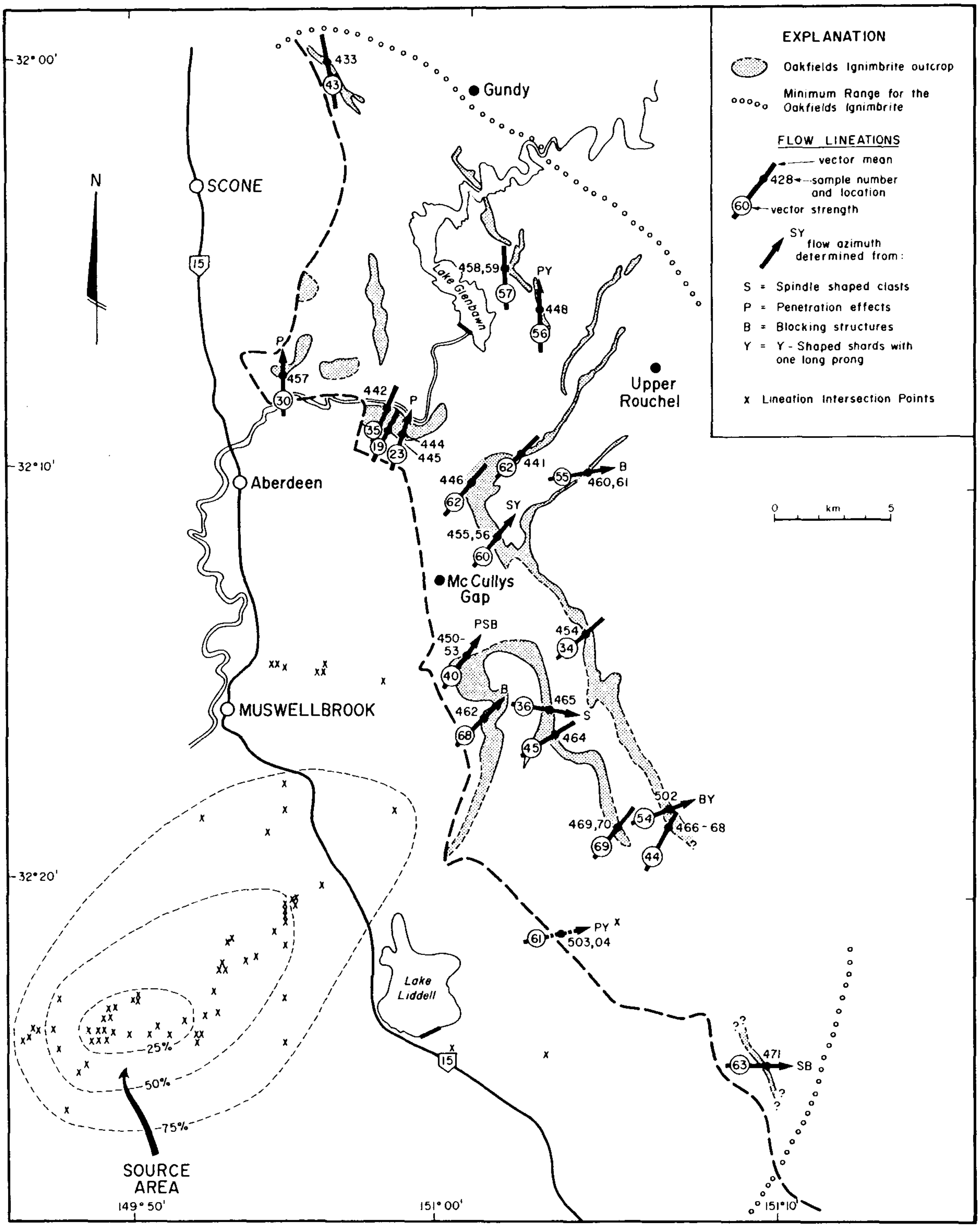


FIGURE 2.9

Palaeo-flow directions and the determined source area of the Oakfields ignimbrite.

from 34 samples of the Curra Keith ignimbrite and a summary of their statistics is included in Table 2.1. Figure 2.8 shows the flow lineation data for both the Curra Keith and McCullys Gap ignimbrites. The flow lineations for the Curra Keith ignimbrite show a distinct fanning arrangement through a sector of 120 degrees, from a northerly trend in the northern part of the Muswellbrook-Rouchel District around to the southeast in the southern part. However, samples 413, 414, 437 and 438 do not follow the main fan shape and it is probable that they have been affected by a pre-existing (palaeo-)topography (see later).

Ten flow lineations obtained from the McCullys Gap ignimbrite follow a similar fan-shaped pattern to the Curra Keith ignimbrite and it is for this reason that they are both plotted on Fig. 2.8 and both used to determine their apparent common source area.

The 28 flow lineations determined from the Oakfields ignimbrite (Fig. 2.9) reveal a 90 degree sector of a fan. The majority of these lineations trend in a northeasterly direction although, in the south, they bear around to the east.

2.8.2 Direction of Flow (Flow Azimuths)

Only 18 flow azimuths (directions) could be determined with any confidence from the ignimbrites in the Muswellbrook-Rouchel District but they unequivocally pointed to the northeast and east. Therefore the ignimbrites flowed in these directions from their source located west of their present outcrop.

2.8.3 Location of Ignimbrite Source Areas

To locate the actual position of the source of the ignimbrites the flow lineations were projected back in the direction of the source, until they intersected, and quite distinct clustering of the intersection points appeared (Figs. 2.8 and 2.9). As only a certain number of intersections (I) are possible from a given number of lines (n) then $I = n! - n$, and contours of percentages of the total number of intersections could be drawn about the clusters. Contours enclosing 50% of the total possible intersection points, on Figures 2.7 and 2.8, define relatively small areas and the source vent for the ignimbrites are assumed to have been located somewhere within this area. Smaller clusters of intersection points within the 50% contour enabled 25% contours to be drawn and it is considered that, within this contour, the source vent was most likely located. Thus, the area within the 25% contour is hereafter referred to as the source area.

2.8.4 Source Areas.

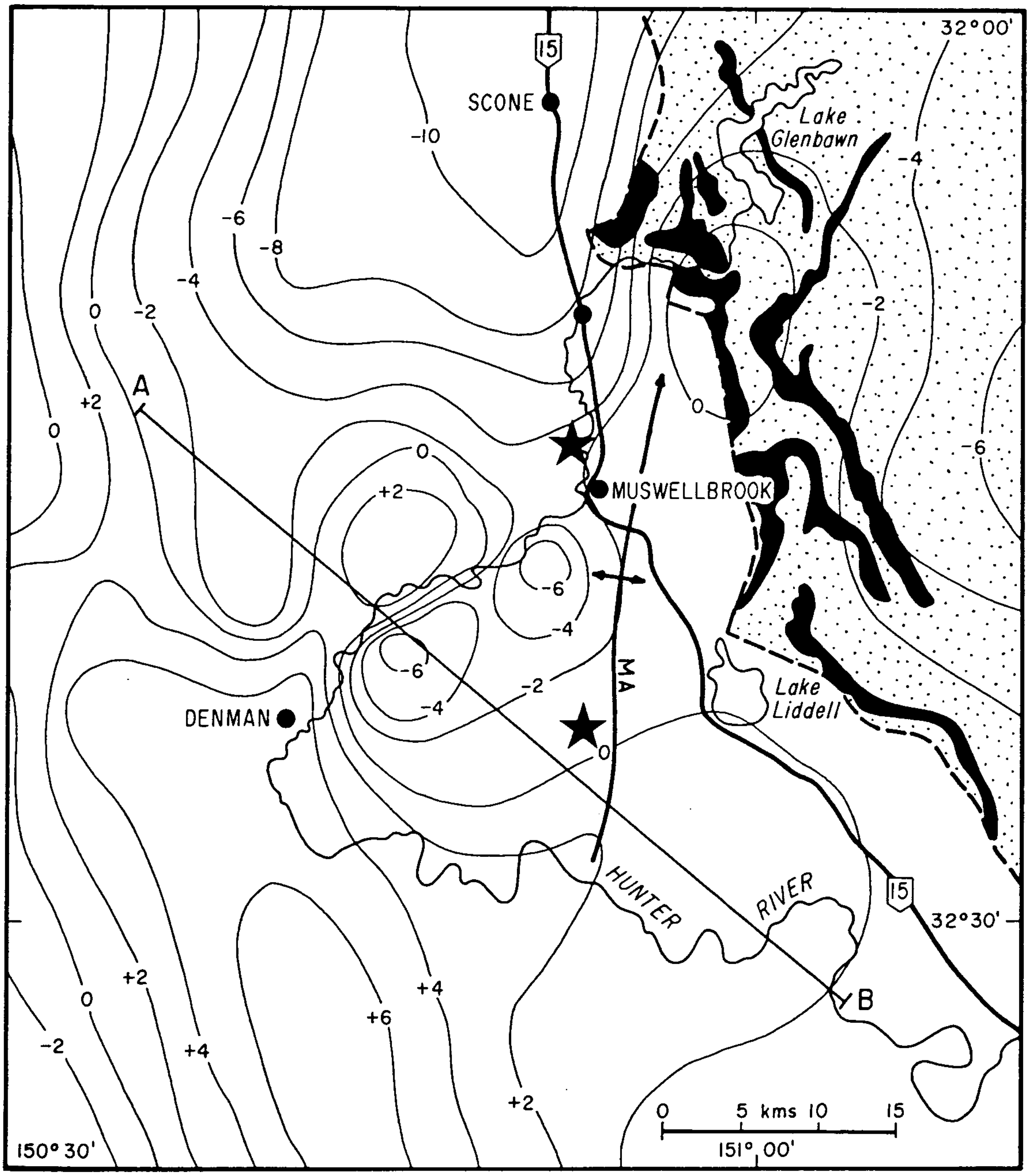
It should be noted that the flow lineations obtained from the distal parts of the ignimbrite have not been used to help determine the source areas of each of the ignimbrites. They tend not to follow the flow directions closest to the determined sources as which is a distinctive fan-shaped pattern.

Intersections of the lineations of the Curra Keith and McCullys Gap ignimbrites cluster well and their determined source area is centered about 4 km north of Muswellbrook (Fig. 2.8). The lineation intersections of the Oakfields ignimbrite overall do not cluster as tightly as the Curra Keith ignimbrite but the 25% contour encloses about the same area. The determined source area of the Oakfields ignimbrite is centred about 12 km SSW of Muswellbrook, at about the present position of Mount Arther. (The contours around the source area of the Oakfields ignimbrite are elongated since the collected lineation data is derived from only a 90 degree quadrant which results in the intersections spread out in the direction of the flow).

The closest outcrops of Curra Keith ignimbrite are thus, about 7 km distance from its determined source area and it is in these most proximal parts of the ignimbrite that the strongest fan-shaped flow pattern occurs. Farther from the

Figure 2.10

Residual gravity map and profile of the gravity anomaly in the Muswellbrook area. The cross-section of the anomaly is drawn parallel to the regional Bouger anomaly gradient which becomes increasingly more negative to the west due to the increasing thickness of the continental crust.The location of the determined source areas of the ignimbrites (solid black shading) are shown by the 'stars'. Stippled area is the Carboniferous rocks and unstippled is the Permian Rocks. Dashed line denotes the Hunter Fault and the axis of the Muswellbrook Anticline (MA) is shown.


32°00'
15
SCONE
Lake
Glenbawn
-10
-4
-6
-8
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0
-2
-2
A
+2
0
0
-6
0
+2
MUSWELLBROOK
-6
-4
MA
-6
-2
Lake
Liddell
DENMAN
-4
0
HUNTER
RIVER
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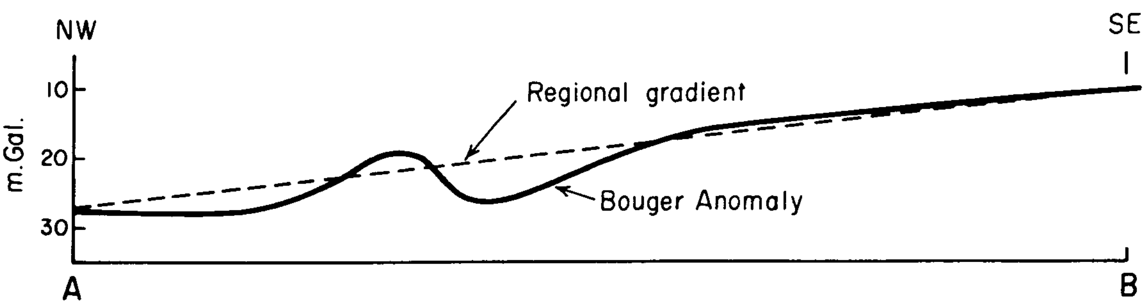
NW
SE
10
20
30
m.Gal.
Regional gradient
Bouger Anomaly
A
B

source, the fan-shaped pattern begins to lose its definition and irregularities appear in the otherwise simple pattern. This could reflect the decreasing velocity of the flow as it moved further from its source and the increasing influence of a regional palaeo-slope (see later) on the flow as the velocity of the flow decreased, or as illustrated by the ignimbrite-producing pyroclastic flows in the 1980 eruption of Mt St. Helens (Rowley *et al.* 1981; Wilson and Head 1981), it could represent paths of individual lobes within the flow, that spread out in the toe of the flow as the distance from the source increased. The most proximal outcrops of the Oakfields ignimbrite, on the other hand, are no nearer than about 18kms from their indicated source area, and a radial flow lineation pattern is thus less pronounced.

2.8.5 Source Areas and Gravity Anomalies

There is no surface expression of the postulated source areas of the ignimbrites as they lie on the opposite side of the Hunter Fault, where the Permian Sydney Basin succession now crops out. This indicates that the sources have either been relocated by movement on the fault or they are just buried, under at least 200m of the Permian strata. The preliminary 1:50,000 Bouger Gravity map (based on the Singleton and Newcastle 1:25,000 topographic sheets) (Fig. 1.7) published by the Australian Bureau of Mineral Resources, Geology and Geophysics reveals a conspicuous, mainly negative, anomaly in the exact viscinity of the two determined source areas. A residual gravity map of the anomaly (Fig. 2.10), which has been generated by removing the regional gravity trend (Fig 2.10, profile), shows two 6 mGal gravity lows combined with a 2 mGal gravity high, which altogether form a roughly circular anomaly, 15 km in diameter. The source area of the Curra Keith and McCullys Gap ignimbrites occur on the northwest perimeter of this anomaly whereas the Oakfields ignimbrite source area falls on its southern perimeter.

Nalaye (1977) calculated average rock densities of 2.6 $\pm$ 0.05 tm^{-3} for the Carboniferous rocks and 2.45 $\pm$ 0.02 tm^{-3} for the Permian Rocks in the Hunter Valley, and it is this density contrast that produces the generally negative gravity values over the Carboniferous strata on the easternside of the Hunter Fault and the westward increasing positive gravity values over the Permian Sydney Basin succession, which thicken in that direction. The Permian Sydney Basin is underlain by Carboniferous strata (Summerhayes 1982).

To produce the predominantly negative gravity anomaly over the source areas, requires either a zone of increased crustal thickness in the confines of the anomaly or, more likely, a confined body of abnormally low density material in the subsurface. Minmura (1984) explained that a negative gravity anomaly is produced over low density (dacitic) rocks which have accumulated over volcanic vents (as flow and domes) which have subsequently been buried. This is possibly the situation for the gravity anomaly in the region of the source area of ignimbrites in the Muswellbrook-Rouchel District, but a more favoured explanation for it is one that is described by Seager and Brown (1979) and Yokoyama (1981) for the negative gravity anomalies over the Organ and Krakatau Calderas, respectively. That is, the anomaly is likely derived from the effects of a now-buried caldera, with a diameter of about 12-15 km, which is filled with a pool of low density, rhyolitic lavas and pyroclastics. Moreover, the caldera is probably underlain by a (sub-caldera) intrusion of 'granitic' composition. The rise in gravity, out of the anomaly, is considered to reflect the rise onto the caldera rim. The fact that the indicated source areas of the ignimbrites in the Muswellbrook-Rouchel District lie on the periphery of the anomaly supports the concept and the position of the caldera since ignimbrite vents are commonly on the caldera ring fracture, as these appear to be.

One could possibly argue that the gravity anomaly is produced by the Muswellbrook Anticline, whose axis is shown on

Fig. 2.10. It is a major structure within in the Permian strata and it extends into the southeastern part of the anomaly. Furthermore, the anticline extends into the Carboniferous succession below the Sydney Basin, as the core of the anticline is regarded as a palaeo-high in the Carboniferous strata by Summerhayes (1982) and Roberts, pers. com., with the Permian sediments draped over it. Magnetic maps (Survey by Austirex in 1984 for the Geological Survey of New South Wales, Camberwell, Dungog, and Buladelah 1:100,000 sheets) support this premise, as strong magnetic intensities characteristic of the Carboniferous rocks continue uninterrupted across the fault in the region of Lake Liddell into the Permian along the axis of the anticline. However, the shape of the gravity anomaly in the area of the ignimbrite source areas does not reflect the NE-SW trend of the Muswellbrook Anticline. Furthermore the higher density Carboniferous rocks in the anticline, enclosed by the lighter Permian rocks, would produce a positive gravity effect. Thus, the Muswellbrook Anticline is unlikely to be the cause of the anomaly.

It is possible that the Carboniferous core of the Muswellbrook Anticline is a remnant of the Kuttung Volcanic Chain, of which the source caldera of these ignimbrites was a part of.

2.8.6 Pre-Ignimbrite Topography

The strong radial fan-shaped flow pattern shown by the flow lineations in the Muswellbrook-Rouchel District ignimbrites are similar to those found in other large scale ignimbrites (Schmincke and Swanson 1967; Elston and Smith 1970; Rhodes and Smith 1972); Ui *et al.* 1989). This flow pattern, on some diverse volcanic landscapes, indicates that the pyroclastic flows, close to their source, were little influenced by pre-existing topography. Their distribution mainly resulted from unrestricted radial movement of the flows, away from their eruptive vents.

The Curra Keith ignimbrite lies conformably on the Ayr Conglomerate and an isopach map of the Ayr Conglomerate drawn by Lindley (1981) shows that it smoothed out a previously irregular topography. Isopachs of the conglomerate thin from 200+ m at Upper Rouchel to 40 m in the west, and to only a few metres as it laps onto a basement high, the early Kuttung Volcanic Chain, on the western side. The conglomerate is 50 m thick under the westernmost outcrops of the Curra Keith ignimbrite in the McCullys Gap area. In the west, the isopachs parallel the Hunter Fault and those in the east run parallel with the most distal outcrops of the Curra Keith ignimbrite. This indicates that the Ayr Conglomerate was deposited over an outwash plain that was some 25 to 30km wide, between the basement high in the west and the coast in the east, both of them running in a similar trend to that of the present trend of the Hunter Fault. The fluvial conglomerate and pebbly sandstone interbedded with the ignimbrites are compositionally and lithologically similar to the Ayr Conglomerate and they indicate that (epiclastic) deposition was not interrupted by the emplacement of the ignimbrites. A 'smooth', flat depositional surface, on which the ignimbrites flowed, appears to have persisted until the hiatus at the end of the Viséan, prior to the deposition of the Mount Johnson Formation.

While the strong radial flow pattern in the proximal parts of the ignimbrites suggest that no significant relief was present on the surface on which the ignimbrites were emplaced, inspection of the flow direction pattern in the distal parts of the Curra Keith ignimbrite (Fig. 2.8) reveals two significant disruptions from the overall fan shape. The first occurs about a line passing, in a ENE direction, through McCullys Gap. North of this line, the flow directions are predominantly aligned northeast, but south of the line the flow directions abruptly swing around to an easterly direction. Furthermore, this line corresponds with a marked thinning of the Curra Keith ignimbrite; in the east it is only preserved as a thin, reworked remnant of the original deposit. It is, therefore, postulated that a low northeast-striking ridge, trending in the direction of the ENE line (Fig.2.8), existed prior to the emplacement of the Curra Keith ignimbrite and that it deflected the flow in the two different directions. The ignimbrite was probably originally emplaced on this ridge but was eroded and reworked soon after, thus expalining its present absence from this area. The deposition of the reworked volcaniclastics, 'equivalent' of the Curra Keith ignimbrite in the east suggests that the ridge did not extend as far as that locality.

The ridge must have been higher than the depositional surface on the top of the Ayr Conglomerate, which suggests that it was either an erosion remnant of a once higher depositional surface of the conglomerate or, more likely, a basement high that protruded above the depositional surface.

The second perturbation in the overall fan-shaped pattern of the flow lineations is a noticeable swing in the lineation vectors of samples 413, 414 437 and 438, from an expected northeast direction to a line of easterly directions. This consistent trend in the lineations suggest that the flow here was also directed by some topographic feature. The favoured explanation is that there was a channel cut into the fluvial plain which directed this part of the flow. This channel, according to the flow directions, appears to have run parallel to the postulated ridge, at the base of the slope on its northern side.

The disruptions to the fan-shaped pattern evident in the Curra Keith ignimbrite does not occur in the McCullys Gap ignimbrite. Thus, it is thought that by the time of the emplacement of the McCullys Gap ignimbrite, the ridge and channel had effectively been buried by the ignimbrites and sediments that succeeded the emplacement of the Curra Keith ignimbrite.

IGNIMBRITE	DISTANCE (km)	VOLUME (km^3)	CALDERA DIAMETER (km)
Fish Canyon Tuff	100	3000	28
Upper Bandelier Tuff	30	200	20
Crater Lake Pumice Flow	58	25	10
Valley of Ten Thousand Smokes Ig.	22	12	9
Rio Caliente Ignimbrite	20	30	12
Shikotsu pyroclatic flow deposit	40	80	12
Hakone pyroclastic flow deposit	18	15	10
Aso III pyroclastic flow deposit	70	175	20
Ito pyroclastic flow deposit	80	110	19
Taupo Ignimbrite	80	30	20
Whakamaru Ignimbrite	48	150	18
Bali Ignimbrite	40	20	11
<u>Muswellbrook-Rouchel Ignimbrites</u>			
Curra Keith Ignimbrite	30	45	12-15
Oakfields Ignimbrite	40	90	12-15

<u>TABLE 2.2</u>
Ignimbrite travel distances, erupted volumes and diameters of the source calderas compared with the ignimbrites in the Muswelbrook-Rouchel District.
Note: the ignimbrite volumes, even though they are published, are mostly only estimates as no account is made of co-ignimbrite ash fall, caldera-fill and subaqueous deposits. Erosion has also reduced the preserved volume and extent of these ignimbrites and this could mean that many of these volumes and travel distances are underestimates.

2.8.7 Size of the Ignimbrites

It is impossible to calculate the actual volume of the ignimbrites in the Muswellbrook-Rouchel district since tops and bottoms of units are rarely exposed and this meant that the true thickness of the ignimbrites were not always measurable. There is also no way of assessing the volume of the caldera-fill deposits which sometimes constitute a significant part of an ignimbrites erupted volume, e.g. the ignimbrite thickness in the Grizzly Peak caldera Colorado is reported to be 2.7 km (Fridrich & Mahood 1987). Furthermore, in many places there has been the erosive removal of the upper, non-welded parts of the ignimbrites and even the complete removal of parts of the Curra Keith ignimbrite, which probably occurred soon after their emplacement. Thus, only remnants of initially much thicker and more extensive units are preserved. However, a determination of minimum volumes of the outflow sheets of the ignimbrites has been attempted, by assuming a constant thickness in an arc across the fan-shaped units, through particular measured sections. Once, having obtained these volumes they are compared with other ignimbrites in respect of the distances that they traveled, as well as with the size of the caldera from which they were derived (Table 2.2). Smith (1979) demonstrated that there is a close correlation between caldera size and volume of the erupted silicic ignimbrite and associated pyroclastics.

The minimum distances traveled by the ignimbrites in the Muswelbrook-Rouchel District are highlighted on Figures 2.8 and 2.9. The most distal outcrops of the Curra Keith ignimbrite are about 10m thick about 30 kms from its source, northwest of Upper Rouchel, and is at least 80 m thick in its most proximal area, at McCullys Gap. Thus, the volume of the exposed ignimbrite, calculated from a decreasing thickness over a the 130^{o} sector of its outcrop, is $16 km^3$. If it was originally a circular deposit, as most large scale ignimbrites are (e.g. Taupo Ignimbrite (Walker 1981a, 1981b), Ata pyroclastic flow (Suzuki and Ui 1981), Upper Bandelier Tuff (Smith and Bailey 1966) and Bishop Tuff (Bailey *et al.* 1976)), then the minimum volume of the outflow sheet would be about 45 km^3. The Upper Bandelier Tuff traveled the same distance as the Curra Keith ignimbrite (Table 2.2) but it is a significantly larger volume unit with an estimated volume of 200 km^3. The Oakfields ignimbrite crops out over a 90 degree sector from 70 m thick closest to source, to 10 m thick in the far north of the area near Gundy, about 40 kms from source. The exposed outflow sheet volume is calculated to be some 23 km^3, but if it was similarly distributed evenly about its vent, then it would be about 90 km^3 in volume. The Shikotsu Pyroclastic Flow Deposit in Japan traveled the same distance as the Oakfields ignimbrite (Table 2.2) and it, with an estimated volume of 80 km^3 indicates that the two ignimbrites were probably of the same order of magnitude of eruption.

The calculated volumes of the Curra Keith and Oakfields ignimbrites, the proposed 12-15 km diameter caldera, and the

30-45 km travel distances of the ignimbrites compare well with other ignimbrites of similar magnitude (Table 2.2).

2.9 DISCUSSION

2.9.1 Rheomorphism vs Primary Flow

Flow lineations (fabrics) in ignimbrites are generally regarded to form and align during the primary late-stage laminar phase of the pyroclastic flow (Schmincke and Swanson 1967; Elston and Smith 1970, Rhodes and Smith 1972), and be oriented in the direction of the flows movement. However, Wolff and Wright (1981) showed that the directional fabric in highly welded tuffs on Gran Canaria and Pantelleria, are largely due to secondary mass flowage (rheomorphism). The flow fabrics in the ignimbrites are thus oriented in the direction of the local palaeo-slope on which they were emplaced, and not in the direction that the flow moved. Suzuki and Ui (1981, 1982, 1983) and Ui *et al.* (1981) showed that flow directions in lower parts of valley-fill deposits of the Ata Pyroclastic Flow are orientated (sub-) parallel to valley directions but were parallel to the slope on the steep valley sides. These observations presumably prompted Cas and Wright (1987, p.250) to state

"the fact that ignimbrites generally slope away from their source volcano has suggested to some workers that these directional fabrics are likely to reflect flow direction.... We have shown .... that this line of reasoning is not valid."

Furthermore, they suggest that

"measuring palaeocurrents (flow directions) in ignimbrites, especially 'ancient' ignimbrites, must be viewed with considerable caution".

Moreover, Ui *et al.* (1989 p. 115) state

"that grain alignment analysis must be used with care when attempting to determine the location of an unknown source"

as they demonstrated that the nature of preferred grain alignments varied within the different kinds of ignimbrite i.e. small scale valley confined (high-aspect ratio) ignimbrites versus large scale plateau-forming ignimbrites, versus thin but widespread (low aspect-ratio) ignimbrites.

However, the observations of Ui *et al.* (1989) also include

> "...grain orientations show better alignment in welded deposits and high-aspect ratio ignimbrites ....
> ...significant grain orientation is obtained only in the middle part of thin flow units ....
> ...the grain orientation is parallel to the source direction in the proximal area or on a pyroclastic flow plateau, but is random or parallel to the regional slope direction, as well as to the pre-flow valley and ridge direction, in the medial and distal areas of large-scale pyroclastic flow deposits and in small-scale valley-ponded pyroclastic flow deposits."

These observations differ little from the observations made in this study. The consistency of the flow directions throughout the thickness of the welded McCullys Gap ignimbrite endorses the statement of Ui *et al.* (1989), that best and consistent flow directions are obtained from welded parts of ignimbrites. As do the flow directions obtained from the lower parts of the Oakfields and Curra Keith ignimbrites, since they are most consistent in orientation where the welding is most intense.

Elston and Smith (1970) clearly showed that the flow lineations in the large scale Mogollon Plateau ignimbrites, which encircle their 'known' source caldera, pointed back to that caldera. The determined flow directions were radially arranged about the caldera and showed only some disturbance from the complex volcanic topography on which they were emplaced. Furthermore, the previous studies of Rhodes and Smith (1972), Aldrich (1976), Sides (1981), Ellwood (1982), and Potter and Oberthal (1987), to locate either a previously known or otherwise conspicuous source of ignimbrites, all determined flow direction fabrics in large-scale ignimbrites. They too had little indication, in the flow directions obtained, of an influence from the pre-existing topography.

The studied ignimbrites in the Muswellbrook-Rouchel District are similarly large-scale, welded ignimbrites and they flowed out onto an expansive, flat depositional surface with only some minor channeling of the ignimbrite indicated in the Curra Keith ignimbrite. The flow directions obtained in this study, overall, are strongly radially arranged, especially in the proximal and medial parts of the ignimbrite units, and they must therefore strongly reflect the primary movement of the pyroclastic flow.

To close this discussion of rheomorphic versus primary flow grain alignments in ignimbrite, the rheomorphic structures in ignimbrites that Wolff and Wright (1981) described, such as folded fiamme, extensional structures, and imbricate structure are not a feature of all ignimbrites, so that all ignimbrites should not be tarred with the same rheomorphic brush. Rheomorphism in ignimbrites has, to date, mainly been observed in either alkalic or peralkalic ignimbrites (Wolff and Wright 1981), or from ignimbrites that had unusually high emplacement temperatures (i.e. usually parts of bimodal basalt-rhyolite associations, as in the Lebombo Rhyolite (Natal) or Snake River Plains ash flow tuffs (Idaho)), which after deposition and welding have viscosities orders of magnitude lower the calc-alkaline ignimbrites that this and all of the previous studies have concentrated on (Prof. W.E. Elston *pers com.* 1989). Rheomorphic structures are not found in any of the ignimbrites in the Muswellbrook-Rouchel District.

2.10 CONCLUSIONS

The main conclusion of this study is that since flow directions can be determined from the Lower Carboniferous ignimbrites in the Hunter Valley then there is no reason why the same procedure cannot be used for well preserved large-scale ignimbrites of any age. The provisos, being (1) that they are large-scale ignimbrites, (2) they are little deformed, whereby the original horizontallity of the flow unit is preserved or easily restored, (3) the ignimbrite is, at least in part, welded so that the original flow fabric is preserved, and (4) the relief over which the ignimbrite traveled is low.

Evidence that this procedure works with more than just the Lower Carboniferous ignimbrites in the Muswellbrook-Rouchel District (Buck 1985, 1986), I have helped students successfully determine flow directions in the Upper Carboniferous Rhylstone Tuff (Langworthy 1986), an Upper Carboniferous ignimbrite in the Currabubula Formation (unpubl.), and some Tertiary basalts lava flows in the southern Sydney Basin (unpubl.).

The determination of flow directions in 'ancient' ignimbrites should be viewed as another tool in mineral exploration. Most volcanic exhalative, epithermal and hydrothermal mineral and base metal deposits in the world are located below or close to the volcanoes or calderas that produced them. Prior to this study the position of the source volcano of the Muswellbrook-Rouchel District ignimbrites was not known. Several companies have held exploration licenses in the outcrop area, trying to locate the ignimbrite source vents, which they hoped would reveal mineralisation. This study shows the source of the ignimbrites to be located well outside the area of the outcropping ignimbrites. As the volcanic centre in this instance is buried below a thick pile of Permian strata, any future exploration in the Muswellbrook-Rouchel District, for mineralisation related to the Lower Carboniferous Volcanic Centre, would require subsurface exploration methods.

There are many hidden volcanoes and calderas around the world and determining the actual location of some of them, using flow directions in ignimbrites and combining this information with other accepted exploration procedures, could lead to new discoveries of economic base metal concentrations.

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CHAPTER 3

LOWER CARBONIFEROUS CALDERAS IN A VOLCANIC CHAIN, REVEALED BY FLOW DIRECTIONS IN IGNIMBRITES, NEW SOUTH WALES, AUSTRALIA.

3.1 ABSTRACT

Lower Carboniferous ignimbrites that crop out extensively in the southeastern part of the New England Orogen in eastern Australia, occur within a thick sequence of volcaniclastic rocks along the western edge of the Tamworth Belt. Flow lineations and some azimuths were determined for five of the most extensive ignimbrite outflow units and they are used to determine the location of the volcanic centres from which the ignimbrites originated. The five ignimbrites examined are named the Curra Keith and Oakfields ignimbrites which crop out in the Muswellbrook-Rouchel District, the Martins Creek ignimbrite which occurs throughout the Paterson District, and the Port Stephens and Nelson Bay ignimbrites that crop out in the Port Stephens District.

Flow-lineation vector means were determined from 120 samples of the ignimbrites and each of the flow patterns in the outflow units exhibit a strong radial arrangement, except for the ignimbrites in the Port Stephens District which principally have a single north-northwest flow direction. By projecting the lineation vectors in the opposite direction of the movement of the pyroclastic flows, until they intersected, a clustering of the intersection points allowed relatively small areas to be defined as most likely to have contained the source vents. Four different source vents could be determined.

The ignimbrite sources do not crop out, as they have been displaced from the ignimbrite outflow units, by movement on the Hunter Fault. Now younger Permo-Triassic sediments of the

Sydney Basin Succession crop out at the surface at the location of the sources. However, nearly circular gravity anomalies with magnitudes (6-18 mgals), typical of those over Cenozoic calderas, occur in the region of all three of the determined sources. Thus, under the Permo-Triassic succession, the sources of the Lower Carboniferous ignimbrites are three calderas and they are likely infilled with lavas and pyroclastics of a similar silicic composition to the ignimbrites. A granitic intrusion forms the root of at least one of the calderas. The calderas are named Muswellbrook, Maitland and Port Stephens. They lie about 60 km from one another and they occur on an arcuate line, that is convex towards the west, parallel to the present western margin of the Tamworth Belt. The calderas are located between 5 and 10 km west of the Hunter Fault and they delineate the eastern edge of a Lower Carboniferous volcanic chain.

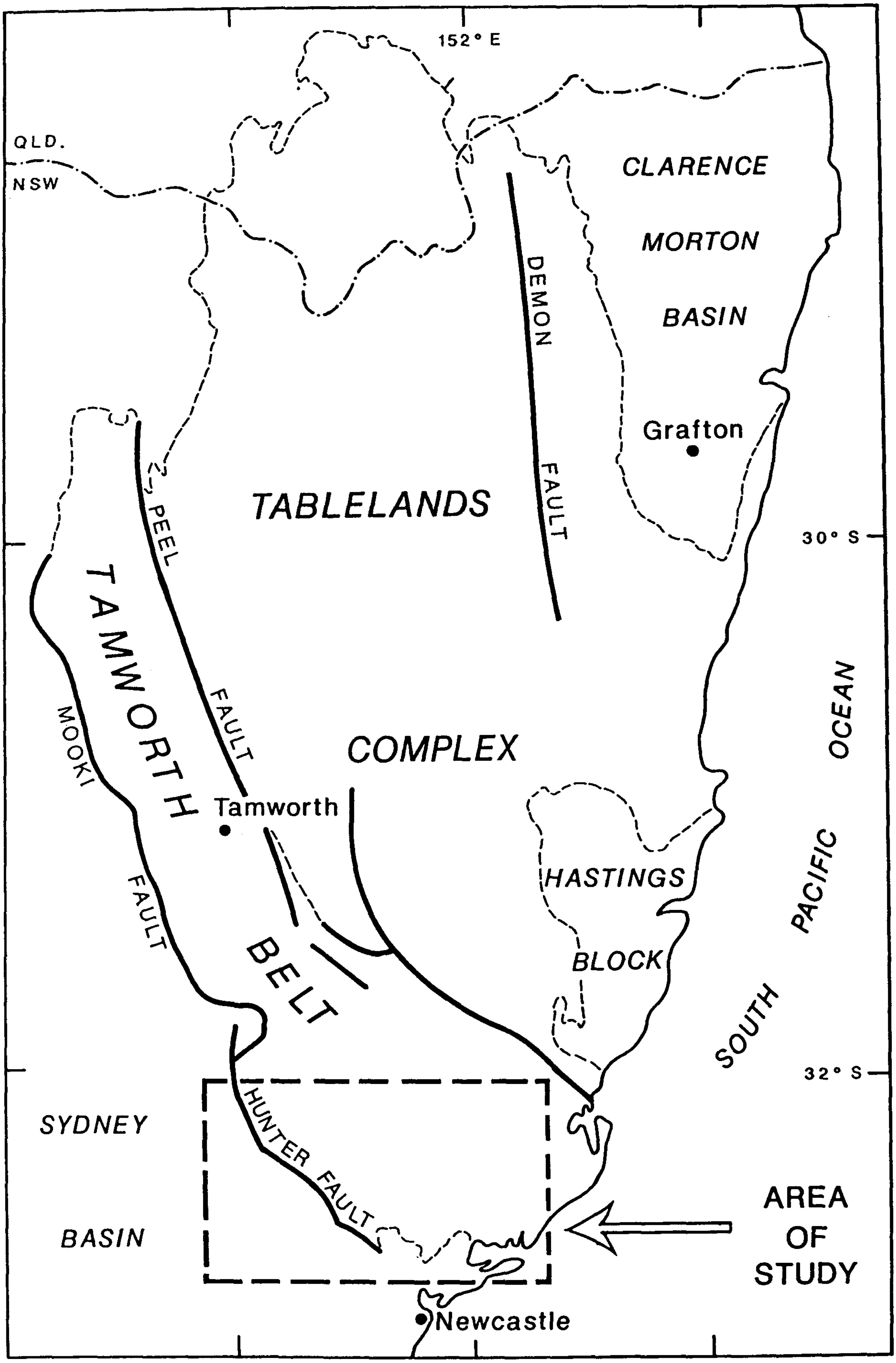
The correspondence of the determined ignimbrite source calderas with the gravity anomalies indicates that, except for vertical movements, on this part of the Hunter Fault there has been insignificant strike-slip movement and thrust movement is less than about 2 km in isolated places.

3.2 INTRODUCTION

Large scale (plateau-forming) silicic ignimbrites of Lower Carboniferous age crop out, extensively along the western edge of the Tamworth Belt (Korsch, 1977) in the New England Orogen (Day *et al*, 1978) in eastern Australia. It is now generally accepted that these ignimbrites were derived from the Kuttung (continental volcanic) Arc (Harrington and Korsch 1985; Roberts and Engel 1987) which lay along the western side of the Belt, some distance inland from a westward dipping subduction zone. However, the volcanoes and the pyroclastic flow deposits (ignimbrites) in typical present day continental volcanic arcs (e.g. the Andes, Indonesia, Alaska, Aleutians, the Cascades

FIGURE 3.1

Location of the study area in relation to the major elements of the New England Orogen. The Hunter Fault and its northern extension, the Mooki Fault, separate the mainly Devonian and Carboniferous rocks of the New England Orogen from the Permo-Triassic Sydney Basin.


152° E
QLD.
NSW
CLARENCE
MORTON
BASIN
DEMON
FAULT
Grafton
TABLELANDS
30° S
PEEL
FAULT
TAMWORTH
BELT
MOOKI
FAULT
COMPLEX
Tamworth
HASTINGS
BLOCK
SOUTH
PACIFIC
OCEAN
32° S
SYDNEY
BASIN
HUNTER FAULT
AREA
OF
STUDY
Newcastle

(USA) etc.) contrast with existent regions with large scale ignimbrites, similar to those in the Tamworth Belt. In continental volcanic arcs the 'usual' volcanoes are large andesitic strato-volcanoes, arranged along the front of a subduction zone, and they typically erupt only small-scale, valley-confined ignimbrites. On the other hand, the regions with modern (Cenozoic) large scale ignimbrites are widely documented as having calderas as the sources of the ignimbrites, and they are sited in either intracontinental rifts (e.g. western USA and central Chile) or the continental extensions of oceanic back arcs (e.g. southern Japan and the central North Island, New Zealand).

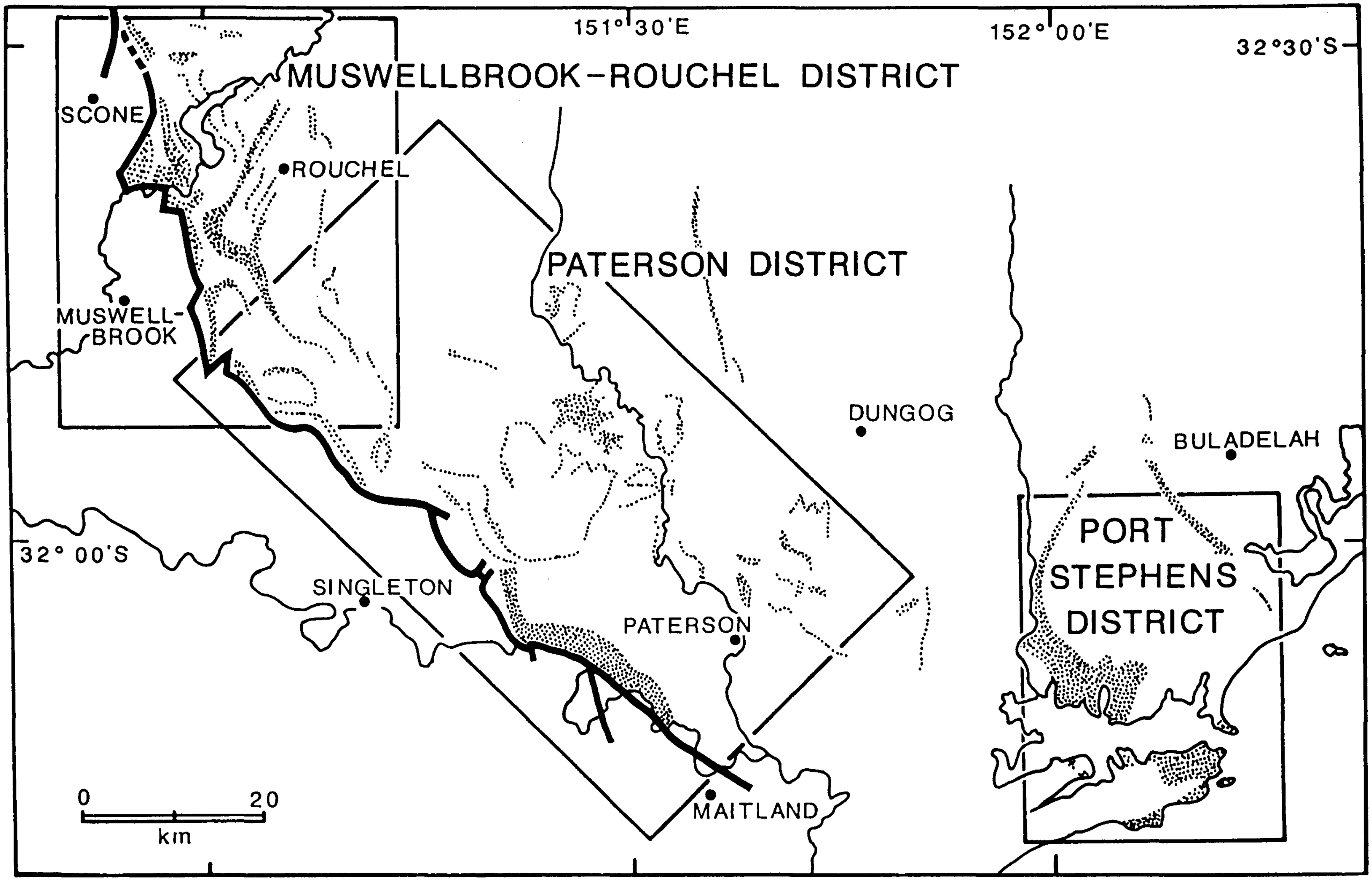
This paper details the position and spacing of the Lower Carboniferous ignimbrite sources, relative to the outcropping ignimbrites on the Tamworth Belt, and it describes the character of those source volcanoes. In doing this, a new model of the Kuttung 'Arc' is conceived.

Elston and Smith (1970) pioneered a method of determining flow directions of ignimbrites by measuring the orientations of elongated shards, pumice fragments and crystals in thin sections. They showed that statistically determined flow lineations in samples of the Bandelier Tuff indicated flowage radially away from its known source, the Valles Caldera. The success of their technique has been endorsed by comparable flow direction studies by Rhodes and Smith (1972), Aldrich (1976), Sides (1981), Suzuki and Ui (1982), Minmura (1984) and Ui *et al.* (1989), and Potter and Oberthal (1987) have succeeded in determining ignimbrite flow directions from the imbrication of pumice clasts.

The oldest ignimbrites in which flow directions have been determined, are the Oligocene-Miocene ignimbrites on the Mogollon Plateau, New Mexico (Rhodes and Smith 1972) and many consider it inappropriate to use the method with much older ignimbrites. However, most of the Lower Carboniferous ignimbrites in the Tamworth Belt are very well preserved for

FIGURE 3.2

Outcrop map of the Lower Carboniferous ignimbrites (stipple) in the southern end of the Tamworth Belt. Defined districts relate to detailed maps of Figs 3.5, 3.7, 3.9 and 3.11. The thick black line represents the Hunter Fault System. (Compiled from Roberts and Oversby 1974; Roberts and Engel 1987)


151° 30'E
152° 00'E
32°30'S
MUSWELLBROOK-ROUCHEL DISTRICT
SCONE
ROUCHEL
MUSWELL-
BROOK
PATERSON DISTRICT
DUNGOG
BULADELAH
PORT
STEPHENS
DISTRICT
32° 00'S
SINGLETON
PATERSON
MAITLAND
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km

their age, still with 'fresh' glass lenses in densely welded parts (Wilkinson 1971). Additionally, they have a low grade of metamorphism (Offler and Diesel 1976) and are only slightly deformed in broad open folds (Roberts and Engel In press). Flow lineations (and some azimuths) were be determined from 117 orientated samples of the five most widespread ignimbrites in the southern part of the Tamworth Belt and from these the location of the ignimbrites source vents could be established.

3.3 REGIONAL GEOLOGY

The study area lies at the southern end of the Tamworth Belt in the Palaeozoic New England Orogen (Fig 3.1). The Tamworth Belt (Korsch 1977) is bounded by the Mooki and Hunter Faults in the west, and the Peel Fault in the east. It formed between a volcanic system along its western side, and a subduction complex, now called the Tablelands (or Central) Complex (Korsch, 1977), on its eastern side (Fig 3.1).

The Tamworth Belt was a region of continental and shelf deposition (Roberts and Engel, 1987) and it existed from the upper Devonian through to the Permian. During the Lower Carboniferous, the southern part of the Tamworth Belt, in the region of the study area, ignimbrites from the volcanoes in the west, were frequently emplaced and interbedded with fluvial volcanicastic sediments. The Carboniferous sea encroached into the area from the east and marine siltstones and mudstones, of equivalent age to the ignimbrites and interbedded fluvial sediments, indicate that the sea progressively deepened towards the east.

The Tablelands (Central) Complex, during the Lower Carboniferous, is described as having been a continental slope and basin province (Day *et al.*, 1978; Roberts and Engel 1980), at which time it received mainly deep ocean sediments, which are preserved as a typical subduction complex (Cawood,1982 and Fergusson, 1984).

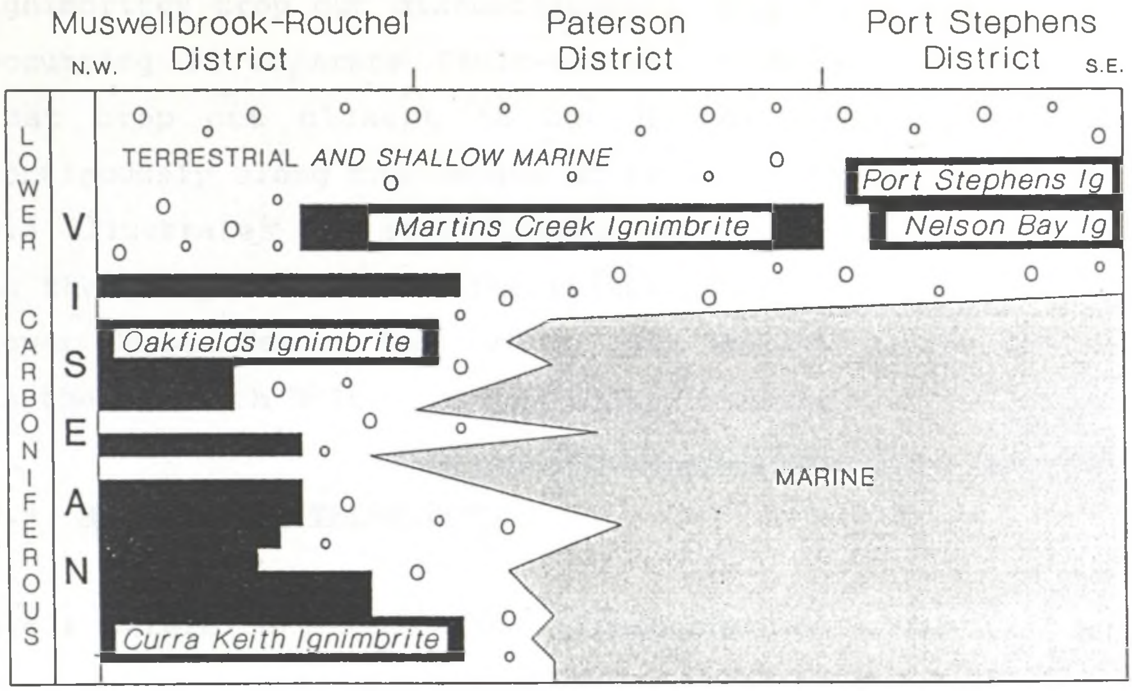


FIGURE 3.3

Schematic time-stratigraphic section of the southern Tamworth Belt to show the respective positions of the ignimbrite units referred to in this paper (after Roberts and Engel 1987).

A convergent plate boundary with a westward dipping subduction zone is generally believed to have shaped the New England Orogen and the volcanoes along the western side of the Tamworth Belt have been assumed to be a consequence of the subduction. Leitch (1975) described the source of the volcanics rocks, which crop out along almost the entire western edge of the Tamworth Belt, as a volcanic chain, which lay to the west trending parallel to the subduction zone. This chain of volcanoes was named the Kuttung (continental volcanic) Arc by Harrington and Korsch (1985).

In the study area, the western boundary of the Tamworth Belt is the Hunter Fault (Fig 3.1) and along this fault the Lower Carboniferous Tamworth Belt succession has been brought juxtapose to the younger Permo-Triassic coal-bearing sedimentary strata of the Sydney Basin.

The Tamworth Belt succession, including the ignimbrites, is gently folded and highly fractured by a system of faults, with one set that runs parallel to the Hunter Fault and another that runs oblique (NNE) to it. As a consequence, ignimbrites crop out discontinuously (Fig 3.2), with exposures occurring in separate fault-blocks. Although the ignimbrites that crop out closest to the Hunter Fault do so almost continuously along the length of this part of the Belt. Figure 3.3 illustrates the stratigraphic position of the ignimbrites in the study area and the relationship between them and the Lower Carboniferous terrestrial and shallow marine succession in the Tamworth Belt.

3.4 METHODS AND TECHNIQUES

3.4.1 Determination of Flow Lineations and their Statistical Significance

Measurements of preferred flow aligned structures in the ignimbrites were made using a method derived from the work of Elston and Smith (1970) who measured crystal and pumice orientations in oriented petrographic thin sections. Large sawn slabs of ignimbrite were substituted for the thin sections and the same kind of measurements were made on them according to the methods described in Appendix III. The slabs were cut parallel to the bedding (plane of flattening) of the unit and by using a specially adapted binocular microscope a tally of the orientations of prismatic crystals and elongate pumice clasts on the slab surfaces was compiled. The data was then analysed using the same vector method as Elston and Smith (1970) which determines a lineation vector mean, and vector strength, and the Tukey Chi Square Test (see Middleton 1965) was applied to assess the significance of the resultant mean. As in all previous flow direction studies of this kind (Elston and Smith 1970; Rhodes and Smith 1972; Suzuki and Ui 1982) a 90% probability level whereby (Tukey) Chi-square for two degrees of freedom is greater than 4.61 is considered statistically significant. Or in other words, the data was rejected if the Chi-square value was less than 4.61. The vector mean is taken to represent the flow lineation and it is this

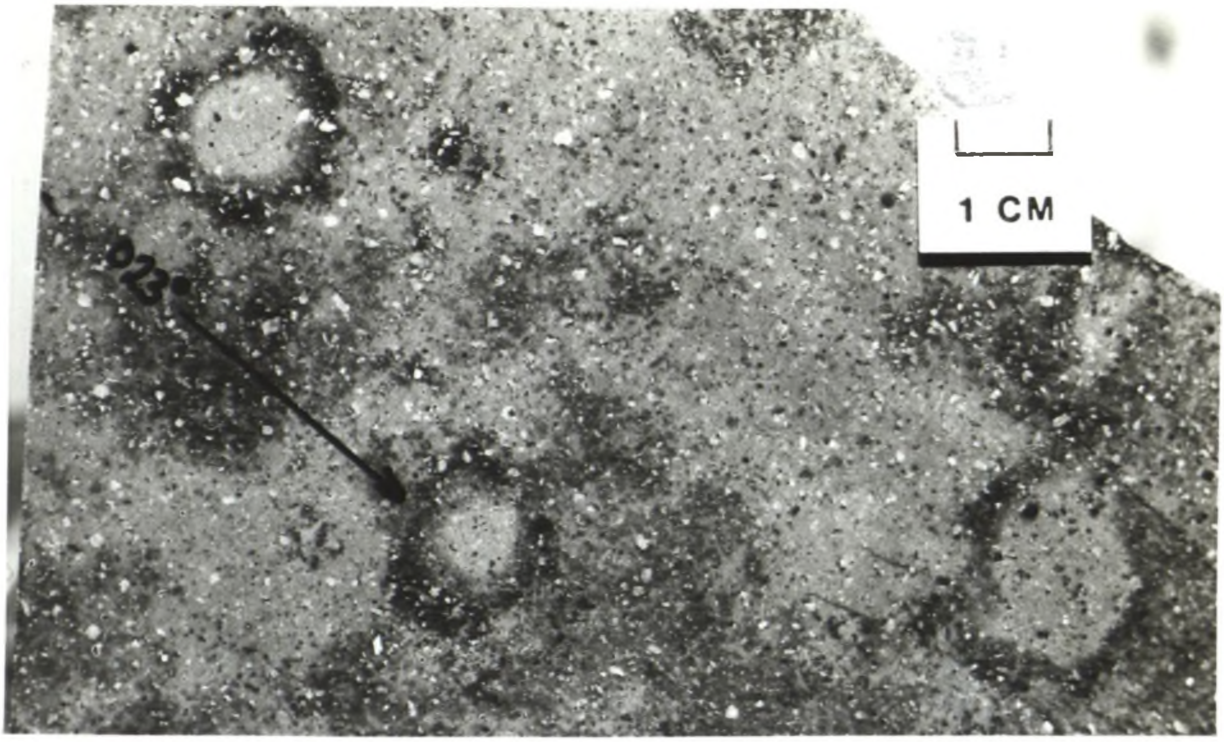


FIGURE 3.4

The Curra Keith (rhyolitic) ignimbrite from a medial-distal location of its outcrop, showing small orange-stained plagioclase crystals in a beige coloured shard-rich matrix. The circular features are a common feature in this ignimbrite, and they have been dubbed 'bloodspots'. They are in fact, orange-red, hematite-stained centres surrounded by black Fe-oxides that have formed during alteration. (MU 36436, G.R. Woolooma 177537).

vector that is plotted on the accompanying maps. The vector magnitude is a measure of dispersion about the vector mean where, a value of 100% indicate perfect parallelism of all lineations and 0% indicate completely random orientations.

3.4.2 Determination of Flow Directions

The flow directions (azimuths) of the ignimbrites were determined using the criteria described by Elston and Smith (1970) and Rhodes and Smith (1972) and these include (1) ***Forked-shaped glass shards***, where one prong, longer than the others, points away from the source; (2) ***Penetration effects***, where pumice fragments are deformed by more rapidly moving crystals orientated in the direction of flow; (3) ***Blocking effects***, where small particles pile up behind larger, slower-

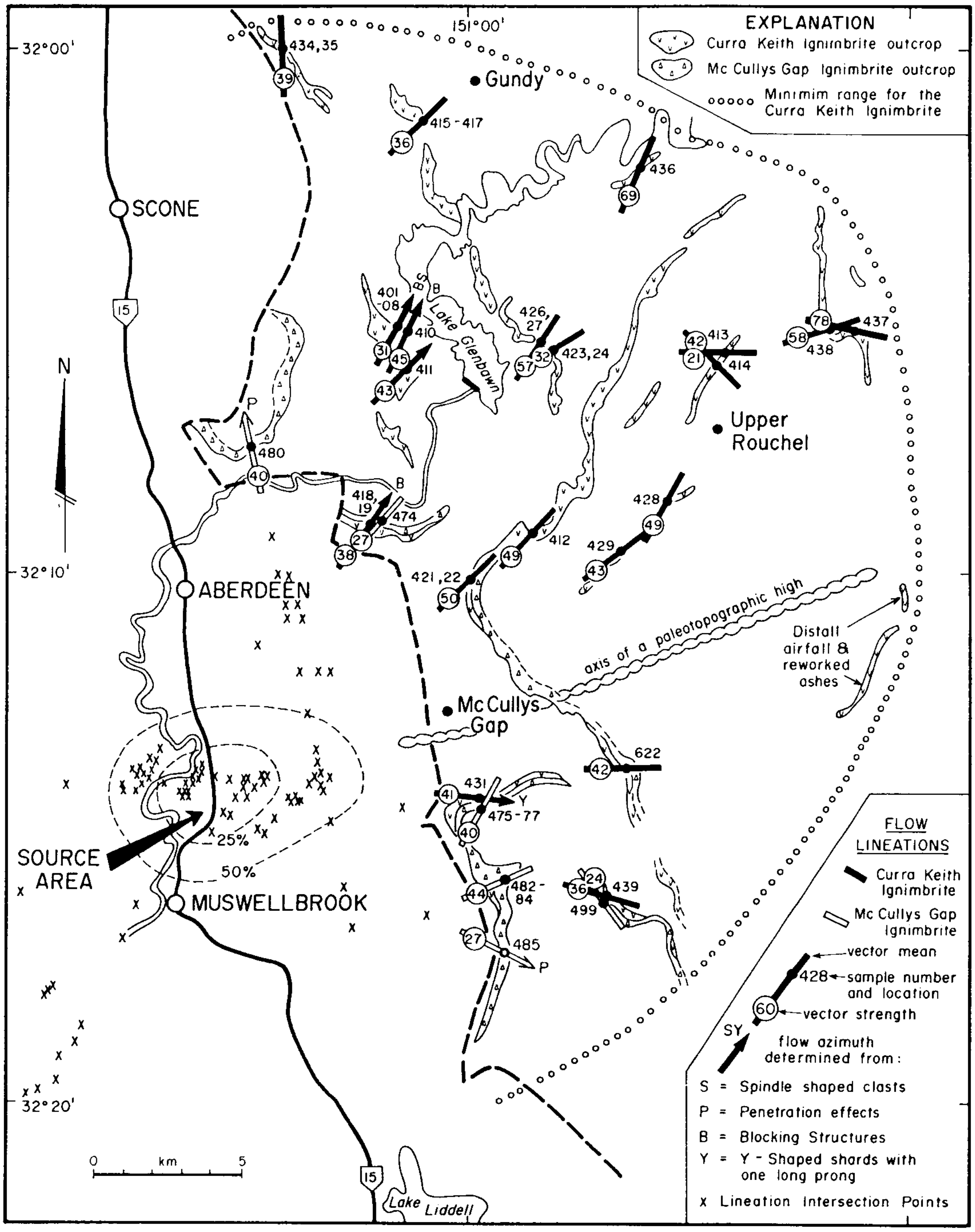


FIGURE 3.5

Flow lineations and azimuths determined for the Curra Keith ignimbrite.

moving fragments; (4) ***Spindle-shaped objects***, which are aligned parallel to the flow lineation with their blunt ends facing toward the source; (5) ***Eddy effects*** similar to those reported by Cummings (1964) in rhyolite lavas, where large fragments develop eddy currents on their leeward sides; and (6) ***Imbrication of crystals and clasts***, where they dip back towards the source.

3.4.3 How the Source Areas were Located

To locate the position of the source vents of the ignimbrites the flow lineation vectors were projected in the opposite direction of the determined azimuths (flow directions) until they intersected. Due to a well developed radial flow pattern in the ignimbrites (see later) the points of intersection clustered in confined areas and as only a certain number of intersections (I) are possible from any given number of lines (n); then $I = n! - n$, and contours of percentages of the total possible intersections could be constructed. A 50% contour was first constructed about the greatest cluster of points and a 25% contour was drawn around the area of maximum concentration within the 50% contour. The source vent for the ignimbrite is assumed to have been located within the constructed contours and the area within the 25% contour is favoured to contain the vent and it is thus called the source area.

3.5 IGNIMBRITES AND THEIR SOURCES

3.5.1 Curra Keith Ignimbrite

The Curra Keith ignimbrite (Fig 3.4) was emplaced in about the middle Viséan (Fig 3.3) and it is the oldest ignimbrite considered in this, as well as any other study, of flow directions of ignimbrites. It outcrops against the Hunter Fault northeast of the township of Muswellbrook and it extends to the

Ignimbrite	No of Samples	Av Tukey Chi-Sq	Av Vector Strength (%)	Total Area (cm^2)	Total Grain Counts
Curra Keith Rhyolite	34 (1)	37.72	45	2952	3118
Oakfields Rhyolite	28 (1)	41.87	48	2485	2467
Martins Creek Dacite	27	53.28	57	3277	2523
Port Stephens Rhyolite	29	51.60	56	4501	2350
Nelson Bay Dacite	11	48.00	55	1819	932

(1) = number of samples not significant at 90% confidence level.

TABLE 3.1
Summary of the flow lineation data obtained from the Lower Carboniferous ignimbrites from the Kuttung Arc in the southern part of the Tamworth Belt.

IGNIMBRITE	DISTANCE (km)	VOLUME (km^3)
Fish Canyon Tuff (USA)	100	3000
Upper Bandelier Tuff (USA)	30	200
Valley of Ten Thousand Smokes Ig.(USA)	22	12
Mount St. Helens (USA)	8	10
Rio Caliente Ignimbrite (S.America)	20	30
Puricipar Ignimbrite (S.America)	35	100
Aso III pyroclastic flow deposit (Japan)	70	175
Ito pyroclastic flow deposit (Japan)	80	110
Hakone pyroclastic flow deposit (Japan)	18	15
Taupo Ignimbrite (NZ)	80	30
Whakamaru Ignimbrite (NZ)	48	150
Bali Ignimbrite (PNG)	40	20
LOWER CARBONIFEROUS IGNIMBRITES *		
Curra Keith Ignimbrite	30	45
Oakfields Ignimbrite	40	90
Martins Creek Ignimbrite	60	150
Port Stephens Ignimbrite	45+	120
Nelson Bay Ignimbrite	45+	85

TABLE 3.2
Minimum distances traveled and bulk volume estimates of some better known ignimbrites (Compiled from Tables 8.1 and 8.2, Cas and Wright 1987).
* Volumes of the Lower Carboniferous ignimbrites are only estimates as they have been determined by calculating the volume of the exposed ignimbrite out-flow sheets, which were then amplified to account for an original circular distribution. The volumes of any caldera-fill deposits are incalculable.

northern and eastern edge of the Muswellbrook-Rouchel District (Fig 3.5).

It is thickest adjacent to the Hunter Fault where it has a measured minimum thickness of 80 metres in the M^c^Cullys Gap area, and it thins to about 10 to 15 metres in its most distal outcrops. The Curra Keith ignimbrite has a rhyolitic composition (Chapter 4.5) and it characteristically contains up to 25 modal % orange (and in some cases white), sericitised andesine (An_{30}-An_{36}) crystals and phenocryst fragments (Fig 3.4) set in a beige coloured matrix. Biotite crystals are also present but they have been partially or totally replaced by chlorite and opaque oxides. The crystals are most commonly crystal fragments. The matrix is wholly devitrified to a finely crystalline mosaic of sericitised feldspar and opaque dust which partly masks an original, partial to densely welded vitroclastic microstructure. The most characteristic feature of the Curra Keith ignimbrite is that it contains little coarse material with only rare lapilli-sized pumice and lithic fragments throughout its entire outcrop.

Statistically valid flow lineations were determined from 33 of the 34 collected samples of the Curra Keith ignimbrite with a collective total of 3,118 grains measured on a total surface area of 2,952 cm^2 (Table 3.1). The flow lineations show a distinct fanning arrangement through a sector of 120 degrees, from a northerly trend in the northern part of the Muswellbrook-Rouchel District around to the southeast in the southern part, with flow directions towards the east and northeast (Fig 3.5). Sample numbers 413, 414, 437 and 438 do not fit the main fan shape and here the flows direction may have been influenced by a channel, cut in the alluvial plain (Chapter 2.8.6), on which the ignimbrite was emplaced.

Ten flow lineations from another ignimbrite in the Muswellbrook-Rouchel area (the M^c^Cullys Gap ignimbrite) (Fig 3.5) follow a similar fan-shaped pattern to that of the Curra Keith ignimbrite. These two ignimbrites appear to have had a

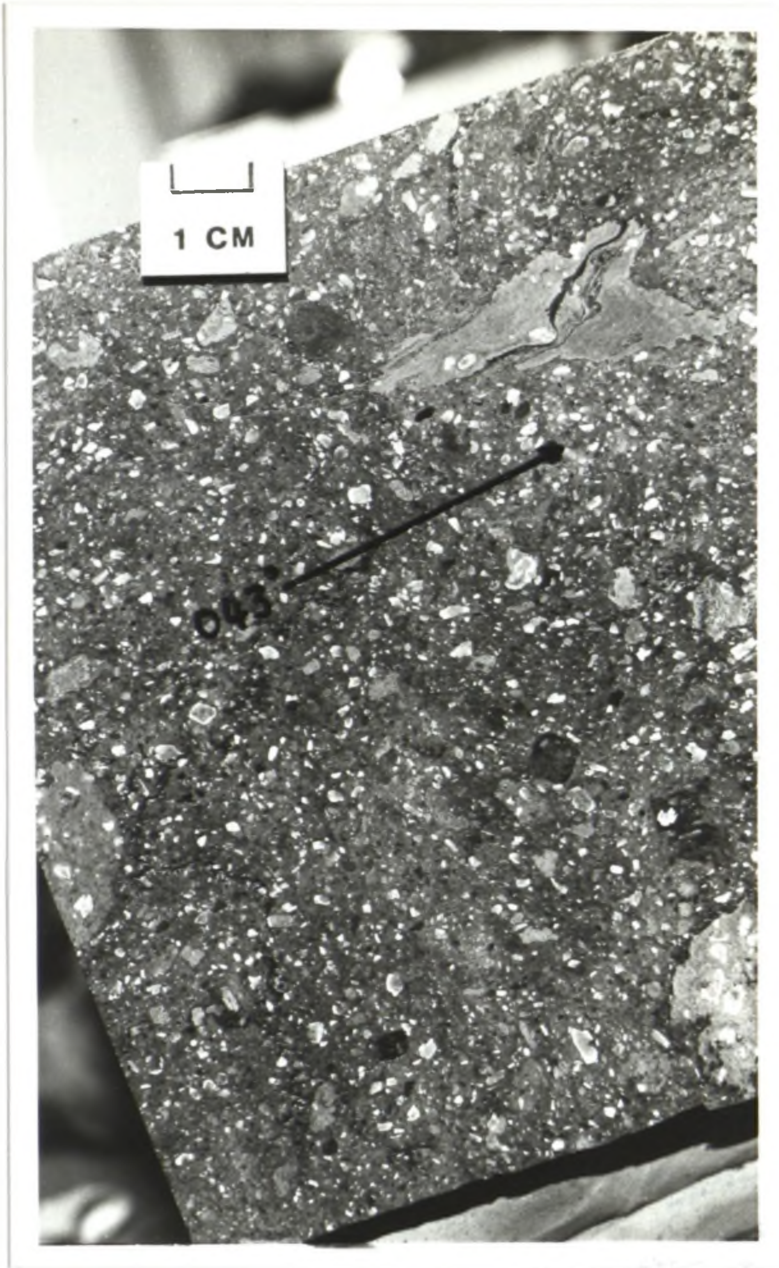


FIGURE 3.6

The Oakfields (rhyolitic) ignimbrite from a medial location of its outcrop, showing flattened pumice clasts and abundant plagioclase crystals. Vector shown is the flow direction (vector mean) determined from this specimen. (MU 36462, G.R. Dawsons Hill 129286).

common source area.

The intersection points of the lineations from the Curra Keith ignimbrite (and McCullys Gap ignimbrite) cluster well and their source area is determined to be centered about 4 kms north of Muswellbrook.

The most proximal outcrops of the Curra Keith ignimbrite thus occur in the McCullys Gap area, about 7 km from the determined source area and the most distal outcrops occur in the Gundy, Upper Rouchel area about 30 km from source. The

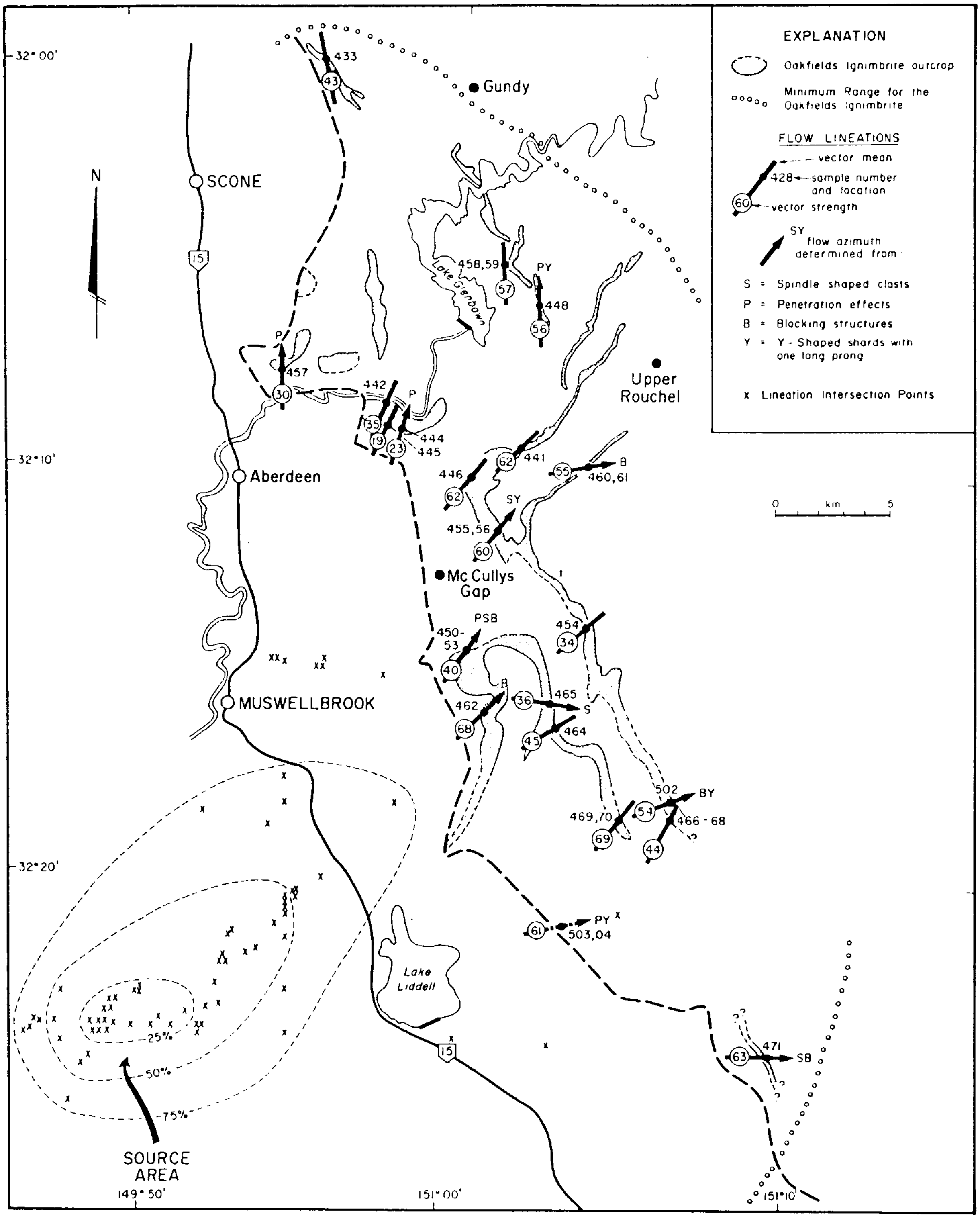


FIGURE 3.7

Flow lineations and azimuths determined for the Oakfields Ignimbrite.

Upper Bandelier Tuff traveled at least 30 km from its source (Elston and Smith 1970), the Valles Caldera, and for further comparison, the travel distances of some Cenozoic ignimbrites are presented in Table 3.2.

3.5.2 Oakfields Ignimbrite

The Oakfields ignimbrite (Fig 3.6) is a purple coloured, cliff-forming unit that outcrops with a similar distribution to the Curra Keith ignimbrite, except that it is more extensive in the southern parts of the Muswellbrook-Rouchel District. It has a similar rhyolitic composition to the Curra Keith ignimbrite (Chapter 4.5), is at least 70 metres thick and is distinctive in having orange crystals and abundant lenticular pumice clasts (Fig 3.6) in a conspicuous purple coloured matrix. Thin section examination of this ignimbrite reveals a considerable variation in the degree of welding although the matrix generally has a distinctive eutaxitic (often deformed) texture and the crystals which form up to 20 modal % of the ignimbrite consist essentially of orange (zeolitised-sericitised) andesine, and biotite now largely altered to chlorite and opaque oxides. Lenticular pumice clasts form up to 35 modal % of the ignimbrite and accidental lithic fragments constitute up to 15 modal % of the ignimbrite in the lower parts of the flow.

Welding in the Oakfields ignimbrite occurs in similar zones as those described by Smith (1960). In the thickest parts of the ignimbrite the greatest degree of welding (flattening) of pumice and shards occurs about 10 metres above the base of the ignimbrite, and both welding (and flattening) of pumice decreases towards both top and bottom of the flow. It is welded to some degree to the base of the flow but the top few metres of the ignimbrite is essentially nonwelded and this nonwelded part is often reworked or in places it has even been completely eroded away.

Statistically acceptable flow lineations were determined from 28 of 29 collected samples of the Oakfields ignimbrite (Table 3.1) and they fan from easterly directions in the southern part of the Muswellbrook-Rouchel District to northerly directions in the north (Fig 3.7).

The intersection points of the vector lineations of the Oakfields ignimbrite overall do not cluster as tightly as those for Curra Keith ignimbrite, but a 25% contour encloses about the same area as that of the Curra Keith. The Oakfields ignimbrite source area is determined to be located about 12kms SSW of Muswellbrook. The elongated distribution of intersection points is a result of the collected lineation data coming from only a 90 degree quadrant which causes the intersection points to spread out in the direction the flow.

The most proximal outcrops of the Oakfields ignimbrite thus occur in the McCullys Gap area, about 15 km from its determined source and the most distal outcrops occur in the

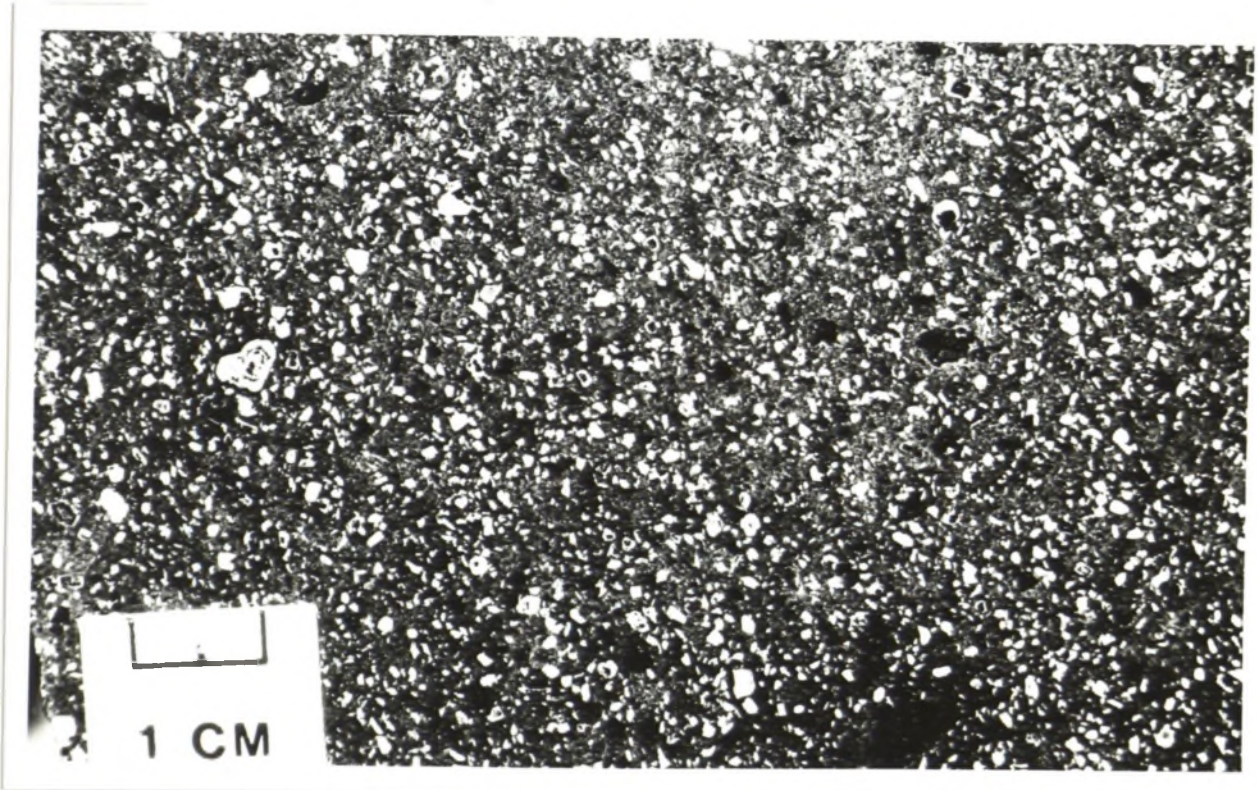
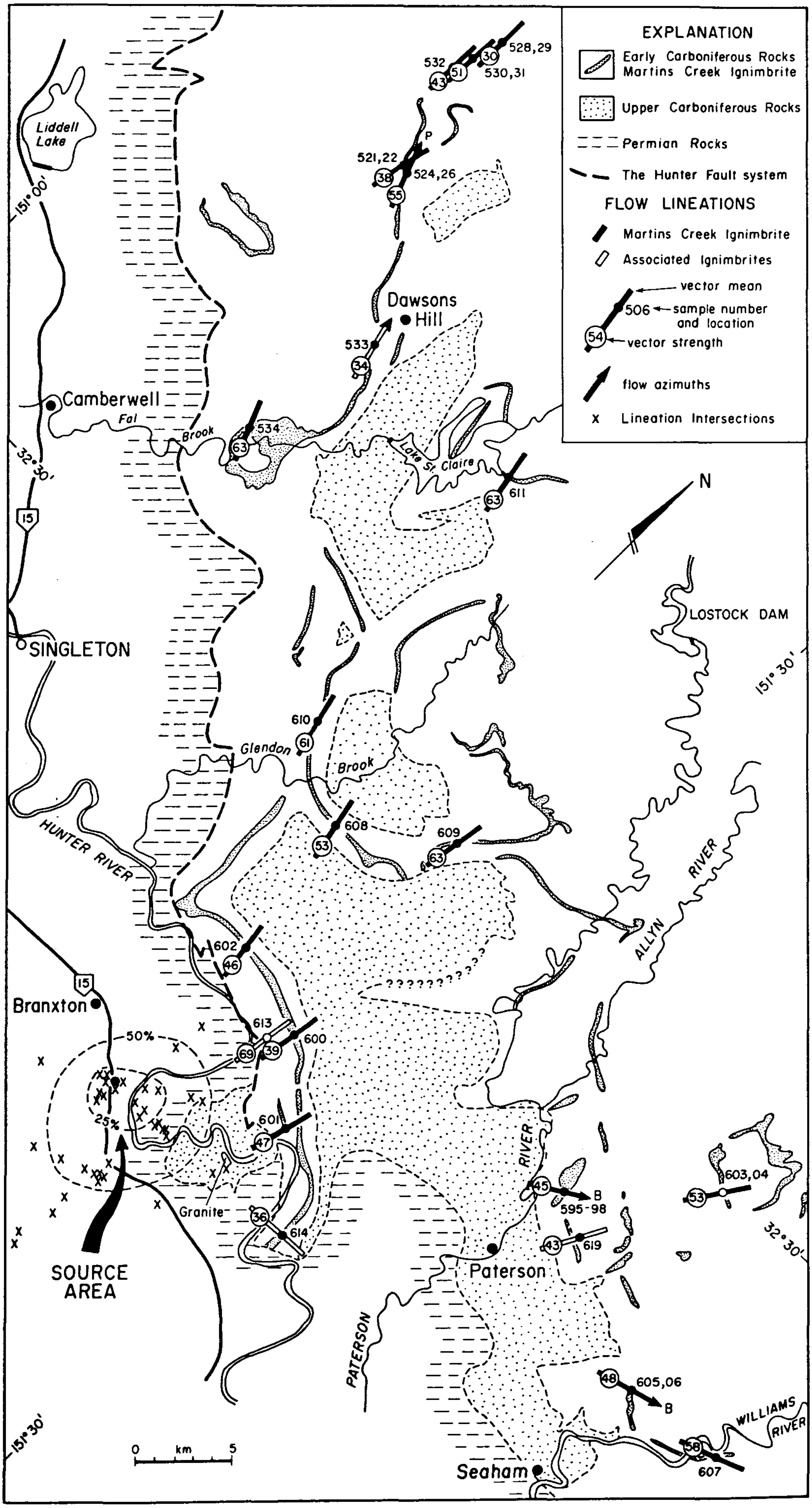


FIGURE 3.8

Martins Creek (dacitic) ignimbrite from a medial location showing its crystal-rich (plagioclase, hornblende) nature. Note, some of the plagioclase crystals have central inclusions of hornblende (MU 36597, G.R. Paterson 708969).

FIGURE 3.9

Flow lineations and azimuths determined for the Martins Creek Ignimbrite.


EXPLANATION
Early Carboniferous Rocks Martins Creek Ignimbrite
Upper Carboniferous Rocks
Permian Rocks
The Hunter Fault system
FLOW LINEATIONS
Martins Creek Ignimbrite
Associated Ignimbrites
vector mean
sample number and location
vector strength
flow azimuths
Lineation Intersections
N
Liddell Lake
Dawsons Hill
Camberwell
Fal Brook
Lake St. Clair
SINGLETON
LOSTOCK DAM
Glendon Brook
HUNTER RIVER
ALLYN RIVER
Branxton
Granite
SOURCE AREA
PATERSON RIVER
Paterson
Seaham
WILLIAMS RIVER
0 km 5
151°00'
32°30'
151°30'

Gundy area about 40 km from its source.

3.5.3 Martins Creek Ignimbrite

The Martins Creek ignimbrite (Fig 3.8) is the most widespread of all the ignimbrites in the Lower Carboniferous succession in the southern part of the Tamworth Belt. But it is also the thinnest of any of the ignimbrites studied. It crops out throughout the Paterson District and its distal parts extend into the Muswellbrook-Rouchel District (Fig 3.9). Its maximum measured thickness is only 35 m nearest to its source and it thins to 10 m or so 50 km away in the Dawson Hill Area. It is a blue-grey, crystal enriched, dacitic ignimbrite (Chapter 4.5), with 40-50 modal % consisting of, mostly broken, crystals of plagioclase (An_{30}), hornblende, Fe-oxides and rare quartz set in a partially to densely welded, devitrified shard-rich matrix. The plagioclase are typically zoned and the cores of many are replaced by alteration products, or have central inclusions of hornblende (see Fig 3.8). Rare fiamme occur throughout the ignimbrite but other coarse clasts are noticeably lacking.

Statistically acceptable flow lineations were determined from all 27 of the collected samples of the Martins Creek ignimbrite (Table 3.1) and they show a distinct fanning arrangement through a sector of 90 degrees, from a northerly direction in the northern part of the Paterson District around to the east in the southern part (Fig 3.9). Flow directions are towards the east and northeast. The intersection points of the lineations cluster tightly and give a well defined source area for the Martins Creek ignimbrite centred on Highway 15 (New England Highway) about 5 km south of Branxton. The most proximal outcrops of the Martins Creek ignimbrite therefore occur along the Hunter River, about 10 km from its determined source. Conversely, the most distal outcrops occur in the Dawsons Hill, Upper Rouchel area, about 60 km from its source.

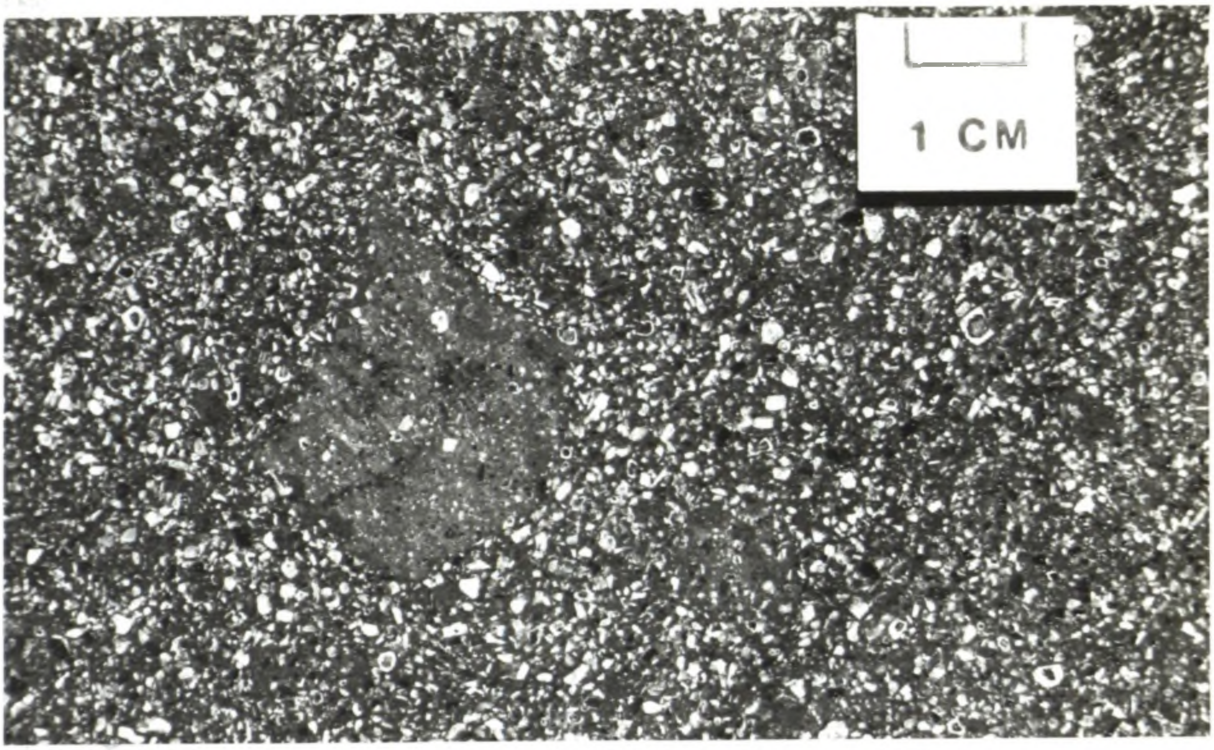


FIGURE 3.10

Nelson Bay (dacitic) ignimbrite from a proximal-medial location, with a transverse section through a fiamme. Zoned plagioclase forms the dominant phenocryst phase with less abundant hornblende (MU 36578, G.R. Port Stephens 190794).

3.5.4 Nelson Bay Ignimbrite

The Nelson Bay ignimbrite is a phenocryst-rich, dark grey dacitic ignimbrite (Chapter 4.5), which is little different in appearance from the Martins Creek ignimbrite, except that it contains abundant flattened fiamme (Fig 3.10). It only has limited exposure in the Nelson Bay area in the Port Stephens District, where it is at least 165 m thick. Crystals normally form 40-50 modal % of the rock and in decreasing order of abundance they consist of plagioclase (An_{40-48}), hornblende, hypersthene, opaques (titanomagnetite, ilmenite), biotite, and quartz. The crystals, plagioclase in particular, are largely crystal fragments (<0.5 mm -2 mm), with less common unbroken euhedral crystals (up to 4 mm).

The matrix constitutes 50-60 modal % (~5 % fiamme) of the ignimbrite and in places extreme welding of the unit has resulted in the original glass shard-rich matrix being

FIGURE 3.11 (opposite page)

Flow lineations and azimuths in the Port Stephens Ignimbrite (rhyolite) and the Nelson Bay Ignimbrite (hornblende dacite) in the Port Stephens District. Rose diagrams illustrate the flow lineation data. See Fig. 3.12 for key to Rose Diagrams and Fig. 3.5 for key to flow direction symbols.

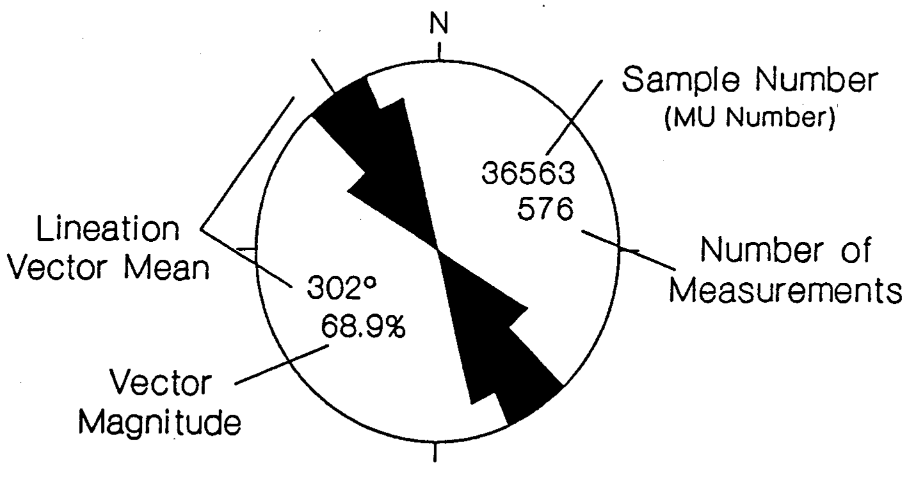


FIGURE 3.12

Key to rose diagrams in Fig. 3.13. Rose diagrams are drawn with the mode class interval taken to the perimeter of the circle and then other classes are determined as proportions of the total number of data points in the mode interval.

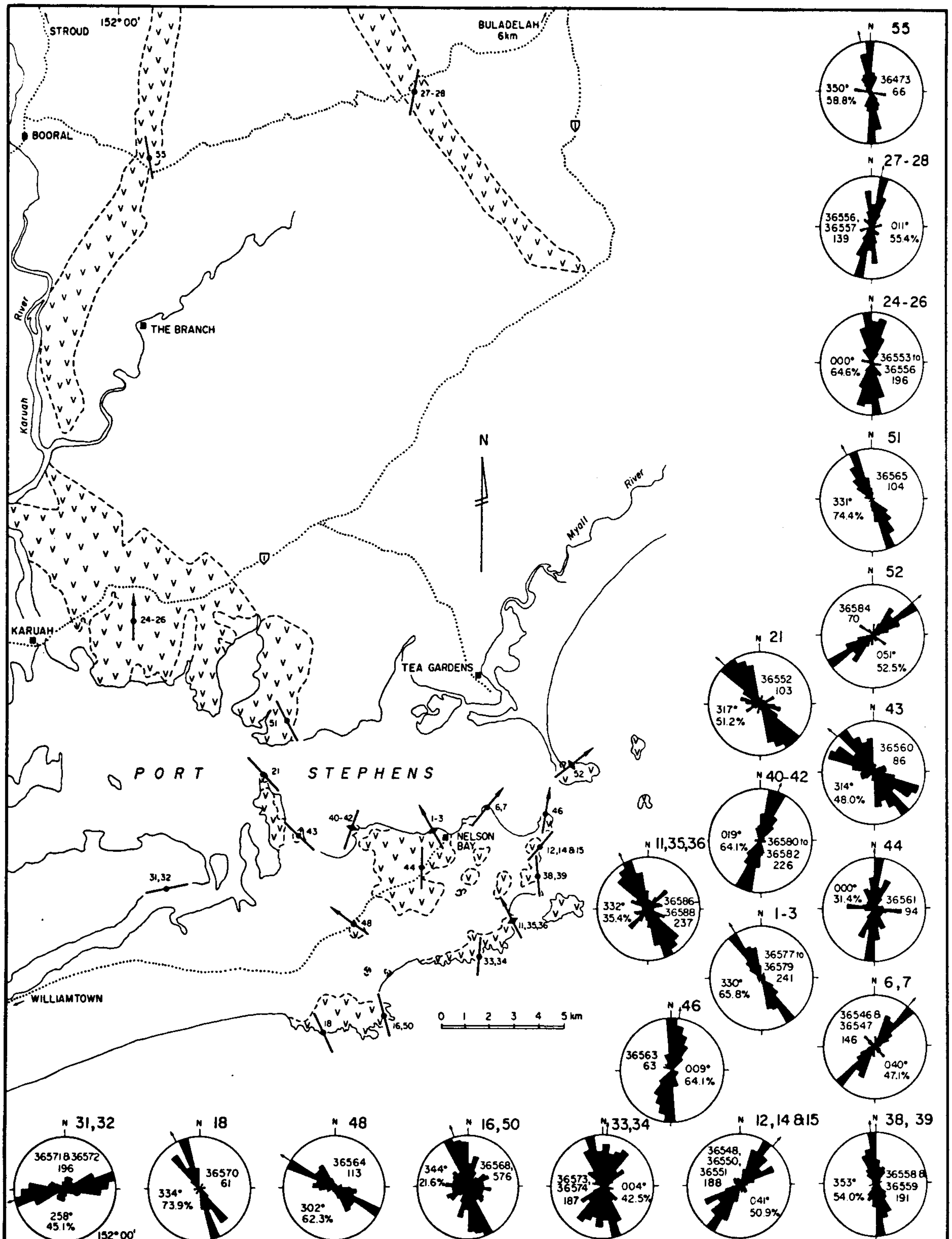
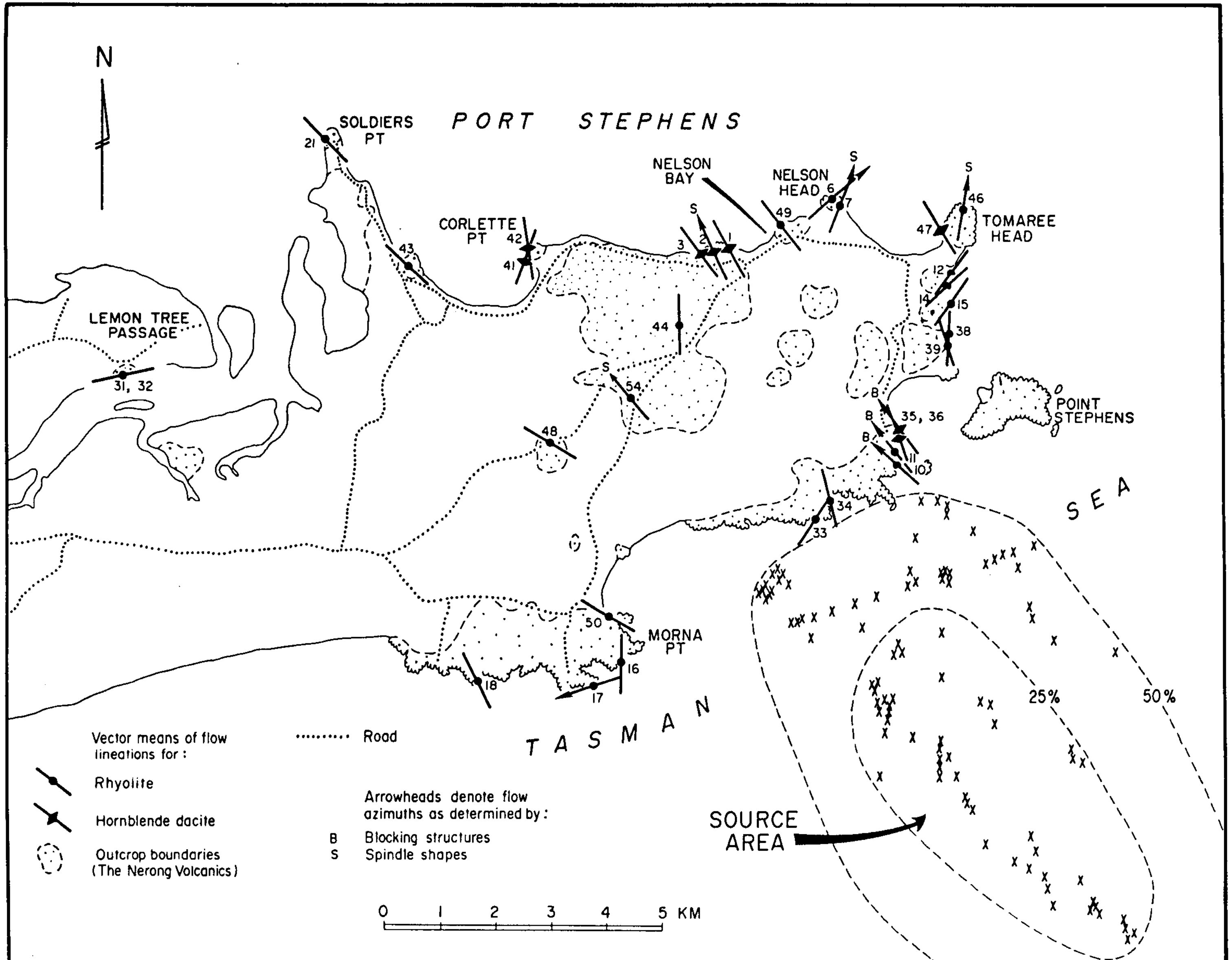

STROUD
152°00'
BULADELAH
6km
BOORAL
THE BRANCH
Karuah River
Myall River
KARUAH
TEA GARDENS
PORT STEPHENS
NELSON BAY
WILLIAMTOWN
0 1 2 3 4 5 km
55
36473
66
350°
58.8%
27-28
36556,
36557
139
011°
55.4%
24-26
000°
64.6%
36553 to
36556
196
51
36565
104
331°
74.4%
52
36584
70
051°
52.5%
21
36552
103
317°
51.2%
43
36560
86
314°
48.0%
40-42
019°
64.1%
36580 to
36582
226
11,35,36
332°
35.4%
36586-
36588
237
44
000°
31.4%
36561
94
1-3
36577 to
36579
241
330°
65.8%
46
36563
63
009°
64.1%
6,7
36546 &
36547
146
040°
47.1%
31,32
36571 & 36572
196
258°
45.1%
152°00'
18
36570
61
334°
73.9%
48
36564
113
302°
62.3%
16,50
344°
21.6%
36568
576
33,34
36573,
36574
187
004°
42.5%
12,14 & 15
36548,
36550,
36551
188
041°
50.9%
38, 39
353°
54.0%
36558 &
36559
191

FIGURE 3.13
Close up of the flow lineation detail in the area closest to source in the Port Stephens area to show how the location of the source area was determined. (x = lineation intersection). Contour values are percentages of the total number of possible intersections. Rhyolite = Port Stephens ignimbrite, Hornblende dacite = Nelson Bay ignimbrite


N
PORT STEPHENS
SOLDIERS PT
CORLETTE PT
NELSON BAY
NELSON HEAD
TOMAREE HEAD
LEMON TREE PASSAGE
POINT STEPHENS
MORNA PT
TASMAN SEA
25%
50%
SOURCE AREA
Vector means of flow lineations for:
Rhyolite
Hornblende dacite
Outcrop boundaries (The Nerong Volcanics)
Road
Arrowheads denote flow azimuths as determined by:
B Blocking structures
S Spindle shapes
0 1 2 3 4 5 KM

converted to a black isotropic glass (obsidian).

Statistically acceptable flow lineations were determined from all 11 collected samples of the Nelson Bay ignimbrite (Table 3.1) and they show mainly a north or northwest flow direction (Fig 3.11). The source area of the Nelson Bay ignimbrite is determined to be located, now under the Tasman Sea, about 5 km ESE of Morna Point (Fig 3.13).

However, as no real fan-shaped pattern in the lineations is developed in the Port Stephens area, there is a poor clustering of the points of intersection of the lineations. This means that the location of the source area is poorly constrained (Fig 3.13) compared with those in the Muswellbrook-Rouchel and Maitland Districts. Nevertheless, the ignimbrite flows traveled northward from a vent lying WSW of the most southerly outcrops of the ignimbrite at Morna Point.

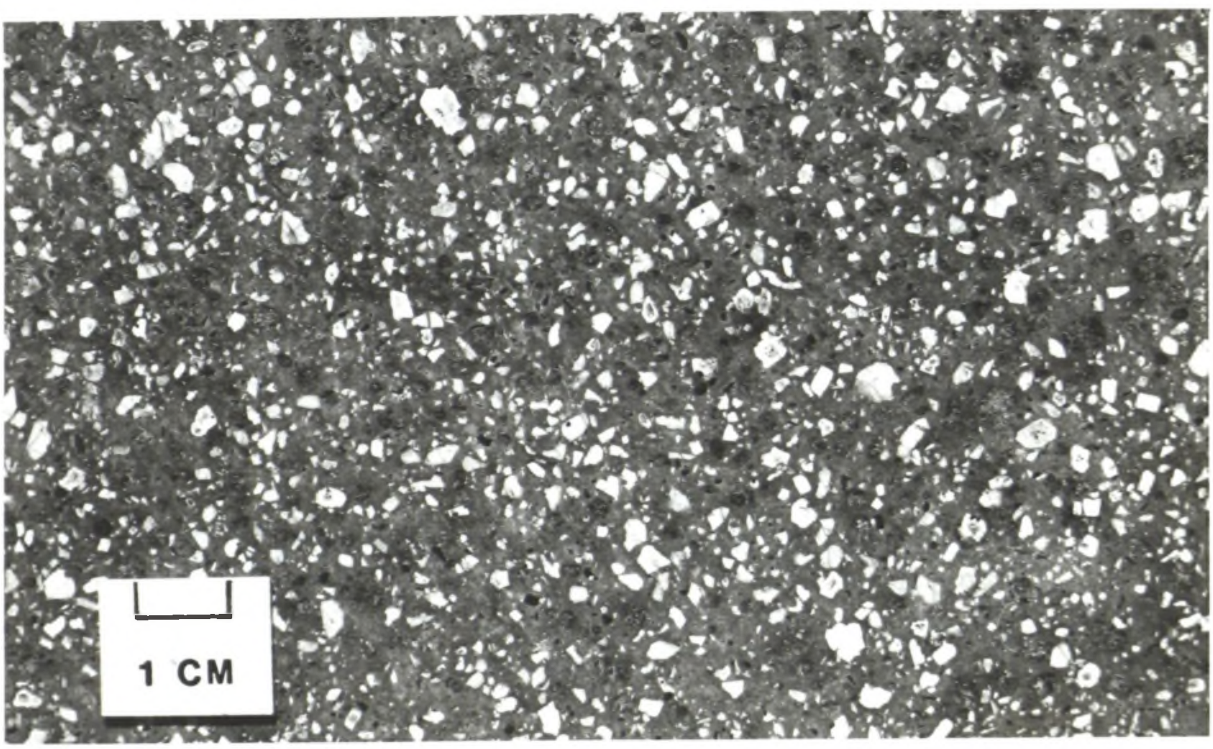


FIGURE 3.14

Port Stephens (rhyolitic) ignimbrite from a proximal location showing crystals of quartz (transparent, dark coloured), plagioclase and K-feldspar (white) and biotite (small black). Note the high proportion of crystal fragments. (MU 36569, G.R. Morna Point 170712).

The most proximal outcrops of the Nelson Bay ignimbrite thus occur at Morna Point, and they are within at least 5 km of the source vent. The most distal outcrops of this ignimbrite, on the other hand, occur north of Booral about 45 km from its source.

3.5.5 Port Stephens Ignimbrite

The Port Stephens (rhyolitic) ignimbrite (Fig 3.14) crops out extensively throughout the Port Stephens area, disconformably overlying the Nelson Bay ignimbrite (Fig 3.3). Its maximum exposed thickness is 190 m. Chemically the ignimbrite is a rhyolite (Chapter 4.5) and 35 to 45 modal % of the ignimbrite consists of coarse crystals of quartz, plagio-clase (AN_{35}) and K-feldspar in near equal proportions (Fig 3.14) (Chapter 4.5). Biotite, and minor hornblende and opaque minerals constitute the rest of the crystals. Intense welding also occurs in this ignimbrite and in parts of it the normal densely welded, deformed shard-rich matrix has been compacted to a black isotropic glass (obsidian). Small (less than 5 cm long) glassy fiamme are uncommon in the unit and at the base of the unit is a co-ignimbrite lag-fall breccia (Chapter 5.9.2).

Statistically acceptable flow lineations were determined from all 29 of the collected samples of the Port Stephens ignimbrite (Table 3.1). They, like those in the underlying Nelson Bay ignimbrite, show a poor fanning arrangement with the lineations in the south tending mostly towards the north or northwest, yet those in the north tending more northwards (Fig 3.11). The determined source area for the Port Stephens ignimbrite appears to have been in the same location as that of the Nelson Bay ignimbrite, that is about 5 km WSW of Morna Point (Fig 3.13). The premise of the two ignimbrites having a common source is bolstered by the fact that flow lineations in both ignimbrites exhibit the same trends in orientation, the most proximal lithologies of both occur in the same region, and closest to their source they crop out one on top of the other.

The apparent inconsistent lineation vectors from the 'normal' northerly direction to a westerly direction, as in the Morna Point area, could relate to either of two factors. The co-ignimbrite lag fall breccia that occurs at the base of the Port Stephens ignimbrite in this area indicates that this part of the ignimbrite was emplaced close to its source (Wright and Walker, 1977), at least within 2 or 3 km of the eruptive vent. In these proximal locations, the outward movement of the flow could have been affected by turbulence associated with the eruptive vent and the flow, perhaps, only "settled down" to give consistent flow directions once it had proceeded beyond the effects of the vent i.e. north of Port Stephens. A second possible cause could be that the 'ignimbrite flow' was either deflected, in the directions shown by the lineations, by a previous uneven or rugged topography or by rheomorphic flow (Wolff and Wright 1981) of the ignimbrite down a slope that the ignimbrite came to rest on. All modern volcanic source regions have a diverse (rugged) landscape and there is some evidence to indicate that this Lower Carboniferous source region was a little the same.

In south Fingal Bay the Port Stephens ignimbrite is resting directly on an eroded surface of the Nelson Bay ignimbrite (see Fig 5.6), whereas only a short distance (4 km) north at Corlette the two ignimbrites are separated by at least 60 m of sediments (see Fig 5.8). Consequently, it appears that from about Fingal Bay, south, towards the determined source, it was a high area undergoing erosion and north of this, it was a low (flat) area undergoing deposition. Therefore, rheomorphic flow in the 'higher, rougher' source region, where welding is also intense, cannot be ruled out, and nor can deflection by the uneven topography. However, on the 'lower' ground in the Port Stephens district, rheomorphic flow is ruled out, as it is in the Maitland and Muswellbrook-Rouchel Districts since the ignimbrites were emplaced on flat alluvial surfaces(Chapter 2). The volcaniclastic sands and conglomerates interbedded with the ignimbrites indicate that the surface, on which the ignimbrites were emplaced, was more than likely a flat, near-horizontal, depositional (flood-plain) surface, that probably had shallow braided channels scoured in it. The influence of any channels on the pyroclastic flows, however, appears to have been insignificant as evidenced by the strong consistency in the flow vectors in these parts.

The distribution of the Port Stephens ignimbrite is little different from the Nelson Bay ignimbrite. The most proximal outcrops of the Port Stephens ignimbrite are similarly in the Morna Point area, within at least 5 km of the determined source and the most distal outcrops also occur north of Booral and Buladelah about 45 km from the source.

3.6 VOLCANIC CENTRES AND GRAVITY ANOMALIES

It has been long recognised that most large volume ignimbrites are erupted from, and contribute to the collapse and formation of calderas, as was first discussed by Williams (1941) and updated by Druitt and Sparks (1985). Indeed the single eruption of many ignimbrites are known to have resulted in the formation of large calderas, e.g. the Aira Caldera in Japan (Yokoyama 1974), Crater Lake in Oregon (Bacon 1983), Santorini caldera (Druitt and Sparks 1982) and Krakatau caldera (Self and Rampino 1981). There is no evidence to suggest that the eruption of the Lower Carboniferous ignimbrites, considered in this study, were any different from any of these modern ignimbrite eruptions.

The first evidence to suggest that calderas were indeed the sources of the Lower Carboniferous ignimbrites came from the Muswellbrook-Rouchel District. Here, the Curra Keith and Oakfields ignimbrites are widely separated from one another in a thick sequence of smaller volume ignimbrites, and sediments

CALDERA	DIAMETER (Km)	IGNIMBRITE	VOLUME (Km^3)
HISTORIC IGNIMBRITE CALDERAS (In Volcanic Arcs)			
Santorini (Aegean)	14	Minoan Ignimbrite, 1470 B.C.	30
Krakatau (Indonesia)	8	1883 ash-flow	12
Aniakchak (Alaska)	9	Val. of Ten Thou. Smokes Ig, 1912	12
CENOZOIC IGNIMBRITE CALDERAS (In intracontinental rifts)			
USA			
La Garita	28	Fish Canyon tuff	3000
Valles	20	Upper Bandelier tuff	200
San Luis	16	Nelson Mountain tuff	500
Bachelor	18	Carpenter Ridge tuff	500
Crater Lake	10	Crater Lake pumice flow	75
Central and South America			
Lake Atitlán	~20	Los Cocoyas ash-flow tuff	200
La Primavera	12	Rio Caliente ignimbrite	30
Cerro Galan	34x20	Cero Galan ignimbrite	1000
Japan			
Towada	11	Towada pyroclastic flows	50
Aso	20	Aso III pyroclastic flow deposit	175
Aira	19	Ito pyroclastic flow deposit	110
New Zealand and Pacific			
Batur (PNG)	11	Bali ignimbrite	20
Rotorua	15	Mamaku ignimbrite	200
Taupo	20	Taupo(30) and Whakamaru(150) igs	180
LOWER CARBONIFEROUS, KUTTUNG ARC CALDERAS			
Muswellbrook	15	Curra Keith and Oakfields igs.	135
Maitland	25	Martins Creek ignimbrite	150
Port Stephens	10	Port Stephens and Nelson Bay igs.	205

* volumes can only be estimated minimums as the volume lost in co-ignimbrite ash fall and buried caldera-fill deposits, and post-emplacement erosion cannot be accounted for.

TABLE 3.3

Diameters of some modern calderas, and volumes of the ignimbrites erupted from them (after Macdonald 1972, Table 12.1, and Cas and Wright 1987, Table 8.1), compared with the Lower Carboniferous calderas in the southern New England Orogen .

FIGURE 3.15

Bouger gravity map of the southern part of the New England Orogen. The Hunter Fault is not shown but it virtually runs parallel to, and slightly east of Highway 15. Drawn from the preliminary, unpublished 1:50,000 Bouger Gravity map (based on the Singleton and Newcastle 1:25,000 topographic sheets) compiled by the Australian Bureau of Mineral Resources, Geology and Geophysics, Canberra. The defined areas are the areas of the residual gravity maps of Figs 3.16, 3.17, 3.18.

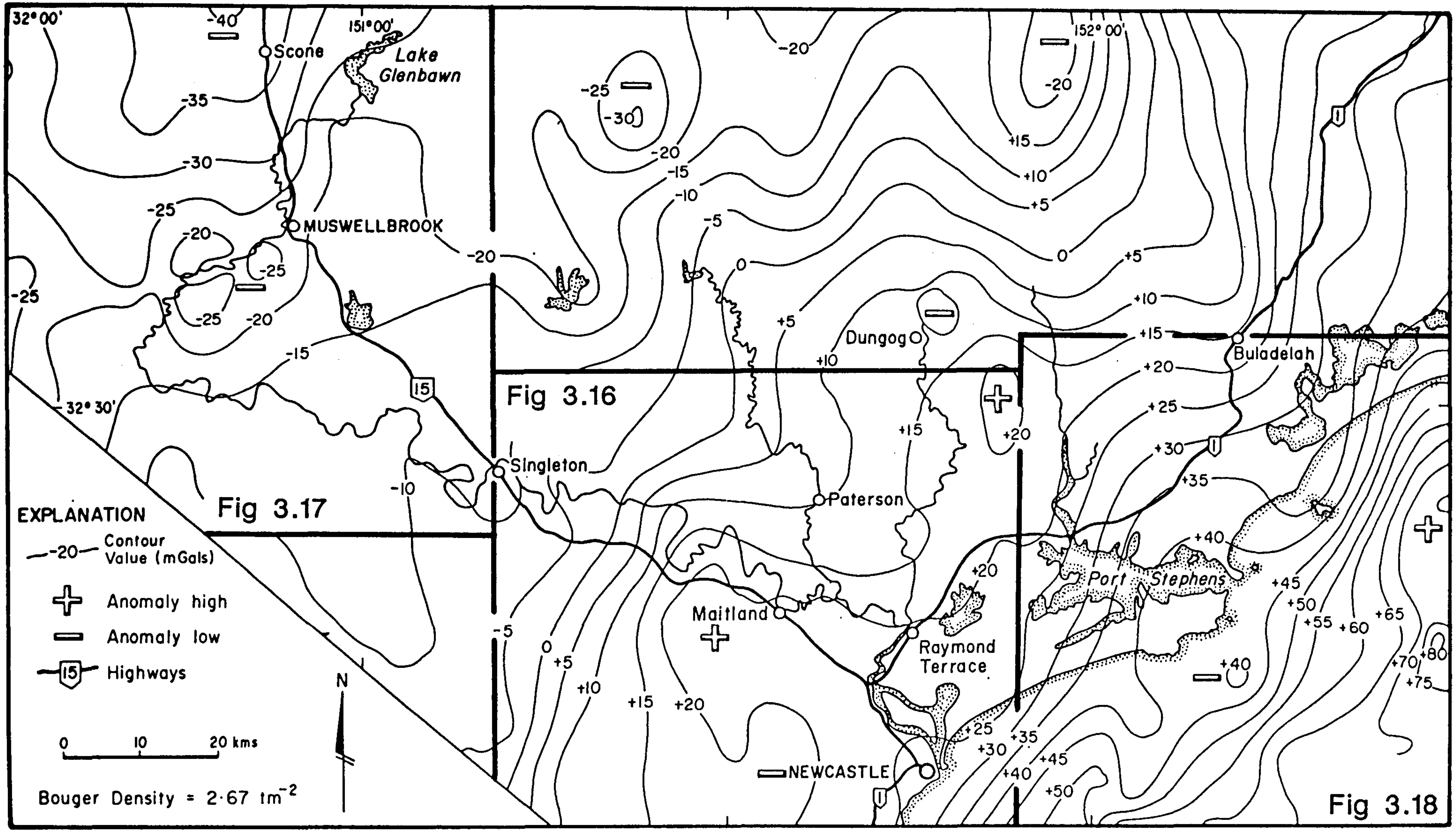

32° 00'
151° 00'
152° 00'
32° 30'
Scone
Lake Glenbawn
MUSWELLBROOK
Singleton
Dungog
Paterson
Buladelah
Maitland
Raymond Terrace
Port Stephens
NEWCASTLE
Fig 3.16
Fig 3.17
Fig 3.18
EXPLANATION
-20 Contour Value (mGals)
Anomaly high
Anomaly low
15 Highways
0 10 20 kms
N
Bouger Density = 2·67 tm⁻²

FIGURE 3.16

Residual Gravity map and Bouger profile of the positive gravity anomaly in the vicinity of determined ignimbrite sources in the Maitland District (see Fig 3.16). The location of the Martins Creek ignimbrite (black) source (large Star) is shown. Stippled area is the Carboniferous succession and the unshaded is the Permo-Triassic Sydney Basin.

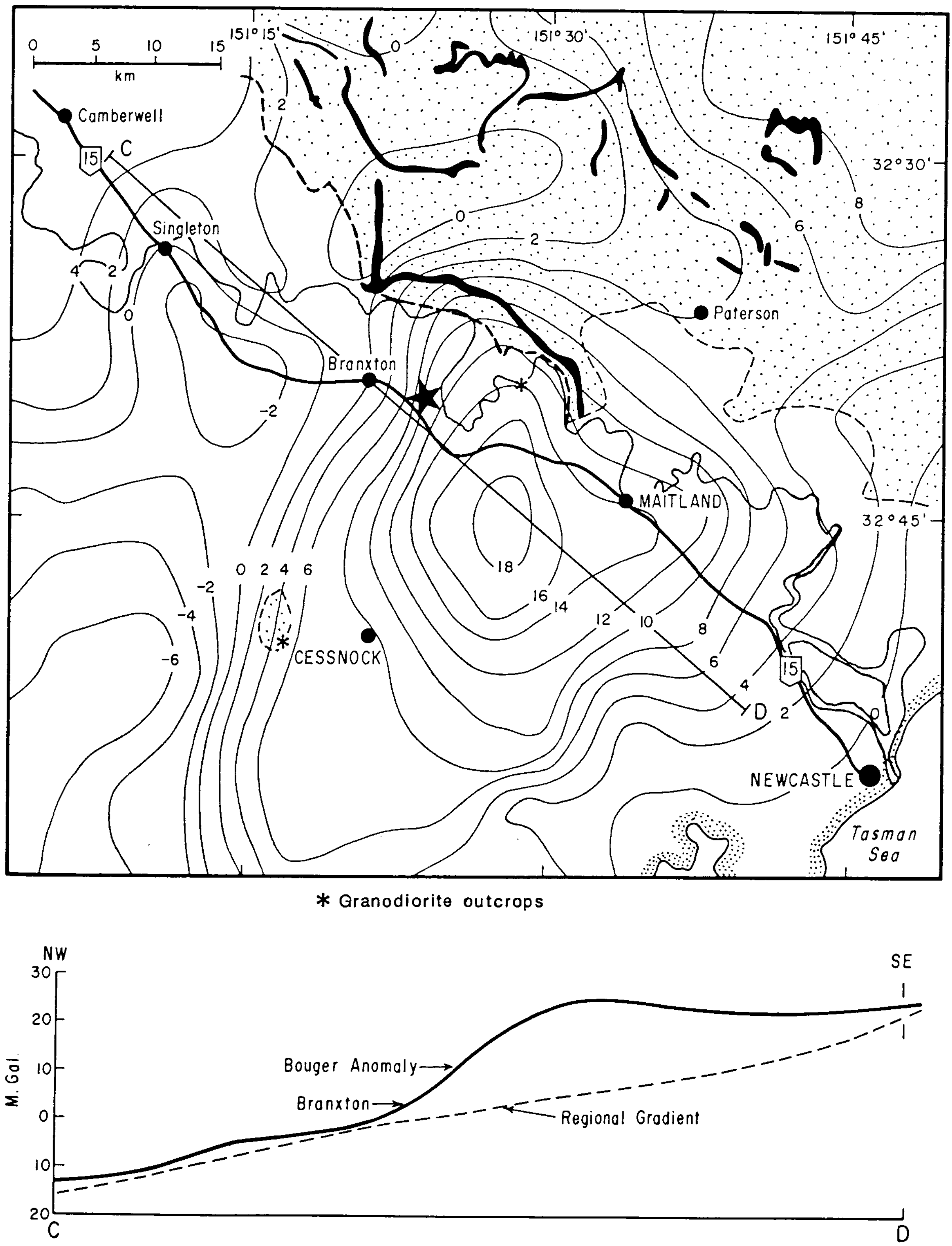
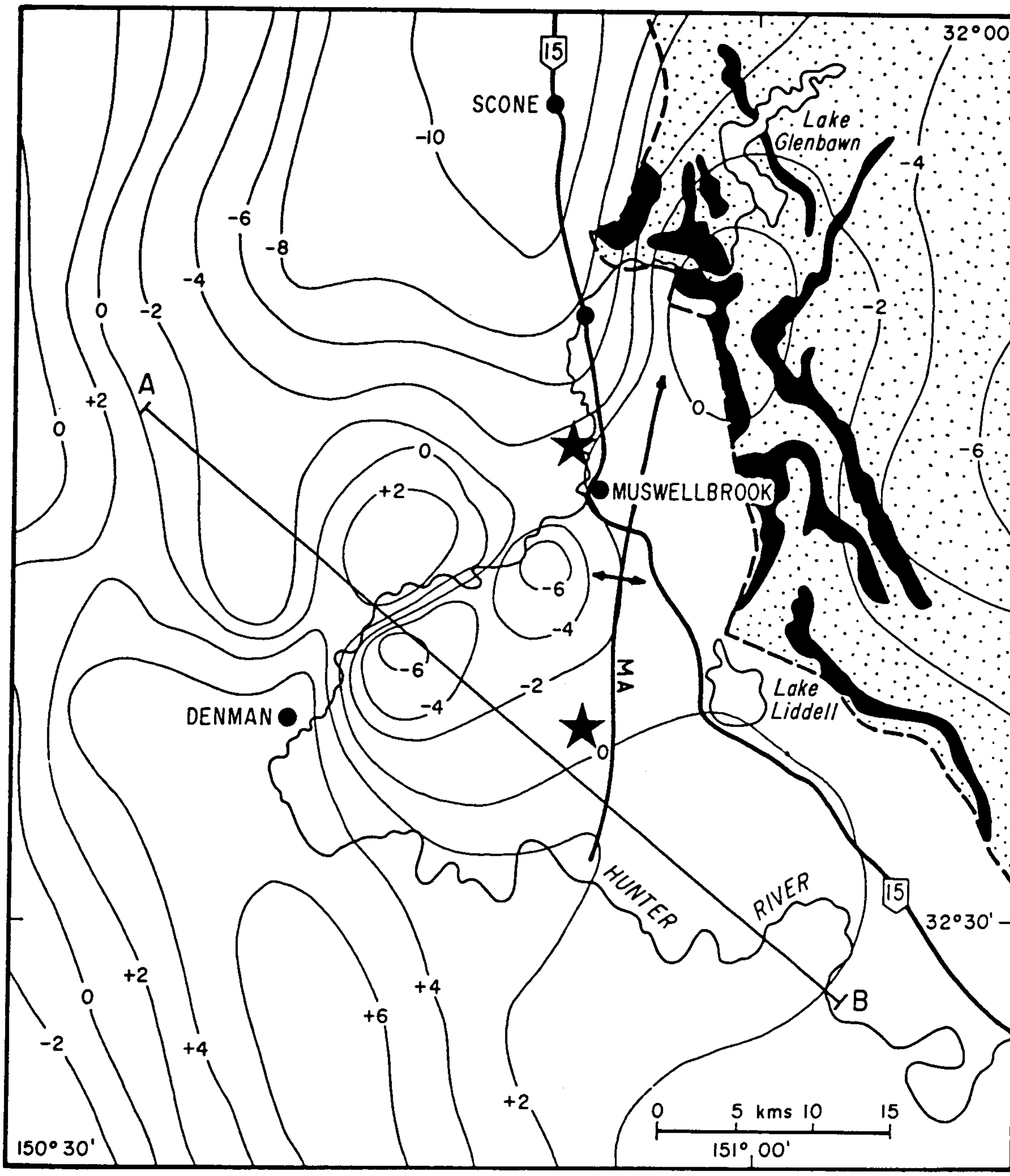

0 5 10 15
km
151° 15'
151° 30'
151° 45'
32° 30'
32° 45'
Camberwell
Singleton
Branxton
Paterson
MAITLAND
CESSNOCK
NEWCASTLE
Tasman Sea
C
D
15
* Granodiorite outcrops
NW
SE
M. Gal.
30
20
10
0
10
20
Bouger Anomaly
Branxton
Regional Gradient

FIGURE 3.17

Residual Gravity map and Bouger profile of the negative gravity anomaly in the vicinity of the determined ignimbrite source in the Muswellbrook District (See Fig 3.16). Locations of the Curra Keith and Oakfields ignimbrites (black) sources (large stars) are shown. Stippled area is Carboniferous succession and the unshaded is the Permo-Triassic Sydney Basin.


32°00'
SCONE
15
-10
Lake
Glenbawn
-4
-6
-8
-4
0
-2
-2
A
+2
0
0
-6
0
+2
MUSWELLBROOK
-6
-4
MA
-6
-2
-4
DENMAN
0
Lake
Liddell
HUNTER
RIVER
15
32°30'
B
+2
0
+4
+6
-2
+4
+2
0
5 kms 10
15
151° 00'
150° 30'

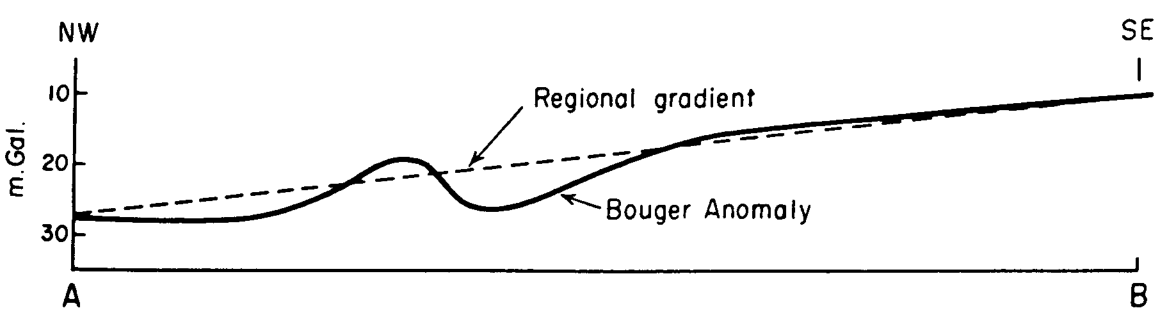
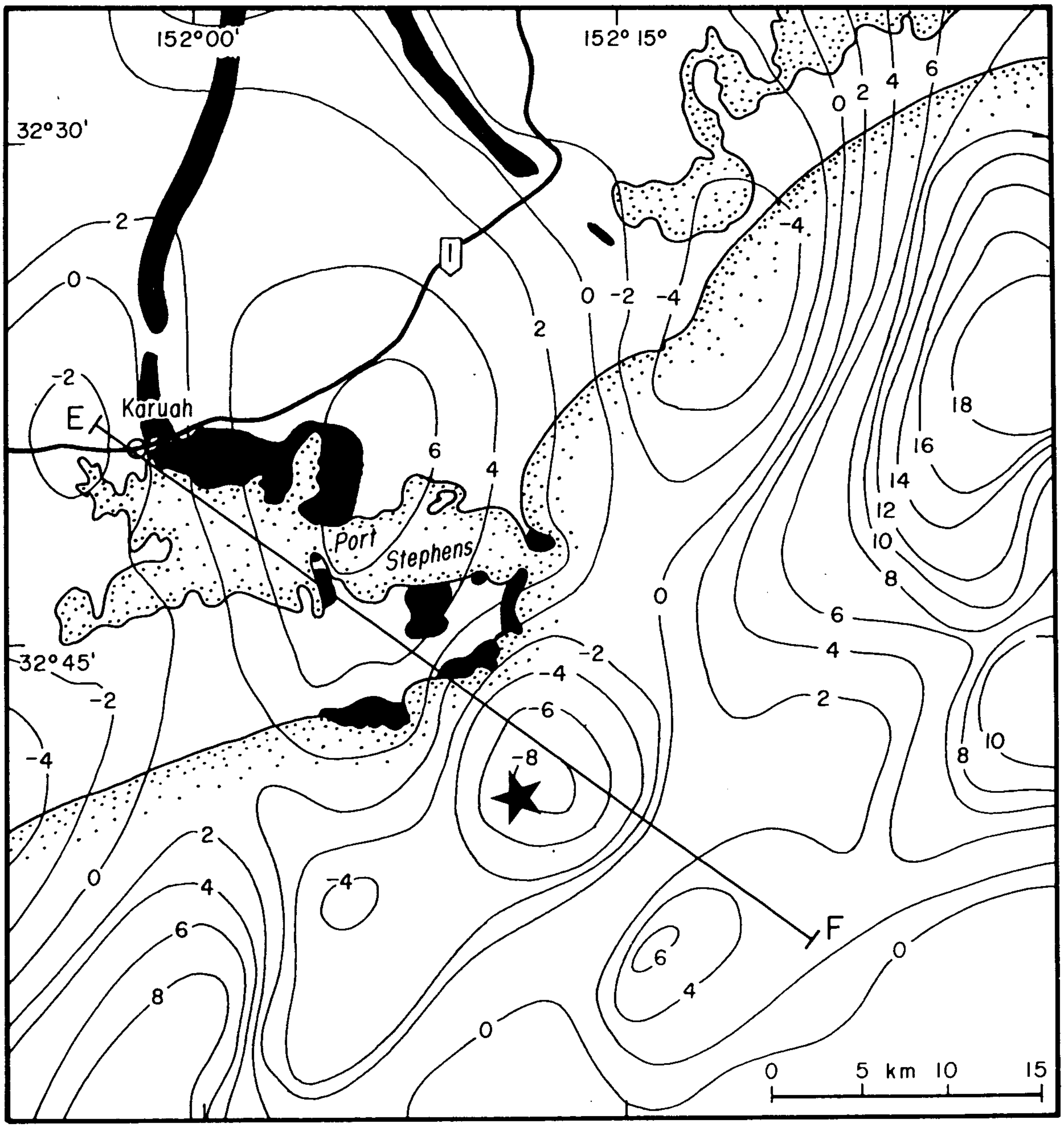
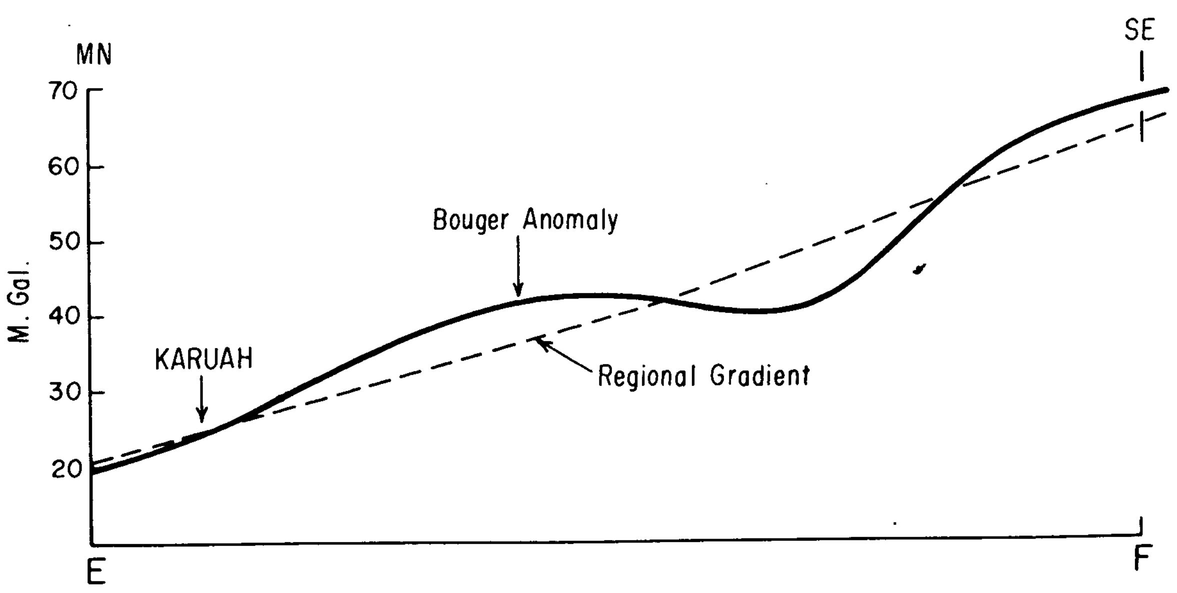

NW
SE
10
20
30
m.Gal.
Regional gradient
Bouger Anomaly
A
B

FIGURE 3.18

Residual Gravity map and Bouger profile showing an elongated negative gravity anomaly in the vicinity of the determined ignimbrite sources in the Port Stephens District. Location of the common source (large star) of the Nelson Bay and Port Stephens ignimbrites (Black) is shown. Stippled area is Carboniferous succession and the unshaded is the Permo-Triassic Sydney Basin.


152°00'
152° 15°
32°30'
32°45'
Karuah
E
F
Port
Stephens
0
5 km
10
15


MN
SE
70
60
50
40
30
20
M. Gal.
Bouger Anomaly
KARUAH
Regional Gradient
E
F

(Fig 3.3), and yet they are shown to have been derived from two separate source vents which have been determined to be only about 12 km apart. This distance is well within the dimensions of known calderas that have produced large volume ignimbrites (Table 3.3), with La Garita, the largest known caldera having a diameter of 28 km (Steven and Lipman 1976). Thus, it has been postulated (Chapter 2) that the source vents of the Curra Keith and Oakfields ignimbrites were sited within the one caldera, and probably on the ring-fracture margin of that caldera (see later).

The three determined source areas (calderas), one in the each of the three districts, are shown to be located on the western side of the Hunter Fault, where the Permo-Triassic strata of the Sydney Basin presently crops out. As a consequence of this, there is no visible evidence to prove their existence. However, there is substantial evidence in the regional gravity map of the area to suggest that the source calderas are are still present, although buried, or in the case of the Maitland Volcanic Centre, partly buried.

The regional 1:50,000 Bouger Gravity map (Fig 3.15), which includes the study region, shows that overall there are very few gravity anomalies in the whole of the southern part of the New England Orogen. Moreover, all of them, except for the three that are in the exact vicinity of each of the three determined volcanic centres, tend to be oblong in shape and can be reasonably explained by folds or intrusions that crop out there. Yet, the anomalies in the vicinity of the determined source areas are nearly circular and cannot be accounted for by any known surface geological structure. Residual gravity maps and profiles are calculated for each of the three anomalies and they reveal a roughly circular, 18 mgal, positive anomaly in the vicinity of the Maitland centre (Fig 3.16) and nearly circular, negative anomalies of 6 mgals in the location of the Muswellbrook centre (Fig 3.17) and 8 mgals at the Port Stephens centre (Fig 3.18).

The anomalies in the vicinity of the Muswellbrook (Fig 3.17) and Port Stephens volcanic centres (Fig 3.18) are little different in shape, size and magnitude from the negative 9 mgal anomaly that Yokoyama (1981) describes as centred over the Krakatau Caldera. Furthermore, Yokoyama (1958, 1963, 1969) establishes that low (negative) gravity anomalies are common over many calderas and are caused by the presence of caldera-fill deposits which usually have a density of about 0.2 - 0.4 g/cm^3 less than the surrounding basement rocks. Seager and Brown (1979) endorsed this concept when they described a negative gravity anomaly over the Organ Caldera which they said is caused by the caldera being infilled with a pool of 'low density', rhyolitic lavas and pyroclastic rocks. Minmura (1984) explained the negative gravity anomaly, in the region of the source of pumice flows near Bend, Oregon was due to low density (dacitic) rocks which had accumulated over vents (as flow and domes) which have subsequently been buried. It is thus postulated that the circular-shaped anomalies in the region of each of the determined volcanic sources, in the southern New England Orogen, are due to the presence of (pyroclastic?) infilled calderas, under the Sydney Basin succession. The periphery of each anomaly probably reflects the rise onto the denser rocks of the caldera rims, as noted over the edge of the Krakatau caldera (Yokoyama 1981).

The positive gravity anomaly in the region of the Maitland volcanic centre is the only one that has so far been modeled. In an unpublished study, Nalaye (1977) showed that the anomalous positive gravity, and the slight distortion of the anomaly from a circular shape in the SW region, are due to the Lochinvar Anticline which trends northwards across the anomaly. But, to satisfy his model Nalaye (1977) proposed that, due to substantial differences in the density between the 'indurated' Permian and the 'highly indurated' Carboniferous rocks, additional to the anticline, a 2 km thick, 'low density', intrusion of granodioritic composition, approximately 2 km from the surface was required to account for the anomaly.

Lipman (1984) proved that there is a close connection between ignimbrite producing calderas and sub-caldera co-genetic magmatic roots, namely granitic plutons. Mt. View Range occurs on the southwestern side of the Maitland anomaly and it is a small inlier of Carboniferous strata lying within the Sydney Basin (Fig 3.18). This inlier consists of a sliver of a granodiorite, overlain by 450 m of flow-banded rhyolite lava flows and Brakel (1972) depicted the outcropping granodiorite to be part of a larger (subsurface) intrusion of batholithic dimension. The rhyolite lavas have been examined and they are, no doubt, part of a rhyolite dome, and the granodiorite, although it is not yet proven, is considered to be part of the subvolcanic cogenetic 'granitic root' that was once the magmatic system for the rhyolite lavas at Mt. View. Another small outcrop of granodiorite occurs on the northern side of the gravity anomaly (Fig 3.15) and it is assumed to be correlative to the granodiorite at Mt View. Furthermore, it is also viewed as being a part of the same sub-volcano 'granitic root'. The granodiorite is of Lower Carboniferous age (Brakel 1972) and, although as yet no study (especially chemical) has been done to confirm their relationship, the granodiorite is assumed to be equivalent in age to the ignimbrites outcropping in the Paterson District. Thus, the granodiorite is considered as an exposed part of a sub-caldera intrusion and it is the remains of the magmatic source of the ignimbrites from the Maitland caldera.

The determined source areas of the Curra Keith, Oakfields and Martins Creek ignimbrites all lie near the edge of their respective anomalies (Figs. 3.16 and 3.17). This probably indicates that these ignimbrites were erupted from vents located on the ring-fracture around the margins of the calderas. The source area of the Port Stephens and Nelson Bay ignimbrites, on the other hand, lies near the centre of the anomaly (Fig 3.18) and perhaps indicates that they were erupted from a vent within the caldera.

The dimensions of the gravity anomalies indicate that the Muswellbrook caldera is about 12 - 15 km across and the Port Stephens caldera about 10 km across. The dimension of the Maitland caldera is masked by the presence of the attendant sub-caldera granodiorite intrusion and the Lochinvar Anticline, but if it is taken that the rhyolites at Mt View represent one centre of activity and the source area of Martins Creek ignimbrite another, they both lie on the edge of the anomaly, and presumably define the margins of the caldera. Thus the Maitland caldera is estimated to be about 25 km across. These inferred sizes of the Lower Carboniferous calderas are similar to the dimensions of other 'modern' ignimbrite-producing calderas (Table 3.3), and the volume of the ignimbrites in comparison with the caldera dimensions are also similar.

3.7 THE 'KUTTUNG' VOLCANOES

3.7.1 Volcanic Arc or Volcanic Chain

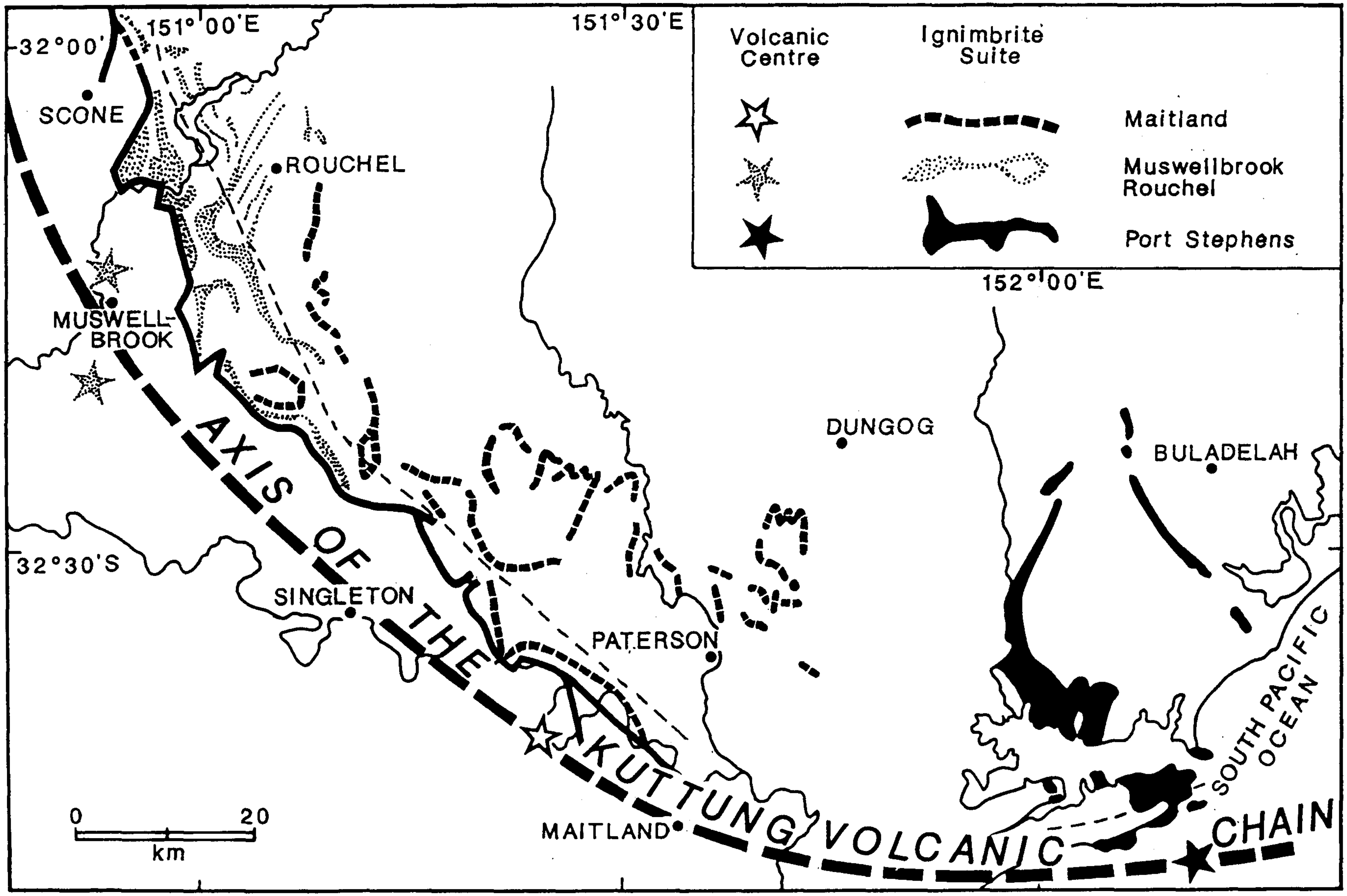
The presently accepted concept that the source volcanoes of the volcanic rocks in the New England Orogen, in the Carboniferous, as being part of a continental volcanic arc (Kuttung Arc) (Harrington and Korsch 1985; Roberts and Engel 1987) is considered to be inappropriate.

The dominant primary volcanic lithology in the Tamworth Belt, in both the Lower Carboniferous (Roberts and Oversby 1974) and the Late Carboniferous (McPhie 1983, 1984), is large-scale silicic ignimbrites which are numerous and interspersed in thick volcaniclastic successions. Large-scale ignimbrite eruptions are atypical of volcanic arc volcanoes, even though the most devastating eruptions in historical time (Table 3.3) have been ignimbrite-producing eruptions from arc volcanoes (e.g. the 1470 B.C. eruption of Santorini and the 79 AD eruption of Vesuvius that destroyed Pompeii, both located on the Aegean Arc; the 1815 eruption of Tambora and the 1883 eruption of Krakatau, both located on the Sunda Arc). But these ignimbrites are volumetrically small in comparison with ignimbrites in western USA, New Zealand, Japan and the central Andes (Table 3.3), which are regions that contain a number of large-scale (Cenozoic) ignimbrites of equivalent size to the ignimbrites in the southern Tamworth Belt. These ignimbrite regions are typified by the presence of calderas, which are the sources of the ignimbrites, and all of the regions are generally accepted to be sited within an ensialic back-arc rift basin of some kind. For example, the intracontinental rift system forming the Basin and Range Province in western USA, which contains the Valles and Snake River - Yellowstone ignimbrite successions is considered to be a continental back-arc basin system analogous to oceanic back-arc basins (Scholtz *et al.* 1971 Eaton 1984); the Taupo Volcanic Zone in New Zealand is the landward extension of the Lau-Harve back-arc (Cole 1984); the ignimbrite-producing calderas in southern Japan are located at the intersection of the Marianas back-arc and Japanese arc (Sugimura & Uyeda 1973); and the eastern Chilean Andes calderas are postulated to be sited in a linear ensialic, verging on ensimatic, back-arc basin (Dalziel 1981; Åberg *et al.* 1984). Therefore, in keeping with this model, it is thus proposed that the Lower Carboniferous ignimbrites, in the southern part of the Tamworth Shelf, similarly originated from calderas and they were also located within an ensialic continental back-arc basin.

The three Lower Carboniferous caldera sites established in this study are almost equally spaced about 60 km apart, between 5 and 10 km west of the Hunter Fault. (cf. the volcanic centres in the Taupo Volcanic Zone which are spaced about 50 km apart (Cole, 1979)). Moreover, M^{c}Phie (1981) postulated that the Upper Carboniferous calderas were spaced, in a line, between 40 and 80 km apart. Thus, during the Carboniferous era in the New England Orogen, there was a chain of volcanoes, dominated by

FIGURE 3.19

Map showing spatial position of the Lower Carboniferous ignimbrites from their respective sources and the axis of the Kuttung Volcanic Chain in the southern part of the New England Orogen. Dashed line marks the change of slope from a flat alluvial plain on the eastern side rising on to the slightly elevated volcanic chain.


151° 00'E
151° 30'E
152° 00'E
32°00'
32°30'S
SCONE
ROUCHEL
MUSWELL-
BROOK
SINGLETON
PATERSON
DUNGOG
BULADELAH
MAITLAND
AXIS OF THE KUTTUNG VOLCANIC CHAIN
SOUTH PACIFIC OCEAN
0
20
km
Volcanic Centre
Ignimbrite Suite
Maitland
Muswellbrook
Rouchel
Port Stephens

calderas, along the western edge of the Tamworth Belt, and it is therefore proposed that the source of the volcanics, cropping out in the Tamworth Belt, from now on be referred to, not as the Kuttung Arc, but as the Kuttung Volcanic Chain.

In the southern part of the New England Orogen the calderas can be located on a west convex arcuate line drawn parallel to the Hunter Fault. This line defines the axis of the Kuttung Volcanic Chain in the study area (Fig 3.19).

3.7.2 Palaeo-topography of the Kuttung Volcanic Chain and Surrounds

In palaeogeographic reconstructions of the southern part of the Tamworth Belt Roberts and Oversby (1974) and Roberts and Engel (1980) indicate that the sea was a mere 30 km east of the Muswellbrook Caldera when both the Curra Keith and Oakfields ignimbrites were erupted. (There is evidence that these ignimbrites flowed into the sea, although they were soon reworked (Chapter 2.8.6)). But by the time of the Martins Creek ignimbrite and the ignimbrites from the Port Stephens source, the sea had retreated some distance to the north (Roberts and Engel 1987). All of the ignimbrites are interbedded with fluviatile conglomeratic sands, which were deposited as an alluvial fan or pediment by braided rivers (Roberts and Oversby 1974).

McPhie (1987) likened the volcanic chain along the northern part of the Tamworth Belt, in the Late Carboniferous, to the Andes in the northern part of Chile but this analogue does not fit the setting of the southern part of the chain in the Lower Carboniferous. Thick, coarse conglomeratic fluvial sediments underlie the ignimbrite succession in much of the southern-part of the Tamworth Belt and they indicate that there was an uplifted and eroding surface (in the west) at that time. Lindley (1981) suggested that, as a consequence of an initial uplift of the volcanic region, in the early part of the Lower Carboniferous, the southern part of the Tamworth Belt was scoured by deep east-west trending channels, running out to the sea. The channels were subsequently infilled with coarse polymictic conglomerates that were derived from the erosion of the uplifted (basement) rocks that had a diverse range of lithologies. The largest clast in a very coarse part of these conglomerates was measured at .75 m, which indicates that there must have been significant relief in the uplifted area to generate the energy to transport this sediment. However, by time of the eruption of first major ignimbrite the relief in the volcanic source area appears to have lessened. The strong radial flow pattern exhibited in the ignimbrites in both the Paterson and Muswellbrook-Rouchel Districts indicates that their outward flow was unhindered across a flat alluvial surface. Furthermore, since the ignimbrites were emplaced on an alluvial plain, only a short distance from both the coast and the (determined) source calderas, then this can only indicate that there was little relief on the region, just east of the chain, at the time of the ignimbrite eruptions.

In the area between the Hunter Fault, out to a line parallel to the fault about 5 km from it, in the Muswellbrook-Rouchel and Maitland Districts, the Carboniferous succession consists essentially of ignimbrites piled one on top of the other, with only minor interbeds of volcaniclastic sediments. Yet, east of this area the ignimbrites are spaced between thick interbeds of sediments. Moreover, as has previously been described, the ignimbrites are also one on top of the other, south of Fingal Bay, in the Port Stephens District, although they are spaced between sediments north of that area. Thus, it seem likely that in the region that the ignimbrites are directly on top of each other it was higher ground where no deposition of sediments and erosion of the ignimbrites occurred. Conversely, where the ignimbrites are spaced between sediments it was 'lower' ground where only deposition occurred. Thus, a line drawn roughly parallel to the Hunter Fault, about 5 km east it (Fig 3.19), would probably mark the place that the slope changed from a flat alluvial plain in the east, rising westward onto the Kuttung Volcanic Chain.

3.8 MOVEMENT ON THE HUNTER FAULT

The Hunter Fault forms the western margin of the Tamworth Belt in the southern part of the New England Orogen and ever since the Fault was defined as the Hunter Thrust by Osborne (1928) there has been much debate over how much displacement, either thrust or strike-slip, has occurred on it. There is only one location that any thrust displacement is known and that is in the Muswellbrook region where a very small length (2-3 km) of the fault is known, from drilling, to be at a low angle, northeastward-dipping (Roberts and Engel, 1987). The Carboniferous ignimbrite-fluvial sedimentary succession is thrust over the Permian strata of the Sydney Basin. The Peel Fault, forming the eastern margin of the Tamworth Belt , runs parallel to the Hunter Fault and it has undergone significant sinistral shear (Corbett 1976; Murray *et al* 1987) and Roberts and Engel (1987) have suggested that sinistral shear may also have occurred along the Hunter Fault, prior to the development of the low angle thrust in the latest Permian or Triassic. However, the close correspondence of the determined volcanic sources with the gravity anomalies suggests (1) little if any lateral movement on this part of the Fault has occurred since the Lower Carboniferous and (2) that thrust movement is also minimal. It is thus suggested that the Hunter Fault is merely a major disjunction in the Australian craton whose inception probably relates to the formation of the rift along the eastern side of the (continental) back-arc basin, in which the ignimbrite-producing calderas were located.

3.9 CONCLUSIONS

Besides the probable savings in time and costs in not having to make thin sections, the results obtained in this study show that there are many benefits in making flow lineation measurements from welded ignimbrites on slabs rather than thin sections. The most significant advantage is the strength of the data can be obtained, as is expressed by vector magnitude and Chi-square values. In this study, only 2 out of the 120 flow lineations data sets obtained were rejected, because their Chi-square values were not significant at the 90 confidence level, and the average vector magnitudes obtained range between 45% and 57% (Table 3.1). These compare with the rejection of 8 out of 47 flow lineations, and 23% and 24% average vector magnitudes obtained in the study of the Mogollon Plateau ignimbrites (Rhodes and Smith, 1972).

The flow directions determined in three rhyolitic and two dacitic ignimbrites, cropping out along the southwestern margin of the Tamworth Belt, point to three separate volcanic sources, spaced approximately 50 km apart, that were located on the Kuttung Volcanic Chain during the Lower Carboniferous. Nearly circular gravity anomalies occur in the vicinity of each of the determined centres and they suggest that calderas, infilled with low density (pyroclastic) rocks, lie at depth below the younger Permo-Triassic Sydney Basin succession.

The calderas, assuming that they were like modern ignimbrite-producing calderas in western USA, Japan New Zealand, and the central Andes, were sited within an ensialic back-arc basin. The relief of the volcanic region was thus 'low' and the ignimbrites flowed, unhindered, out over alluvial plains sloping away from the volcanoes.

Along the edge of the Tamworth Belt, several ignimbrites are piled one on top of the other, up to about 10 km from the edge of the calderas (about 5 km east of the Hunter Fault) and beyond this distance, the ignimbrites are spaced between thick fluvial sediments. The pinching-out of the sediments appears to mark a westward rise, from the alluvial plains, onto the volcanic chain.

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CHAPTER 4

GEOCHEMISTRY OF THE LOWER CARBONIFEROUS DACITIC AND RHYOLITIC IGNIMBRITES IN THE SOUTHERN NEW ENGLAND OROGEN, NEW SOUTH WALES, AUSTRALIA.

4.1 ABSTRACT

53 samples of the six most extensive silicic ignimbrites in the Lower Carboniferous succession in the southern part of the New England Orogen were analysed for both major and trace elements. Chemical 'fingerprinting' of these ignimbrites is achieved by the analyis of several samples of the ignimbrites from localities scattered throughout their outcrop. Locally parts of the ignimbrites are highly welded, forming a black glassy porphyritic obsidian-like rock. These are the most ancient glassy volcanics, so far, found.

Three accepted chemical classifications schemes (K_2O vs SiO_2, Na_2O+K_2O vs SiO_2 and 30<AN>50) give the same result for each of the ignimbrites which indicates that their present (anhydrous) elemental abundances are close to their original ones. The Port Stephens ignimbrite from the Port Stephens Caldera and the Curra Keith and Oakfields ignimbrites from the Muswellbrook Caldera are each high-K rhyolites. The Nelson Bay ignimbrite from the Port Stephens Caldera and the Martins Creek ignimbrite from the Maitland Caldera are both high-K dacites, and the M^c^Cullys Gap ignimbrite, also from the Muswellbrook Caldera, is probably best called a sodic trachyte.

A plot of Sr vs V discriminates each of the ignimbrites from one another. Notable hiatus occur in some of the trace element data which allows some distinctions to be made. For example, Ni+Cr abundances distinguish the rhyolites (<10 ppm) from the dacites (>18 ppm) and Zr differentiates the Muswellbrook Caldera (>225 ppm) from the Port Stephens and

Maitland Calderas (<200 ppm).

The Lower Carboniferous ignimbrites have their own distinctive chemistry although both major and trace element abundances, in part, correlate with similar dacites and rhyolites in the 4 regions of the world today that have a number of 'modern' large-scale ignimbrites - the high-K volcanics in the Basin and Range Province in western USA and the South American Andes, and the calc-alkaline volcanics in southern Japan and New Zealand. Al_2O_3, TiO_2, total iron oxides and MgO show comparable trends to those in the other four regions, whereas CaO and P_2O_5 in comparison are depleted. K_2O matches the other high-K regions of western USA and Andean South America. The Lower Carboniferous dacites are notably enriched in Na_2O.

The trace elements (Rb, Ba, Cu Y, Rb, Sr, V, Cu), and Rb/K abundances are comparable with the four regions except that the Lower Carbonifeours ignimbrites show their own individual trends. The most evolved ignimbrite compositions, the most silica-rich rhyolites, are almost identical in composition to the similarly evolved ignimbrites in the western USA. This perhaps indicates that the thickness of the crust under the Kuttung Volcanic Chain in the Lower Carboniferous was about the same as it is in western USA today. Thus, it is proposed that the sialic crust under the Kuttung Volcanic Chain in the Lower Carboniferous was about 35-40 km thick, and this is no different from its thickness today.

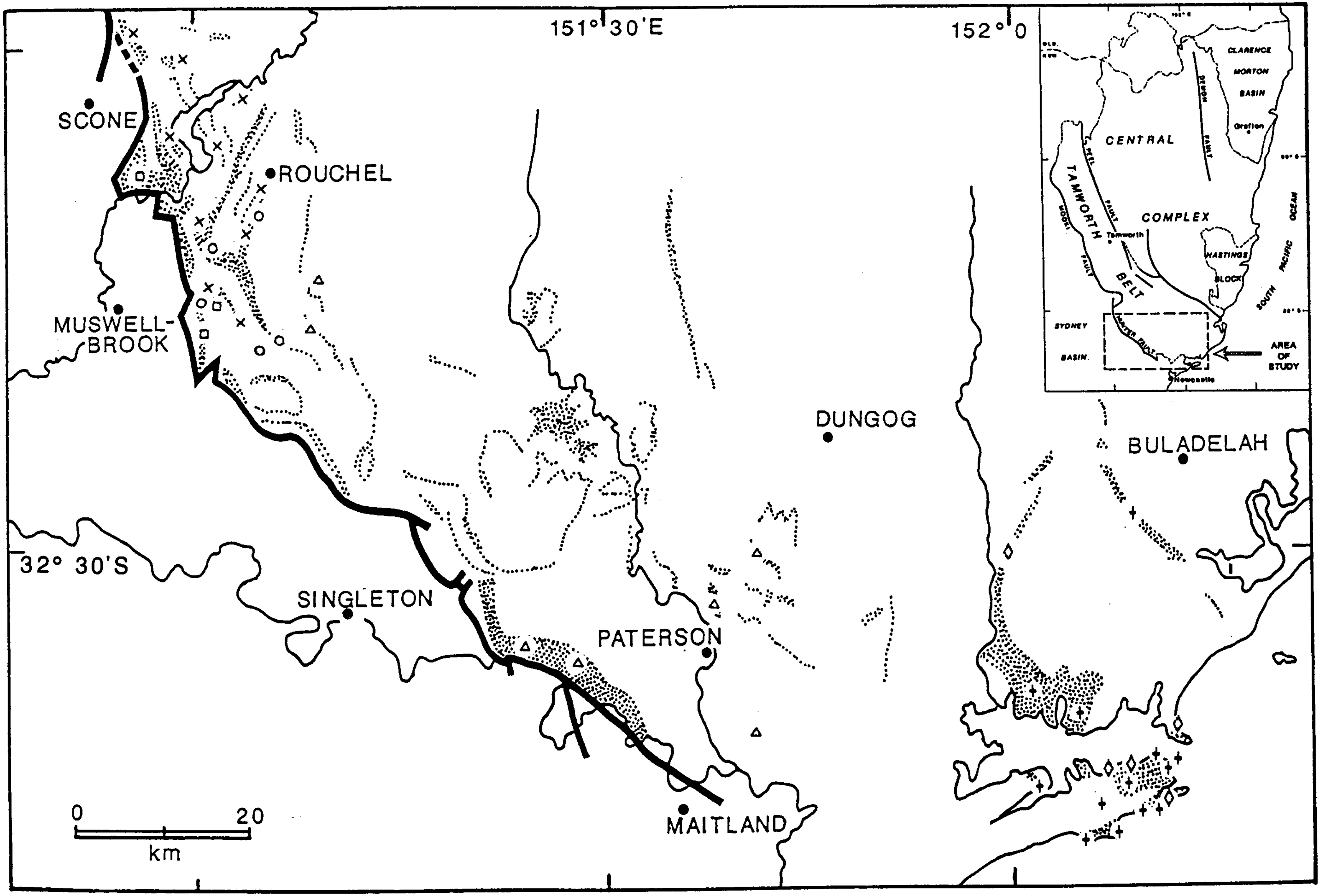
4.2 INTRODUCTION

Roberts and Oversby (1974) and Roberts and Engel (In press) have mapped a number of ignimbrites in the Lower Carboniferous succession in the Tamworth Belt (Korsch 1977) at the southern end of the New England Orogen (Day *et al* 1978) (Fig. 4.1, inset). The ignimbrites range in composition from

FIGURE 4.1

Outcrop map of the Lower Carboniferous ignimbrites (stipple) in the Hunter Valley with sample localities shown. See Fig 4.2 for the key to symbols used to indicate samples from the different ignimbrite units. Stars denote the locations of the three ignimbrites source calderas.

Inset shows the area of study, at the southern end of the Tamworth Belt, in relation to the tectonic elements of the New England Orogen.


151° 30'E
152° 0
SCONE
ROUCHEL
MUSWELL-
BROOK
DUNGOG
BULADELAH
32° 30'S
SINGLETON
PATERSON
MAITLAND
0
20
km
CLARENCE
MORTON
BASIN
Grafton
CENTRAL
TAMWORTH
COMPLEX
Tamworth
HASTINGS
BLOCK
BELT
SYDNEY
BASIN
SOUTH
PACIFIC
OCEAN
AREA
OF
STUDY
Newcastle

andesite to rhyolite and the most extensive outflow sheets are the rhyolites and dacites. They crop out on the eastern side, and within 30 km, of the Hunter Fault System, which forms the western edge of the Tamworth Belt in this region. The ignimbrite outcrop almost continuously in a NNW-trending arcuate belt from the coast at Port Stephens to north of the township of Scone (Fig 4.1). Some of these ignimbrites are unique in that densely welded parts of them are locally still glassy, making them among the most ancient vitrophyric volcanics in the world yet encountered (Wilkinson 1971).

Previous geochemical research on the Lower Carboniferous ignimbrites has concentrated on either the glassy parts of the ignimbrites (Wilkinson 1971) or on the andesitic units (Jakeš 1970, and White 1972) and to date little has been published on the chemistry of the more differentiated dacites and rhyolites. Some previous analyses of the same dacites and rhyolites considered in this study were listed in local studies (Osborne 1925, Sussmilch and Clark 1928, David 1950, Osborne 1950, Roberts and Oversby 1974). (Appendix VII), but most of these analyses do not compare with the consistent results obtained in this study, nor with other analyses in recent geochemical theses on the area (Jakeš 1970, Nguyen 1976). Therefore, these analyses are not considered in any major context in this study.

Most of the Lower Carboniferous ignimbrites in the southern part of the Tamworth Belt were produced from three calderas which were located at Port Stephens, Maitland, and Muswellbrook (Fig 4.1). The identification of these calderas (Chapter 3) has provided a logical volcano by volcano approach to a study of the chemistry of the ignimbrites, and this paper is both a beginning to 'fingerprinting' the major and trace element chemistry of the Lower Carboniferous ignimbrites in the southern part of the Tamworth Belt, and the characterisation of the chemistry of the products from each caldera.

4.3 IGNIMBRITES AND THEIR CENTRES OF ERUPTION

The Lower Carboniferous ignimbrites that crop out in the Tamworth Belt were derived from calderas sited on the Kuttung Volcanic Chain (Buck 1986; Chapter 3), which was located along the length of the westernside of the Tamworth Belt. The ignimbrites were emplaced on the eastern flank of the chain and they interfinger with terrestrial volcaniclastic sediments.

In the Upper Carboniferous succession, in the northern part of the Tamworth Belt, McPhie (1987) determined that there are the remains there of three separate pyroclastic fields (or aprons) and proposed that the ignimbrites and volcaniclastic facies in the three aprons were produced from at least seven separate volcanic centres. These included five individual ignimbrite sources (calderas?) and two stratovolcanoes. In the Lower Carboniferous succession in the southern part of the Tamworth Belt there are also the remains of at least three pyroclastic aprons, although the volcanic products in these aprons have been determined (Chapter 3) to have been derived from only three calderas. These calderas, each with a diameter of at least 10 km, were sited between 5 and 10 km west of the Hunter Fault and they consitute the southernmost volcanoes of the Kuttung Volcanic Chain. The caldera that is located in the Upper Hunter Valley has been named the Muswellbrook Caldera, that in the lower Hunter Valley the Maitland Caldera, and the Port Stephens Caldera is located, just off the coast, at the eastern end of the Hunter Valley. These calderas are now completely buried by the Permian Sydney Basin succession and are only revealed by strong, circular Bouger gravity anomalies over them (Chapter 3).

The three calderas were active at slightly different times during the Lower Carboniferous and of the three, the Muswellbrook Caldera produced both the greatest thickness and number of ignimbrites. The Muswellbrook caldera commenced activity in the early Viséan and it was possibly active for as

Sample	36401	36404	36407	36414	36417	36421	36427	36429	36431	36435	36436	36439	36450	36453	36456	36461	36466	36468
Ig.Unit	CKI	CKI	CKI	CKI	CKI	CKI	CKI	CKI	CKI	CKI	CKI	CKI	OI	OI	OI	OI	OI	OI
G.Ref	086476	086476	089476	200467	097552	112392	138471	168404	123320	041575	177537	162282	122317	122316	131367	170399	213244	213244
Map	Sc	Sc	Sc	Wo	Sc	Ab	Wo	RB	RB	Sc	Wo	DH	RB	RB	RB	RB	DH	DH
MAJOR ELEMENTS (Weight %)																		
SiO_2	68.52	69.02	67.60	71.30	70.69	69.66	70.88	69.63	68.24	68.65	72.53	69.23	70.63	74.09	69.85	73.90	74.61	72.92
TiO_2	.45	.43	.46	.39	.42	.44	.41	.46	.45	.45	.36	.46	.28	.19	.35	.29	.22	.26
Al_2O_3	14.87	14.68	15.09	14.40	14.54	14.86	15.02	14.91	15.16	15.09	14.14	16.12	14.91	13.50	15.54	13.71	14.14	14.42
Fe_2O_3	2.68	1.94	1.33	1.53	2.27	2.52	2.09	2.94	2.15	1.25	2.03	2.23	2.58	1.93	3.14	2.16	1.35	2.25
FeO	.23	.23	.90	1.25	.27	.29	.31	.14	.29	.56	.34	.32	.14	.10	.14	.23	.19	.17
MnO	.07	.07	.09	.05	.08	.06	.03	.12	.04	.06	.05	.03	.05	.04	.06	.06	<.01	.02
MgO	.56	.64	.26	.46	.48	.39	.37	.35	.38	.52	.34	.47	.26	.10	.18	.29	.27	.22
CaO	1.23	1.29	2.36	.54	.64	.53	.39	.58	1.75	2.04	.34	.75	.43	.24	.33	.39	.71	.28
Na_2O	4.00	4.20	3.85	3.74	4.48	5.03	5.07	5.02	4.35	3.22	4.41	3.74	4.75	4.34	3.66	4.37	3.81	3.80
K_2O	4.38	4.28	2.94	4.81	3.95	4.06	4.17	3.93	3.65	4.18	4.19	4.70	3.78	3.82	4.33	3.77	2.50	4.38
P_2O_5	.09	.10	.11	.09	.10	.09	.10	.10	.10	.13	.09	.12	.03	.02	.05	.06	.02	.03
H_2O+	2.31	2.19	3.37	1.22	1.55	1.33	1.61	1.65	2.31	2.57	1.34	2.06	2.01	1.55	2.30	1.51	2.54	1.94
CO_2	.78	1.18	2.13	.11	.39	.40	.35	.20	1.97	1.84	.12	.54	.51	.27	.31	.14	.08	.29
Total	100.17	100.25	100.49	99.91	99.86	99.66	100.80	100.03	100.84	100.56	100.28	100.77	100.36	100.19	100.24	100.88	100.44	101.00
TRACE ELEMENTS (p.p.m.)																		
Nb	7	8	6	7	7	7	7	7	7	6	8	7	8	10	9	7	9	9
Zr	248	245	246	249	251	262	248	275	241	180	228	184	278	255	290	256	288	286
Y	25	24	27	29	26	23	24	32	28	23	25	24	39	41	46	40	46	37
Sr	165	139	73	133	140	96	125	121	111	149	145	184	109	66	123	76	81	127
Th	17	22	17	22	17	16	17	20	16	8	20	14	17	17	14	16	16	13
Pb	9	12	7	17	10	11	8	10	12	11	10	9	15	13	11	14	39	15
U	4	7	3	9	5	4	4	4	2	2	3	5	4	3	<2	<2	3	5
Rb	139	162	80	150	120	128	144	139	111	109	134	172	124	127	131	66	87	143
Ga	19	21	18	16	15	18	19	17	18	16	15	17	15	16	17	14	19	18
Zn	53	39	43	55	54	49	44	37	45	38	40	42	70	44	77	70	47	34
Cu	14	10	11	14	16	13	11	11	11	6	11	15	5	3	5	6	4	6
Ni	3	2	3	3	2	3	2	4	3	4	4	2	2	<2	3	3	2	3
Mn	527	537	725	353	585	484	198	905	333	435	357	236	367	315	452	448	61	116
Cr	<2	4	6	5	6	3	2	4	6	5	6	5	2	<2	3	5	<2	4
V	35	23	33	23	31	30	28	33	35	29	18	36	8	2	10	6	2	2
Ti	2895	2840	2895	2481	2840	2882	2832	2949	2895	3136	2512	3176	1886	1169	2401	2010	1545	1811
Ba	600	557	402	597	563	498	567	532	510	524	483	662	573	624	676	676	686	760
K/Rb	262	219	305	266	273	263	240	235	273	318	260	227	253	250	274	474	239	254
C.I.P.W. NORMS																		
Q	24.34	24.15	28.11	28.57	26.90	22.52	23.59	22.87	24.21	28.67	29.09	26.76	26.34	32.88	29.99	32.12	40.53	32.37
Or	25.88	25.29	17.37	28.42	23.34	23.99	24.64	23.22	21.56	24.70	24.76	27.77	22.33	22.57	25.58	22.27	14.77	25.88
Ab	33.83	35.52	32.56	31.63	37.89	42.54	42.88	42.66	36.79	27.23	37.30	31.63	40.17	36.71	30.96	36.96	32.22	32.14
An	5.51	5.74	10.99	2.09	2.52	2.04	1.28	2.22	8.03	9.27	1.10	2.94	1.94	1.06	1.31	1.54	3.39	1.19
C	1.53	1.04	1.55	2.28	1.97	1.45	1.70	1.59	1.11	1.87	1.95	3.81	2.30	1.84	4.35	1.88	3.03	2.99
Di	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hy	.3.51	3.04	2.24	3.35	3.03	2.97	2.58	3.22	2.58	2.38	2.59	2.88	2.83	1.92	3.04	2.61	1.76	2.43
Mt	1.45	1.09	1.15	1.44	1.26	1.41	1.20	1.52	1.22	.93	1.19	1.28	1.35	1.00	1.62	1.19	.77	1.20
Il	.85	.82	.87	.74	.80	.84	.78	.87	.85	.85	.68	.87	.53	.36	.66	.55	.42	.49
Ap	.21	.23	.25	.21	.23	.21	.23	.23	.23	.30	.21	.28	.07	.05	.12	.14	.05	.07
AN	14.10	13.91	25.24	6.20	6.24	4.58	2.90	4.95	17.92	25.40	2.86	8.50	4.61	2.81	4.06	4.00	9.52	3.57

Sample	36469	36470	36475	36476	36481	36482	36578	36581	36582	36584	36586	36588	36594	36546	36550	36555	36557	36561
Ig.Unit	OI	OI	McGI	McGI	McGI	McGI	NBIn	NBIn	NBIn	NBIn	NBIf	NBIn	NBIb	PSIp	PSIp	PSIp	PSIp	PSIp
G.Ref	186246	188244	122318	122318	035436	123286	191794	157792	157793	249821	225753	225761	174083	213804	234787	066863	176085	186780
Map	DH	DH	RB	RB	Ab	DH	PS	PS	PS	PS	MP	MP	Bu	PS	PS	PS	Bu	PS
MAJOR ELEMENTS (Weight %)																		
SiO_2	72.97	73.74	65.51	66.78	70.33	64.70	63.34	65.62	64.36	63.92	63.15	62.81	64.99	74.66	74.47	74.26	75.15	75.20
TiO_2	.26	.19	.69	.67	.45	.71	.69	.65	.64	.70	.69	.70	.64	.23	.22	.22	.22	.22
Al_2O_3	14.08	18.77	16.72	16.19	15.28	17.14	15.93	15.77	15.46	16.15	16.01	15.94	15.27	13.39	13.39	13.46	13.50	13.48
Fe_2O_3	2.21	2.00	2.57	3.39	2.22	3.87	2.58	1.78	1.60	2.88	2.50	2.62	1.82	.67	.63	1.40	.72	.74
FeO	.10	.14	1.08	.32	.29	.15	2.16	2.02	1.99	1.80	2.05	2.12	2.38	.81	.66	.24	.52	.52
MnO	.05	<.01	.10	.10	.04	.09	.11	.07	.07	.08	.08	.13	.08	.04	.03	.04	.04	.04
MgO	.28	.16	.90	.36	.58	.28	1.80	1.41	1.76	1.93	2.07	2.14	1.72	.30	.27	.27	.26	.22
CaO	.35	.17	1.21	.97	1.36	1.30	4.17	3.74	4.93	4.09	3.95	4.05	2.32	.59	.38	.70	.59	.57
Na_2O	4.33	3.99	6.36	5.84	4.26	6.80	3.65	2.94	3.89	3.85	3.70	3.60	4.67	3.64	3.59	3.69	3.45	3.44
K_2O	4.45	4.38	3.28	3.52	4.35	2.64	3.10	3.52	.89	2.83	2.94	2.83	3.51	4.92	4.79	4.82	4.94	4.92
P_2O_5	.02	.02	.20	.18	.10	.20	.15	.13	.14	.16	.16	.16	.14	.03	.04	.03	.03	.03
H_2O+	1.36	1.62	1.75	1.52	1.87	2.23	1.86	1.86	3.96	1.79	2.10	1.90	1.81	1.10	1.27	.96	.94	.77
CO_2	.23	.46	.06	.15	.19	.63	.08	.02	.11	.09	.01	.07	.05	.10	.10	.10	.01	.05
Total	100.69	100.64	100.40	100.17	101.32	100.78	99.66	99.53	99.80	100.27	99.41	99.07	99.40	100.48	99.84	100.19	100.37	100.20
TRACE ELEMENTS (p.p.m.)																		
Nb	9	9	6	6	7	7	8	8	8	8	7	7	8	10	10	11	10	9
Zr	280	250	291	283	258	269	160	155	163	162	161	163	162	181	174	181	185	173
Y	35	48	36	35	25	34	34	21	23	25	25	23	23	37	32	35	38	34
Sr	80	75	307	334	294	297	423	402	594	412	416	429	442	172	169	185	156	159
Th	13	12	8	12	17	7	12	16	14	14	12	15	18	26	27	27	26	22
Pb	23	17	13	11	12	13	14	12	17	11	12	13	13	20	33	24	25	25
U	5	4	<2	<2	6	2	2	4	3	3	3	3	5	6	8	7	9	5
Rb	138	121	96	113	150	71	119	122	64	110	112	114	142	212	201	223	226	221
Ga	18	16	19	18	18	21	21	16	18	19	19	18	18	14	14	15	14	14
Zn	58	21	72	71	55	94	74	68	69	62	61	64	66	47	61	38	29	42
Cu	4	6	8	11	13	9	21	17	17	20	18	19	23	4	4	4	5	4
Ni	<2	<2	4	<2	4	3	10	9	7	11	9	10	10	3	3	<2	3	2
Mn	418	55	760	743	297	662	838	522	520	653	635	1063	700	314	198	328	196	339
Cr	6	2	5	<2	5	<2	23	22	18	20	18	20	22	5	5	4	4	<2
V	<2	4	36	37	30	37	100	102	84	102	88	91	89	4	4	2	4	3
Ti	1749	1230	4260	4045	2875	4660	4276	4200	4032	4258	4055	4195	3949	1599	1613	1515	1547	1545
Ba	604	741	485	583	526	448	430	479	372	451	454	433	459	752	814	749	792	775
K/Rb	268	300	284	259	241	309	202	240	115	214	218	206	205	193	198	179	181	185
C.I.P.W. NORMS																		
Q	28.84	32.46	11.46	16.17	24.65	11.17	18.77	25.07	24.49	17.85	17.53	17.73	15.64	32.52	34.38	31.98	34.21	34.49
Or	26.29	25.88	19.38	20.80	25.70	15.60	17.13	20.80	5.26	16.72	17.37	16.72	20.74	29.07	28.30	28.48	29.19	29.07
Ab	36.62	33.75	53.79	49.39	36.03	57.51	30.87	24.87	32.90	32.56	31.29	30.45	39.50	30.79	30.36	31.21	29.18	29.09
An	1.61	.71	4.69	3.64	6.09	5.14	18.52	16.71	22.10	18.43	18.40	18.98	10.35	2.73	.14	3.28	2.73	2.63
C	1.56	2.21	.99	1.44	1.33	1.22	.00	.00	.00	.00	.00	.00	.00	1.08	2.25	.97	1.48	1.53
Di	-	-	-	-	-	-	.97	.81	1.17	.66	.12	.05	.20	-	-	-	-	-
Hy	2.52	2.11	4.80	3.47	3.15	3.47	8.23	6.32	6.83	8.54	9.05	9.55	7.89	1.91	1.63	1.93	1.57	1.48
Mt	1.15	1.06	1.86	1.84	1.25	1.99	2.16	1.75	1.65	2.12	2.07	2.16	1.94	.77	.67	.83	.64	.65
Il	.49	.36	1.31	1.27	.85	1.35	1.31	1.23	1.22	1.33	1.31	1.33	1.22	.44	.42	.42	.42	.42
Ap	.05	.05	.46	.42	.23	.46	.35	.30	.32	.37	.37	.37	.32	.07	.09	.07	.07	.07
AN	4.21	2.06	8.02	6.86	14.46	8.20	37.50	40.19	40.18	36.14	37.03	38.40	20.76	8.14	.46	9.51	8.56	8.29

Sample	36562	36564	36565	36568	36569	36571	36573	36575	36522	36523	36527	36595	36597	36600	36602	36603	36605	Sample
Ig.Unit	PSIp	PSIp	PSIp	PSIm	PSIm	PSIm	PSIm	PSIm	MCIb	MCIb	MCIb	MCIp	MCIp	MCIp	MCIp	MCIp	MCIp	Ig.Unit
G.Ref	236802	162757	133838	175715	170712	084769	210743	225753	251286	251286	240378	708972	708969	541918	492932	767033	808921	G.Ref
Map	PS	MP	PS	PS	PS	PS	PS	PS	DH	DH	RB	Pa	Pa	El	El	Pa	Pa	Map
MAJOR ELEMENTS (Weight %)																		
SiO_2	74.87	74.87	74.51	74.74	74.43	75.56	75.12	73.61	71.58	68.30	69.22	67.73	67.33	65.53	64.23	66.49	66.42	SiO_2
TiO_2	.25	.22	.23	.23	.21	.20	.23	.22	.37	.44	.43	.52	.51	.57	.58	.50	.54	TiO_2
Al_2O_3	13.58	13.43	13.55	13.64	13.38	13.42	13.82	13.37	14.13	14.97	14.73	15.78	15.60	16.31	16.36	15.93	16.18	Al_2O_3
Fe_2O_3	.68	.70	1.31	.91	1.06	.60	.71	1.27	1.23	1.12	1.02	1.78	1.40	1.90	2.30	1.60	1.75	Fe_2O_3
FeO	.26	.68	.25	.43	.51	.41	.10	.28	1.28	1.72	1.68	1.68	1.88	1.89	1.76	1.95	1.76	FeO
MnO	.01	.03	.03	.04	.04	.04	<.01	.08	.05	.05	.05	.06	.05	.07	.08	.06	.07	MnO
MgO	.10	.23	.23	.30	.30	.20	.07	.35	.76	1.17	.99	1.28	1.31	1.64	1.70	1.49	1.28	MgO
CaO	.32	.66	.72	.89	.87	.59	.41	.99	2.10	3.29	1.52	2.97	2.76	3.07	4.17	2.97	3.20	CaO
Na_2O	3.63	3.47	3.78	3.41	3.38	3.64	3.56	3.41	3.02	3.09	4.11	3.87	3.75	3.82	3.63	3.91	3.92	Na_2O
K_2O	5.21	5.00	4.93	5.11	5.00	5.03	5.01	5.11	4.50	3.51	4.27	3.60	3.71	3.38	3.11	3.59	3.53	K_2O
P_2O_5	.03	.02	.03	.20	.03	.02	<.01	.02	.10	.10	.10	.11	.10	.10	.12	.10	.10	P_2O_5
H_2O+	.81	.90	.74	.62	.80	.00	.73	.92	1.43	2.22	1.69	1.47	2.09	1.88	1.68	1.97	1.75	H_2O+
CO_2	.02	.04	.07	.09	.06	.02	.40	.01	.03	.03	.14	.02	.00	.00	.03	.00	.00	CO_2
Total	99.77	100.25	100.38	100.43	100.07	99.74	100.15	99.64	100.58	100.05	99.95	100.84	100.49	100.14	99.82	100.56	100.50	Total
TRACE ELEMENTS (p.p.m.)																		
Nb	11	12	11	11	11	11	11	11	8	8	8	7	8	8	8	7	7	Nb
Zr	176	182	183	184	179	114	180	176	174	182	184	189	191	195	138	189	191	Zr
Y	58	33	41	32	34	26	22	35	29	31	30	30	30	32	31	30	36	Y
Sr	165	178	162	167	152	174	166	168	341	348	321	357	328	436	426	309	376	Sr
Th	23	28	26	29	22	24	23	28	24	20	23	19	17	19	16	14	17	Th
Pb	24	23	24	21	24	22	11	27	19	16	20	17	17	16	20	17	16	Pb
U	10	7	8	4	10	8	3	6	6	5	8	2	6	5	4	3	6	U
Rb	227	199	239	214	229	215	197	238	221	139	159	152	153	143	131	153	156	Rb
Ga	13	14	16	17	15	17	17	18	18	16	18	16	18	20	19	19	19	Ga
Zn	39	38	37	36	44	36	25	38	46	60	44	57	54	65	54	62	58	Zn
Cu	6	5	5	4	4	2	4	5	11	12	10	14	14	13	14	13	15	Cu
Ni	4	3	3	2	2	2	2	4	6	10	6	6	8	7	7	9	7	Ni
Mn	116	248	269	299	309	292	46	631	370	390	414	440	368	551	587	449	547	Mn
Cr	6	<2	3	3	2	2	3	2	9	17	12	19	15	19	19	17	17	Cr
V	9	<2	5	5	3	4	3	8	58	53	64	57	60	66	75	56	66	V
Ti	1654	1545	1604	1560	1494	1377	1620	1460	2401	2936	2755	3227	3172	3506	3629	3179	3417	Ti
Ba	938	808	789	808	719	526	829	765	508	470	522	500	482	463	471	475	454	Ba
K/Rb	191	209	171	198	181	194	211	178	169	210	223	197	201	196	197	195	188	K/Rb
C.I.P.W. NORMS																		
Q	32.85	33.39	31.35	32.62	32.78	33.32	34.08	31.08	30.40	27.28	23.46	22.12	22.46	20.17	18.60	20.27	20.24	Q
Or	30.78	29.54	29.13	30.19	29.54	29.72	29.60	30.19	26.59	20.74	25.23	21.27	21.92	19.97	18.37	21.21	20.86	Or
Ab	30.70	29.35	31.97	28.84	28.59	30.79	30.11	28.84	25.54	26.13	34.76	32.73	31.72	32.31	30.70	33.07	33.15	Ab
An	1.39	3.14	3.38	4.28	4.12	2.80	2.03	4.78	9.76	15.66	6.89	14.01	13.04	14.57	19.17	14.08	15.22	An
C	1.46	1.16	.76	.93	.90	.97	1.80	.48	.72	.35	.83	.30	.64	1.03	.00	.46	.36	C
Di	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.60	-	-	Di
Hy	.76	1.62	1.73	1.74	2.08	1.23	.57	2.12	4.23	5.39	4.84	6.23	6.12	7.37	7.61	6.91	6.28	Hy
Mt	.48	.71	.78	.68	.80	.52	.41	.78	1.15	1.32	1.26	1.58	1.52	1.74	1.88	1.64	1.61	Mt
Il	.47	.42	.44	.44	.40	.38	.44	.42	.70	.84	.92	.99	.97	1.08	1.10	.95	1.03	Il
Ap	.07	.05	.07	.05	.07	.05	.00	.05	.23	.23	.23	.25	.23	.23	.28	.23	.23	Ap
AN	4.33	9.66	9.56	12.92	12.60	8.34	6.32	14.22	27.65	37.47	16.54	29.97	29.13	31.08	38.44	29.86	31.47	AN

TABLE 4.1

Major element oxides, trace elements and C.I.P.W. norm calculations of the rhyolitic and dacitic ignimbrites in the Hunter Valley, N.S.W. Norms have been calculated with Fe_2O_3/FeO = 0.3.

KEY TO IGNIMBRITE UNITS

CKI	Curra Keith Ignimbrite
OI	Oakfields Ignimbrite
McGI	McCullys Gap Ignimbrite
NBI_n	Nelson Bay Dacitic Ignimbrite from the Nelson Bay Area
NBI_f	Nelson Bay Dacitic Ignimbrite from Fingal Bay
NBI_b	Nelson Bay Dacitic Ignimbrite from the Buladelah Area
PSI_p	Port Stephens Rhyolitic Ignimbrite from around Port Stephens
PSI_m	Port Stephens Rhyolitic Ignimbrite from around Morna Point
MCI_b	Martins Creek Dacitic Ignimbrite from the Bowmans Creek Area
MCI_p	Martins Creek Dacitic Ignimbrite from the Paterson Area

KEY TO MAPS FOR GRID REFERENCES
(1:25,000 Topographic Series)

Ab	Aberdeen, 9033-I-S
Bu	Buladelah, 9333-III-S
DH	Dawsons Hill, 9133-III-N
El	Elderslie, 9132-I-N
MP	Morna Point, 9332-III-N
Pa	Paterson, 9232-IV-N
PS	Port Stephens, 9332-IV-S
RB	Rouchel Brook, 9133-IV-S
Sc	Scone, 9033-I-N
Wo	Woolooma, 9133-IV-N

long as 20 m.y. Then, as the it died out, in the mid to late Viséan, both the Maitland and Port Stephens Calderas became active. The full period of activity of these two calderas is unknown however, as the products of both are truncated by a major disconformity, which occurs throughout much of the southern part of Tamworth Shelf succession at the end of the Viséan (Roberts and Engel 1987).

The ignimbrites studied here include the Curra Keith, Oakfields, and M^c^Cullys Gap ignimbrites which were derived from the Muswellbrook Caldera, the Martins Creek ignimbrite from the Maitland Caldera, and the Port Stephens and Nelson Bay ignimbrites from the Port Stephens Caldera. Table 4.1 presents the 53 major and trace element analyses of these ignimbrites carried out in this study.

4.4 MUSWELLBROOK CALDERA IGNIMBRITES

4.4.1 Curra Keith Ignimbrite

The Curra Keith ignimbrite occurs at the base of the Native Dog Member in the Isismurra Formation (Roberts and Oversby 1974). It crops out extensively adjacent to the Hunter Fault just west of Scone and Muswellbrook and in a 120^{o} sector it fans out to the north and east for about 30 kms from its source vent sited about 4 kms north of the township of Muswellbrook.

The Curra Keith ignimbrite is a porphyritic, devitrified lithoidal ignimbrite. It is readily distinguished, as it contains up to 30 modal % orange andesine crystals which are set in buff to grey coloured fine-grained ash matrix, and is notably impoverished in pumice and lithic clasts. The matrix is wholly recrystallised from its original vitroclastic texture and pseudomorphs of glass shards in the matrix are the one remaining visible feature of the ignimbrites' original fragmental nature. Pseudomorphs of biotite now largely replaced by chlorite and Fe-oxides occupy less than 1 modal % of the rock.

Of the twelve samples of the Curra Keith ignimbrite analysed (Table 4.1), three samples (36401, 36404 and 36407) were taken from the same 20 metre thick outcrop of the ignimbrite in a small disused quarry alongside the road leading into Glenbawn Dam. Sample 36401 was taken from the base of the outcrop, 36404 from the middle and 36407 from the top. All of the remaining samples were taken from outcrops scattered throughout the unit, with 36417 and 36436, taken from about 25 km from the ignimbrites source, being the most distal of the samples. All of the samples analysed were welded, lithoidal ignimbrite.

4.4.2 McCullys Gap Ignimbrite

The McCullys Gap ignimbrite occurs in about the middle of the Native Dog Member of the Isismurra Formation, approximately half-way in the stratigraphic column between the earlier Curra Keith ignimbrite and the later Oakfields ignimbrite (see below). It crops out in much the same fan-shape as the Curra Keith ignimbrite although it crops out less frequently and it appears to have traveled only about half the distance as that of the Curra Keith ignimbrite.

The ignimbrite is characteristically a highly indurated rock, consisting of up to 35 modal % white or cream coloured andesine and less than 5 modal % biotite crystals, now replaced by chlorite and iron oxides, which are set in a brown densely welded, deformed eutaxitic matrix. Lithic fragments of similar composition to the ignimbrite are abundant throughout the unit.

Four samples of the McCullys Gap ignimbrite have been analysed (Table 4.1). Samples 36475 and 36476 were taken from one outcrop of the ignimbrite, one from the bottom and one from the top of the unit, respectively. The other two samples were taken from more distal outcrops.

4.4.3 Oakfields Ignimbrite

The Oakfields ignimbrite occurs at the top of the Native Dog Member in the Isismurra Formation (Roberts and Oversby 1974). In the field, it is a distinctive unit as, it contains abundant pumice clasts that are usually flattened (to various degrees), and orange crystals which are set in a purple coloured matrix. It crops out in a 90^{o} sector from the north through to the east, up to 40 km from its determined source vent which is sited about 12km south of Muswellbrook township, within the Muswellbrook Caldera.

Modal analysis of the Oakfields ignimbrite reveals that it can contain up to 35 modal % pumice clasts, 23% crystals, and 15% lithic clasts which are set in a coarse ash-sized vitroclastic matrix. Opaque oxides form less than 1 modal % of the ignimbrite. The matrix is devitrified to a microcrystalline mosaic of feldspar and opaque grains, although the original shard texture is still evident in plane polarised light.

Eight samples of the Oakfields ignimbrite were analysed (Table 4.1). Samples 36450, 36466 and 36469 are from the top and 36453, 36468 and 36470 are from the bottom of the outcrops of the ignimbrite at three different locations, and the others represent samples from scattered outcrops of the unit. 36461, taken from about 30 km from source, is the most distal sample. All of the samples are welded lithoidal ignimbrite.

4.5 MAITLAND CALDERA IGNIMBRITES

4.5.1 Martins Creek Ignimbrite

The Martins Creek ignimbrite is the most widespread of any of the ignimbrites in the Hunter Valley. It crops out throughout the Paterson area north of the Maitland centre and up to 60 km to the northwest, to near Muswellbrook, where it extends into the same area as the ignimbrites from the Muswellbrook Centre. The Martins Creek ignimbrite occurs in the upper part of the Isismurra Formation in the Scone-Rouchel District, whilst it is in the Lower part of the Newtown Formation in the Maitland District (Roberts and Engel 1987).

This ignimbrite is largely lithoidal in character but it locally has a glassy selvage at the base of the unit. The lithoidal ignimbrite has a typical blue-grey 'andesite colour' and consists of about 35 modal % crystals of white oligoclase-andesine, with lesser hornblende, magnetite and quartz. Quartz crystals are not evident in every hand specimen of this ignimbrite but when they are found they are invariably much larger (up to 5 mm) than the other crystals. The hornblende has largely been replaced and is now found as chlorite- and magnetite-filled pseudomorphs. The crystals are set in a partially welded, devitrified, shard-rich matrix.

The glassy parts of this ignimbrite have identical crystal components and abundance as the lithodal parts, but the crystals are set in a partially devitrified black glass (obsidian). The hornblende in the glassy ignimbrite, in contrast to the lithoidal ignimbrite, is usually largely unaltered.

Nine analyses of the Martins Creek ignimbrite are presented in Table 4.1. Samples 36522 and 36523, from the bottom and top of the ignimbrite respectively, and 36527 are samples from the most distal outcrops of the Martins Creek ignimbrite in the Muswellbrook area. Samples 36595 and 36597 were taken from the bottom and top, respectively of the Martins Creek ignimbrite in the Martins Creek Quarry, and the other samples are from scattered localities around the Maitland District.

4.6 PORT STEPHENS CALDERA IGNIMBRITES

4.6.1 Nelson Bay Ignimbrite

The Nelson Bay ignimbrite (Chapter 5.9.1) is a unit within the Nerong Volcanics (Engel 1962) and it lies directly below the Port Stephens ignimbrite (Chapter 4.6.2). It crops out only in isolated places along the shores of Port Stephens, and it been found to extend as far as Buladelah on the western limb of the Girvan Anticline (Sample 35594).

The Nelson Bay ignimbrite is generally a lithoidal rock with 40-50 modal % crystals which in decreasing order of abundance are plagioclase (An_{40-48}), hornblende, hypersthene, opaques (titanomagnetite, ilmenite), biotite, and quartz. The quartz crystals are normally deeply embayed due to resorption. The matrix is normally blue-grey coloured with abundant flattened, glassy pumice clasts throughout. However, where extreme welding of this ignimbrite is present there are lenses of glassy (vitrophyric) ignimbrite and here the crystals are set in a black, isotropic, matrix of highly deformed glass-shards.

Eight analyses of the Nelson Bay ignimbrite are presented in Table 4.1 and each of the samples were collected from separate localities. Sample 36582 is the one analysis of the glassy part of this ignimbrite carried out in this study, although two other analyses, one each by Wilkinson (1971) and Nguyen (1976), are included here, and they exhibit all of the chemical characteristics (see later) typical of the glassy parts of any Lower Carboniferous ignimbrites in the Hunter Valley.

4.6.2 Port Stephens Ignimbrite

The Port Stephens ignimbrite is also a unit within the Nerong Volcanics and it lies on top of the Nelson Bay ignimbrite. It crops out prominently along most of the shoreline of Port Stephens and it forms prominent steep isolated hills and cliffs in the Port Stephens area, as well as very extensive rocky shore platforms. Extensive outcrops are present along the north side of Port Stephens and it is almost continuous in outcrop along the limbs of the Girvan Anticline, north to at least Buladelah where it is about 45 km from its source.

This ignimbrite was one of the best known ignimbrites in New South Wales and indeed Australia, when it was once called toscanite. However modern volcanic rock classification terminology no longer recognises toscanite, but the ignimbrite still has its distinctive mineralogy of up to 43 modal % of the rock consisting of coarse crystals of plagioclase, quartz and orthoclase, in approximately equal proportions (Chapter 5.9.2), and minor biotite. The ignimbrite normally occurs as a lithoidal variety of rock with the crystals set in either a altered pink, or a grey coloured densely welded, deformed, devitrified eutaxitic matrix. Although locally, as with the Nelson Bay ignimbrite, where the ignimbrite is thickest and highly welded, there are irregularly shaped 1-2 metre thick lenses where the matrix of the ignimbrite is a black obsidian. These glassy lenses are usually surrounded by the lithoidal (less welded) rock.

Thirteen samples of the Port Stephens ignimbrite have been analysed (Table 4.1) with each sample having been taken from different localities. Sample 36557, from the Buladelah area, about 40 km from the source caldera, is the most distal sample.

4.7 ANALYTICAL METHODS

All of the data presented here are whole rock analyses which were determined on the Macquarie University X-Ray fluorescence spectrometer. Major elements were analysed on glass discs prepared by a method based on that of Norrish and Hutton (1969) and trace elements were analysed on pressed powder pellets with mass absorptions calculated from the major element compositions following the method of Norrish and Chappell (1967). H_2O and CO_2 were determined with a Leco apparatus and ferrous iron was determined by ceric sulphate titration with Fe_2O_3 calculated by

$$Fe_2O_3 = Fe_2O_{3(total)} - (FeO \times 1.11134).$$

For the C.I.P.W. norm calculations the total iron was split according to the average igneous rock compositions listed in Nockolds (1954) i.e. total iron in the rhyolitic and rhyodacitic ignimbrites was split 66% FeO : 33% Fe_2O_3 according to the the average ratio of them in granite and granodiorite, and for the dacites an average tonalite ratio of 70% FeO : 30% Fe_2O_3 was used.

The full analyses of the ignimbrites are given in Table 4.1 but on all of the following figures the major element data shown has been recalculated to 100% after excluding H_2O and CO_2.

4.8 PREVIOUS ANALYSES

Only a few major element analyses, and only some incomplete trace element analyses of the felsic ignimbrites in the southern part of the New England Orogen have been so far published. B.M.R. sample 0262, in Roberts and Oversby (1974), is an analysis of the Curra Keith ignimbrite. It is the only previous analysis of any ignimbrite derived from the Muswellbrook Caldera. Analyses of the Martins Creek ignimbrite were presented by Osborne (1925) and David (1950) and Sussmilch and Clarke (1928). Samples I and II, are analyses of both the glassy and lithoidal parts of the Martins Creek ignimbrite. B.M.R. sample 0263 (Roberts and Oversby 1974) is an analysis of the distal part of the Martins Creek ignimbrite in the Muswellbrook area and seven analyses of the Martins Creek ignimbrite form part of the 'continental margin dacite' data-base of Jakeš and White (1972). Four analyses of the Nelson Bay ignimbrite also form part of the 'continental margin dacites' data-base of Jakeš and White (1972). Wilkinson (1971) and Nguyen (1976) each presented single analysis of the same glassy part of the Port Stephens ignimbrite exposed at Nelsons Head, Nelson Bay. Sussmilch and Clark (1928) published two analyses of 'toscanite' and two of rhyolite from the Port

Stephens area, but their four samples were all taken from the Port Stephens (rhyolitic) ignimbrite. It was only the inaccuracies of their analyses, that prompted them to separate out two different 'rhyolitic' ignimbrites in the Port Stephens area.

Most of the earlier analyses cited here were reproduced in either Nashar (1969) or Wilkinson (1971). Although, except for the more recent analyses of Jakeš (1970) and Nguyen (1976), all of the earlier analyses vary considerably from the analyses obtained in this study, in virtually all elemental abundances. The consistency in the analyses obtained in this study of samples from different outcrops of the same ignimbrite and from the identical locations of the previous researchers, indicates that their analyses need to be regarded with considerable caution. The analyses of both Jakeš (1970) and Nguyen (1976) are, with few exceptions, consistent in both major and trace element abundances with the analyses presented here (Appendix VII).

The vitrophyric part of the Nelson Bay ignimbrite (Sample 36582) was analysed so that comparisons could be made with the previously published analyses of the vitric parts of the ignimbrites and the analyses of the lithoidal part of the same ignimbrite.

4.9 CHEMICAL CLASSIFICATION OF THE IGNIMBRITES

There is little doubt that the Lower Carboniferous ignimbrites in the Hunter Valley have been somewhat altered. They show devitrification of the glassy components, replacement of the Fe/Mg minerals and sericitisation of the feldspars. Moreover, several of the analyses have over 2% H_2O and/or 0.5% CO_2 (Table 4.1) which according to Le Maitre (1984) customarily rule them out as being 'fresh' and rendering them unreliable for classification purposes. However, excluding these analyses, there is considerable evidence to suggest that the bulk rock

FIGURE 4.2

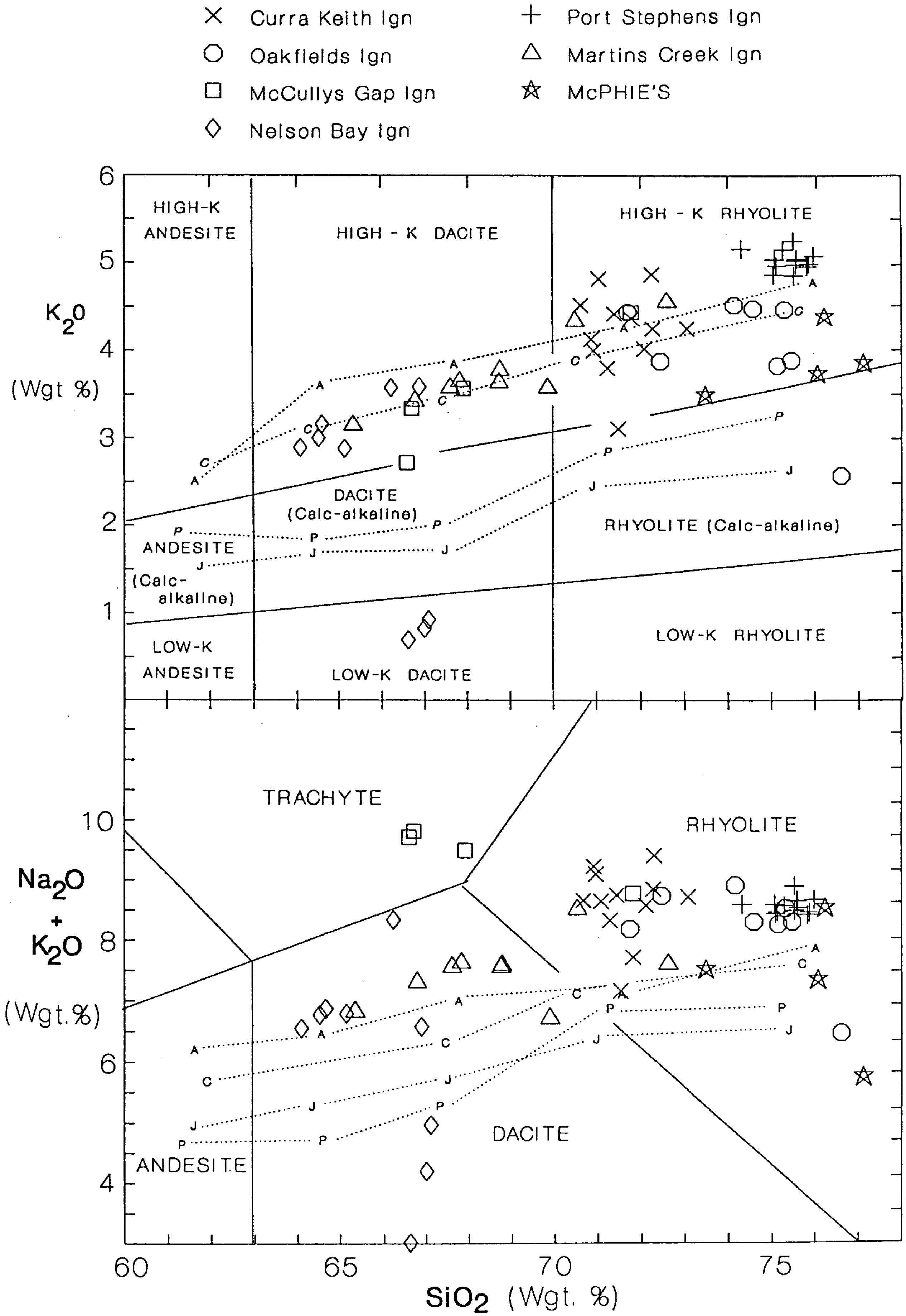
Chemical classification of the Lower Carboniferous dacitic and rhyolitic ignimbrites in the Hunter Valley.

Top: K_2O vs SiO_2 classification of Peccerillo and Taylor (1976).

Bottom: Na_2O + K_2O vs SiO_2 classification of the I.U.G.S. described by Le Maitre (1984).

Note that the samples that plot in the alkali rhyolite/rhyolite field are rhyolites as their Peralkaline Indexes ($(Na_2O+K_2O)/Al_2O_3$) are all less than 1.

Trend lines connecting average analyses of other volcanic provinces shown for comparison are; A----A, western USA, C----C, western (Andean) South America, J----J, Japan, and P----P, S.W. Pacific including New Zealand, (data from Ewart 1979). The 4 stars represent the average analyses of four ignimbrites in the Upper Carboniferous Currabubula Formation (from McPhie 1987).



Curra Keith Ign
Oakfields Ign
McCullys Gap Ign
Nelson Bay Ign
Port Stephens Ign
Martins Creek Ign
McPHIE'S
K2O (Wgt %)
HIGH-K ANDESITE
HIGH - K DACITE
HIGH - K RHYOLITE
DACITE (Calc-alkaline)
ANDESITE (Calc-alkaline)
RHYOLITE (Calc-alkaline)
LOW-K ANDESITE
LOW-K DACITE
LOW-K RHYOLITE
Na2O + K2O (Wgt.%)
TRACHYTE
RHYOLITE
DACITE
ANDESITE
SiO2 (Wgt. %)

chemistry of all samples of the lithoidal ignimbrites analysed, when recalculated to 100% to exclude H_2O and CO_2, are still reasonably representative of the original ignimbrite compositions. The first evidence in support of this view is derived from the fact that the same results are obtained in classifying the ignimbrites using three different chemical classification schemes.

There are three currently accepted chemical classification schemes of volcanic rocks; the SiO_2 vs K_2O classification of Peccerillo and Taylor (1976), the Irvine and Baragar (1971) system which has been adopted and modified by the I.U.G.S. and is described by Le Maitre (1984) which considers total alkali (Na_2O + K_2O) versus SiO_2, and the C.I.P.W normative plagioclase composition (100an/(ab+an) = AN) based system of Wilkinson (1986) which discriminates dacites from more mafic rocks by them having $30 < AN \geq 50$, $Al_2O_3 > 16$ wgt. % and $Qz > 10\%$.

The Peccerillo and Taylor (1976) SiO_2 versus K_2O classification (Figure 4.2 top) identifies all, but two samples (see later), of the Hunter Valley ignimbrites as high-K volcanic rocks. The Curra Keith and Port Stephens ignimbrites all fall in the field of high-K rhyolites, and so does the Oakfields ignimbrite, except that one sample (Sample 36466) whose K_2O plots in the field of the calc-alkaline rocks. This sample, however, contains more than 2% H_2O which suggests that leaching of K_2O was likely and if one was to follow accepted practices then it would be excluded from the classification.

The M^c^Cullys Gap, Martins Creek and Nelson Bay ignimbrites all essentially plot within the field of high-K dacites. The least spread in the data is shown by the Nelson Bay ignimbrite, except that, because of very low K_2O, three samples plot in the field of low-K dacites. These low K_2O analyses are all of the analyses of the glassy part of the ignimbrite to date, which includes sample 36582 of this study. The glassy ignimbrite, under the microscope, appears to be very 'fresh' with remarkably unaltered crystals in an isotropic glass matrix. Yet, these seemingly unaltered glassy rocks invariably have much lower K_2O (Wilkinson 1971, Nguyen 1976, McPhie 1987) than the equivalent lithoidal rock and very high H_2O. Sample 36528 has, for example, a third to a quarter of the K_2O that the lithoidal part of the same ignimbrite contains and almost 4 weight % H_2O. Thus, it seems that the glassy rocks have been preferentially leached of K_2O during the hydration of the glass, and this is most likely to have been caused by percolating groundwaters.

The analysed samples of the Martins Creek ignimbrite show considerable variation in SiO_2 from 65% to 72% whilst K_2O is consistently greater than 3 weight %. The variation in SiO_2 to a large extent appears to be determined by the post-emplacement welding and vapour phase alteration in the ignimbrite, both of which increase towards the source vent. Samples 36600 and 36602 have the lowest SiO_2 values and they were taken from outcrops that are about 5 km from the source vent, whereas the highest SiO_2 values occur in samples 36522 and 36523 and they come from the most distal outcrops of the ignimbrite in the Muswellbrook area, about 45 km from the source. This attribute is evident in hand specimen also as these distal samples are notably hardened (indurated) by silicification. The increase in SiO_2 away from the source vent is probably caused by the decreasing degree of welding (and porosity) which is evident in the ignimbrite with increasing distance from source. Nearest the source vent welding tends to be greatest which produced a rock with lowest porosity and this therefore restricted post-emplacement alteration and silicification. However, in contrast, the distal parts of the ignimbrite in the Muswellbrook area are only incipiently welded and a higher original porosity of the rock presumably allowed greater alteration and post-emplacement silicification to occur.

The McCullys Gap ignimbrite samples show the greatest variation in both K_2O and SiO_2. The lowest K_2O content (2.64 weight %) occurs in sample 36482, which has more than 2% H_2O.

IGNIMBRITE UNIT	CLASSIFICATION SCHEME Peccerillo and Taylor (1976) K_2O vs SiO_2	Le Maitre (1984) K_2O+Na_2O vs SiO_2	Wilkinson (1986) 30<AN>50, Al_2O_3>16, Q>10
Curra Keith	High-K Rhyolite	Potassic Rhyolite	
Oakfields	High-K Rhyolite	Potassic Rhyolite	
M^{c}Cullys Gap	High-K Dacite	Sodic Trachyte	
Martins Creek	High-K Dacite	Potassic Dacite	Low Al_2O_3, med-high K/Na Dacite
Port Stephens	High-K Rhyolite	Potassic Rhyolite	
Nelson Bay	High-K Dacite	Potassic Dacite	Low Al_2O_3, medium K/Na Dacite

TABLE 4.2
Comparison of three chemical classification schemes using the Lower Carboniferous dacitic and rhyolitic ignimbrites from the Hunter Valley.

This suggests that the M^{c}Cullys Gap ignimbrite has also been preferentially leached of K_2O althought it is not to the same extent as the glassy dacites. Sample 36481 that has 70.33 weight % SiO_2, just within the defined field of rhyolites, was taken, from the top slightly less welded part of the same outcrop as sample 36482 which has 64.70 weight % SiO_2. Thus secondary silicification, which is evident by a highly flinty hand specimen, relates to welding of the ignimbrite in the vertical sense as well. The less welded upper parts of the ignimbrite are thus most silica-rich.

The I.U.G.S. K_2O + Na_2O versus SiO_2 classification plot (Fig 4.2 bottom) gives essentially the same names to the ignimbrites as the K_2O versus SiO_2 plot (Table 4.2) except that due to unusually high Na_2O contents (about 6 wgt.%). 3 out 4 analyses of the M^{c}Cullys Gap ignimbrite plot as sodic trachytes.

The Wilkinson (1986) classification based on normative plagioclase composition where AN = 100an/(ab+an) also shows the McCullys Gap ignimbrite not to be a dacite due to its low CaO high Na_2O contents. They combine to produce AN values between 6 and 15 and these values fall well below the 30<AN>50 criteria for dacites. Thus the McCullys gap ignimbrite cannot be classified as a dacite according to this scheme. Therefore, as SiO_2 and K_2O are variable in this ignimbrite due to leaching and silicification, the key to its composition is probabaly its Na_2O content which average approximately 6 weight %. Thus, the McCullys Gap ignimbrite is best called sodic trachyte, following the I.U.G.S. classification scheme, rather than the high-K dacite in the other scheme.

The Martins Creek and Nelson Bay ignimbrites plot as low Al_2O_3 dacites in the I.U.G.S. system (Table 4.2).

To enable the Lower Carboniferous silicic ignimbrites in the Hunter Valley to be compared with other areas in the world, which contain a number of recent similarly large scale ignimbrites, the trends in total average compositions within each of five SiO_2 compositional groupings (60-63, 63-66, 66-69, 69-73, >73 weight %) of Western (Andean) South America, the Western U.S.A., the South Pacific including New Zealand, and Japan (Ewart 1979) are included on the accompanying figures. The Andean South America and Western USA volcanics are high-K suites similar to the Lower Carboniferous ignimbrites and their K_2O vs SiO_2 average trends plot almost as best-fit lines for the Hunter Valley data (Fig 4.2 top). On the K_2O + Na_2O vs SiO_2 diagram, however, the combination of the two alkalis in the Hunter Valley ignimbrites are consistently higher than any of the other volcanic provinces. The trend in average alkalis in the western USA is the closest to the average trend in the Hunter Valley ignimbrites (Fig 4.2 bottom).

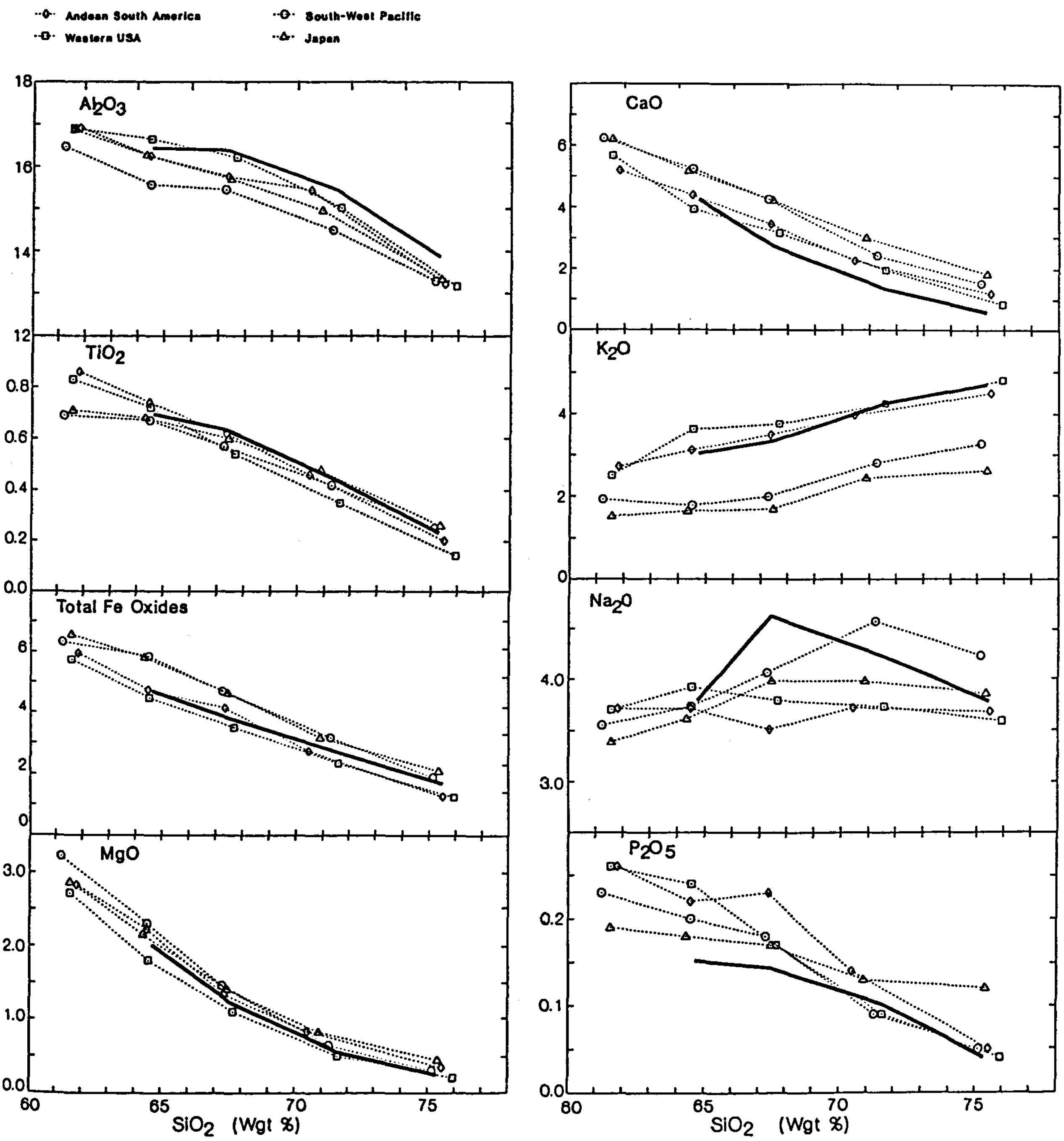
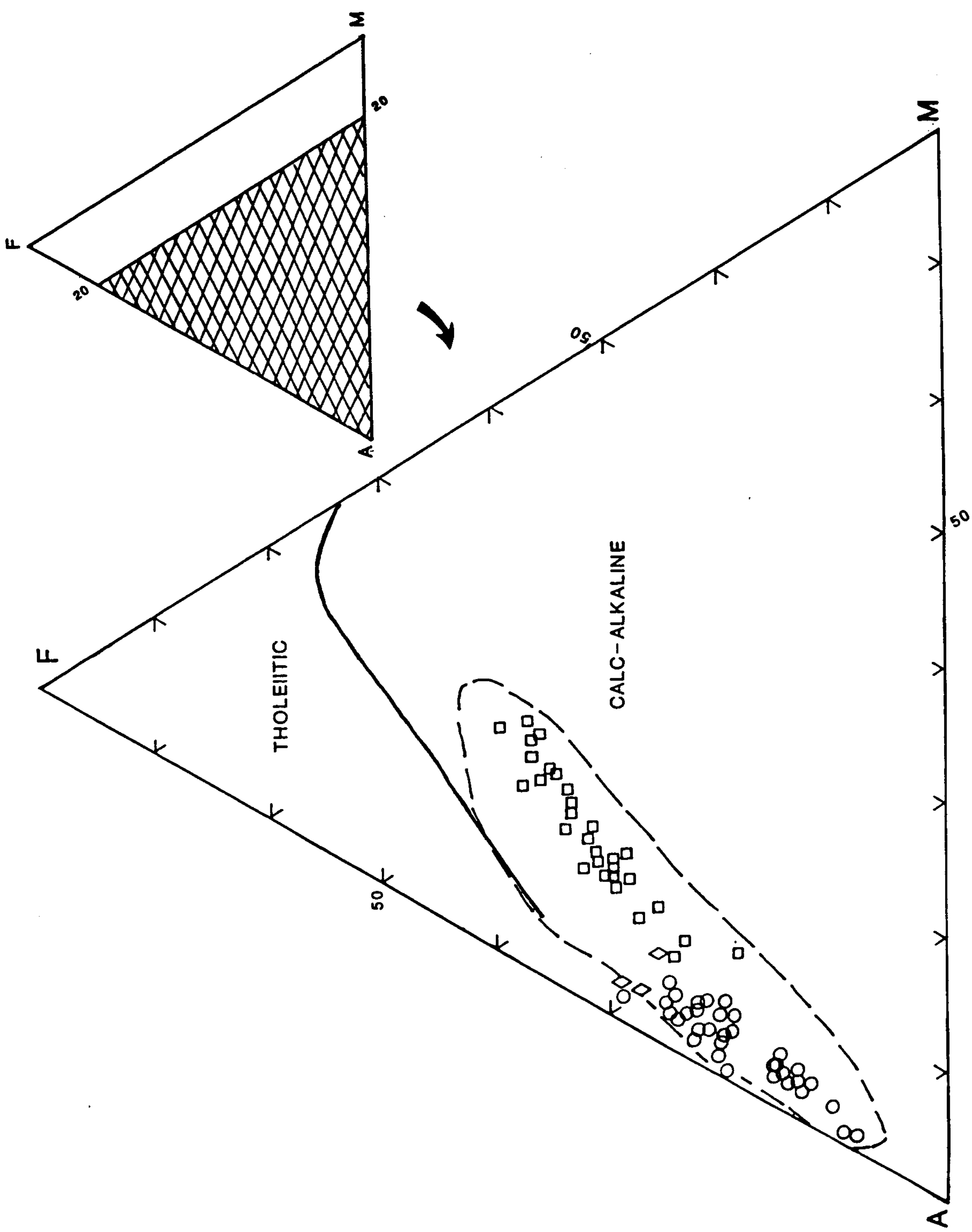


FIGURE 4.3

Modified Harker variation diagrams of the major elements in the Hunter Valley ignimbrites compared with other volcanic provinces with similar large scale ignimbrites. The solid black line connects average analyses of the Hunter Valley ignimbrites.

FIGURE 4.4

AFM diagram showing the ignimbrites of the Hunter Valley in relation to the tholeitic and calc-alkaline fields of Irvine and Baragar (1971). Dashed line defines the field enclosing the ignimbrites in northern Chile (Francis *et al.* 1974) and the western USA (after Ewart 1979).


F
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50
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THOLEIITIC
CALC-ALKALINE

4.10 MAJOR ELEMENT CHEMISTRY

Variations in major elements, plotted against SiO_2, of the Hunter Valley ignimbrites are illustrated in modified Harker plots (Fig 4.3). Using the same procedure as Ewart (1979), the 53 major element analyses (Table 4.1) of the Hunter Valley ignimbrites have been reduced to trend lines connecting four points representing average compositions within the ranges 63-66, 66-69, 69-73, and <73 weight % SiO_2.

All of the major elements show expected trends with SiO_2 (Fig.4.3), i.e. K_2O and Na_2O increase with increasing SiO_2, whereas Al_2O_3, TiO_2, Total Fe oxides, MgO, CaO and P_2O_5 decrease. The variations in the major elements with SiO_2 contents illustrated in Fig 4.3 graphically depict the similarity of the chemistry of the Hunter Valley volcanics to the chemistry in the four other regions with large scale ignimbrites. Consistently the trends in Al_2O_3, TiO_2, Total Fe Oxides and MgO of the Hunter Valley ignimbrites plot similarly to those of the other volcanic regions, but CaO and P_2O_5 tend to be depleted. The Hunter Valley dacites with 66 - 69 weight % SiO_2 show an unparalleled high concentration in Na_2O.

An overall pattern is that the trends in the major element chemistry of the Hunter Valley ignimbrites most often parallel the trends in either western USA (e.g. Al_2O_3, total Fe oxides, and MgO) or Andean South America (e.g. TiO_2, K_2O and Na_2O to a lesser degree).

An A.F.M. diagram (Fig. 4.4) shows the Hunter Valley ignimbrites to have a typical 'calc-alkaline' trend in the data and they are occur in the same field that both the Chilean Andes (Lefèvre 1973, Francis et al. 1974) and the western USA (after Ewart 1979) occupy. Their trend shows typical decreases in Fe and Mg with alkali enrichment, and a marked depletion in Fe and Mg in the rhyolites.

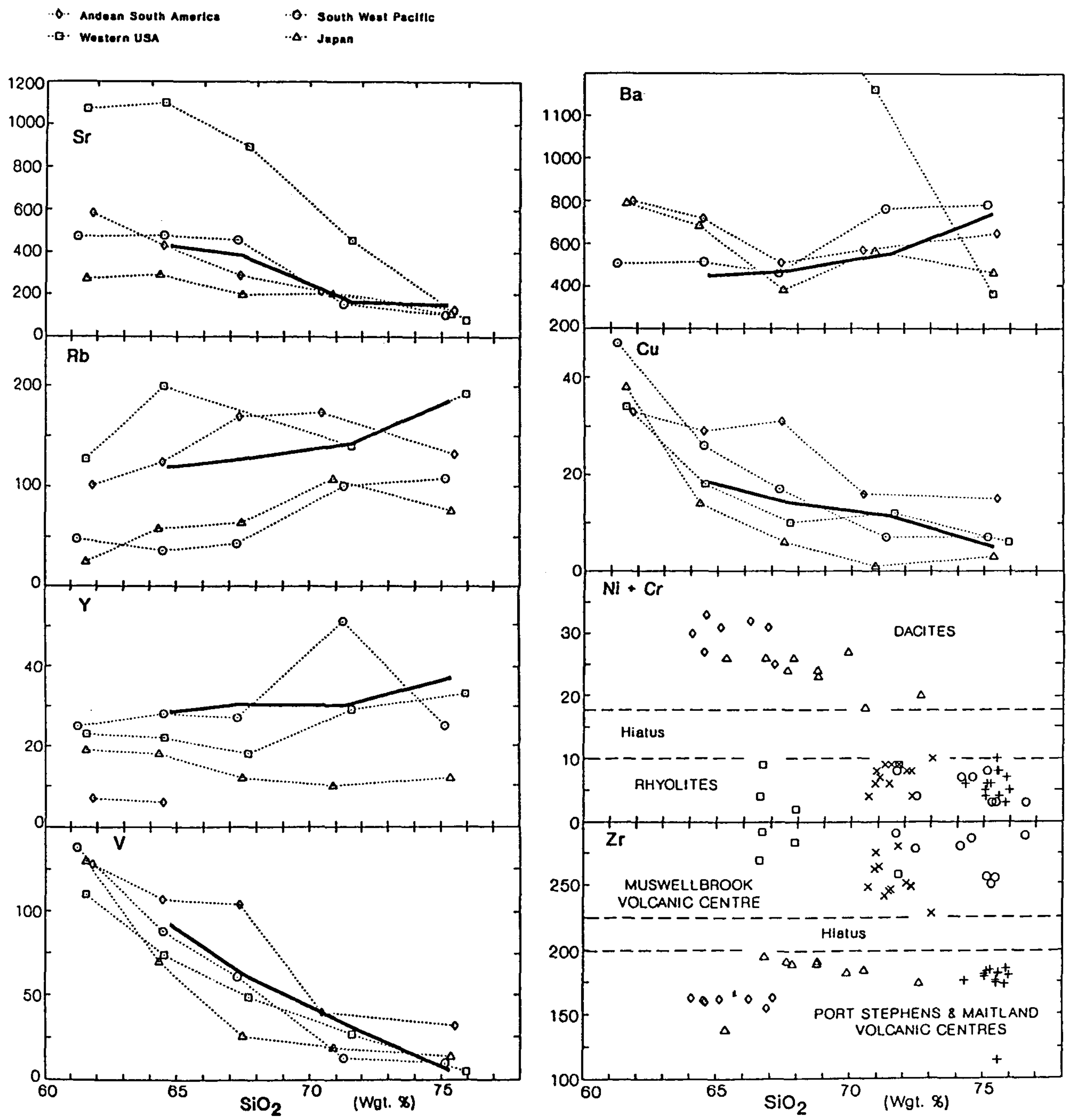

FIGURE 4.5

Trace element variation diagrams, comparing the trends in trace elements in the Hunter Valley ignimbrites with other regions that have large scale ignimbrites. The solid black line connects the average values of the Hunter Valley data.

4.11 TRACE ELEMENT CHEMISTRY

Trace-element variations with SiO_2 (Fig. 4.5) in the Hunter Valley ignimbrites are like the major elements in that they too follow trends that are generally expected of them. The general behaviour of Ba is closely correlated with K during crystallization due to the similar atomic size, so that the increase in K_2O with increasing SiO_2 shown in Figure 4.3 is imitated by Ba. This same positive association with SiO_2 (and K_2O) also occurs with Rb, and with less inclination so does Y. But the metals Cr, Ni, Cu and V, as well as Sr, all show marked decreases with increasing SiO_2.

Although the trends in the major elements in the Hunter Valley volcanics show some similarities with other ignimbrite regions, their true uniqueness is revealed in their trace element character (Fig 4.5). Each of the volcanic suites in the four ignimbrite regions, and the Hunter Valley ignimbrites, have their own distinctly different trend in virtually all trace elements. However, there is a consistent match of trace elements in one particular composition.. The most fractionated rhyolites (>72 weight % SiO_2) as depicted by the end point of the trend lines in Figure 4.5, show the Hunter Valley ignimbrites to plot consistently at about the same point as the average rhyolites in western USA. Thus, it appears that the rhyolites in the two regions have very similar compositions and probably similar genesis.

Cr, Ni, Zr, V and Sr abundances prove to be useful for separating various components of the Lower Carboniferous ignimbrites in the Hunter Valley. A plot of combined Ni and Cr (p.p.m.) versus SiO_2 (weight %) (Fig. 4.5) shows these elements both generally decrease as SiO_2 increases except that there is a small hiatus in the Cr+Ni values (between 10-18 ppm) which allows the Nelson Bay and Martins Creek dacites (>18 ppm) to be separated from the Curra Keith and Port Stephens rhyolites and Oakfields trachyte (<12 ppm). A plot of Zr (ppm) versus SiO_2

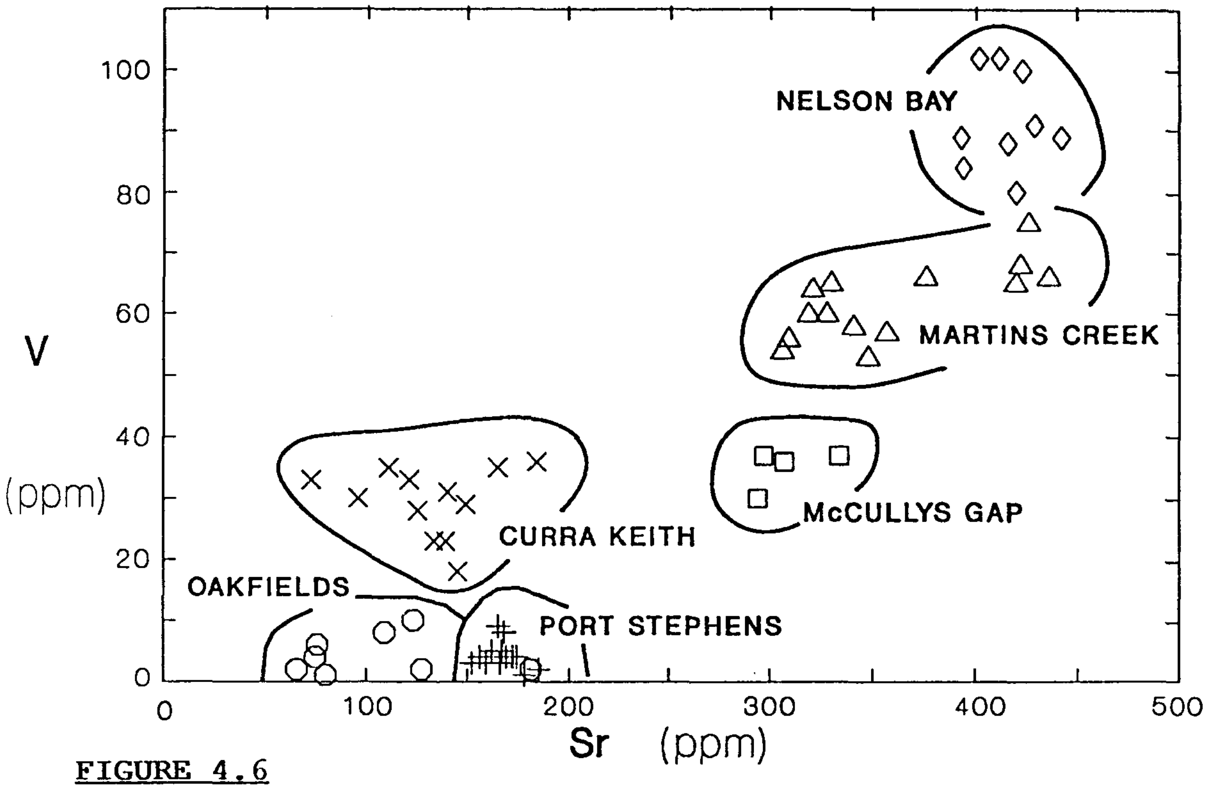

FIGURE 4.6

This plot of V versus Sr 'fingerprints' the Hunter Valley ignimbrites. Also included on this plot are data from Jakeš (1970) and Nguyen (1976).

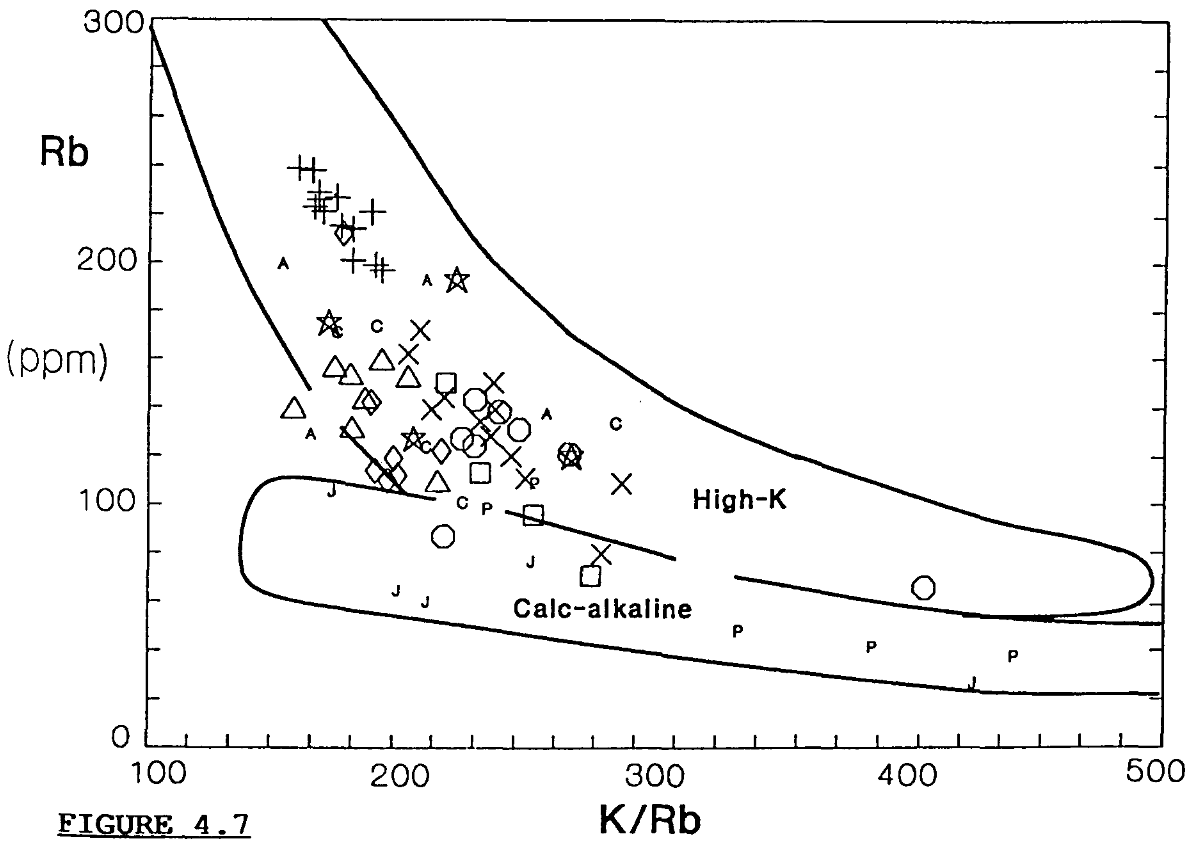

FIGURE 4.7

Rb versus K/Rb plot of the Hunter Valley ignimbrites showing them in relation to fields of high-K and calc-alkaline volcanics, which are derived from Ewart (1979, Fig.4). A = western USA, C = Andean S. America, J = Japan, and P = S.W. Pacific averages in compositional groups.

(weight %) (Fig 4.5) shows Zr to have only a slight positive relationship to SiO_2 and there is a similar hiatus between 200 and 225 ppm Zr. This hiatus allows the ignimbrites from the Muswellbrook Caldera (>220 ppm) to be differentiated from the Maitland and Port Stephens Centres (<200 ppm).

A plot of V (ppm) against Sr (ppm) (Fig. 4.6) clearly separates each of the ignimbrites from one another. The clustering of the data points in well defined fields in this plot suggests that both V and Sr are near their original abundances, although the spread in Sr values in the Oakfields and Martins Creek ignimbrites show them, as they are, to be most affected by alteration.

A Rb versus K/Rb plot (Fig. 4.7) of the Hunter Valley Lower Carboniferous ignimbrites further endorses the high-K characteristics of this suite of rocks . All of the Hunter Valley ignimbrites plot within the field of high-K volcanics which are characterised by having higher Rb contents, and lower K/Rb ratios than the calc-alkaline and low-K volcanics.

4.12 <u>NATURE OF THE VOLCANIC SOURCE REGION</u>

Most, if not all, of the Lower Carboniferous ignimbrites in the Hunter Valley originated from three calderas, located at the southern end of the Kuttung Volcanic Chain (Chapter 3). The predecessor of the chain originated in the Middle to Late Devonian (Leitch 1975; Harrington and Korsch 1985; Roberts and Engel 1987), at which time, it is considered to have been an andesitic island arc (Marsden, 1972; Cawood, 1983; Murray *et al.* 1987). Ignimbrite clasts from the earliest 'Kuttung' volcanoes in the Hunter Valley are contained in conglomerates within the Goonoo Goonoo Mudstone and after using a plot of Ce/Y against Sr/Y (in the clasts) Morris (1988) concluded that by the late Devonian-Early Carboniferous the volcanoes were "underlain by a thin continental crust". This crust was described as "an intermediate thickness, between oceanic and continental crust". I suggest that the 'intermediate' crustal thickness envisaged would be in the order of 20 to 25 km, comparable with the thin continental (sialic) crust found in northern Japan (Grushinsky 1967) and the Campbell Plateau off the east of New Zealand at present (Steven 1980).

By comparing lithofacies and geochemical characteristics of the ignimbrites and epiclastic sediments in the northern-end of the Tamworth Belt, McPhie (1987) likened the northern part of the Kuttung volcanic system, in the Upper Carboniferous, to the central portion of the Andean arc in northern Chile. This contrasts significantly with Morris's conception of crustal thickness in the Early Carboniferous since the Andean arc (in Chile) is atop thick continental (mature) crust (James 1971) which is estimated to be between 50 and 70 km thick (Lomnitz 1962).

There is some evidence to indicate the probable thickness ot crust under the Kuttung Volcanic Chain in the Lower Carboniferous. A co-magmatic (granodiorite) intrusion crops out in the source area of the Martins Creek ignimbrite (Chapter 3) and it is generally believed that the origin of such intrusions requires there to have been a sialic (continental) crust at least 20 km thick i.e. thick enough for anatexis of the lower crust to occur (Cas and Wright 1987, p.458). Further to this, the most differentiated rhyolites in the Lower Carboniferous ignimbrite succession in the Hunter Valley, are shown to have very similar average trace element composition to their counterparts in the Basin and Range Province in western USA. Thus, if the rhyolite (granitic) magmas in both areas fractionanted on their way up from a similar crustal depth, then one could also assume that the crustal thicknesses, in both the Hunter Valley in the Lower Carboniferous and the western USA at present are also comparable. Grushinsky (1967) shows the crust in the Basin and Range Province is 40 - 45 km thick.

The present continental crust of Australia ranges in thickness from about 35 km, near the edge of the continent, to 42 km in some Archean sedimentary basins (Dooley 1976). A seismic transect of Drummond and Collins (1986) actually traverses the determined location of the buried Kuttung Volcanic Chain, near Maitland, and their data shows the crust thickens slightly from about 36 km in the central Sydney Basin to about 40 km under the chain. The clastic sediments in the northern Sydney Basin are mostly derived from the erosion of the Carboniferous succession in the Tamworth Belt (Gray 1974) and some of them from the erosion of the volcanic chain. Thus, this erosion no doubt reduced the original Lower Carboniferous crustal thickness, under the chain, but perhaps only by 1 or 2 km.

Therefore, it is proposed that the thickness of the crust under the southern part of the Kuttung Volcanic Chain, in the Lower Carboniferous was probably only 1 or 2 km thicker than it is now and there are no indications that it has varied in thickness since that time Carboniferous. Nguyen's (1976) work supports this proposal in that he determined that the Lower Carboniferous andesitic rocks (not considered in this study) in the Hunter Valley were derived from partial fusion of mantle peridotite (under hydrous conditions) at or near 15 kb, which occurs at under a depth of 50 km.

The chemical similarities between the western USA and the Lower Carboniferous Kuttung Volcanic Chain, perhaps suggests that there is some geographic similarity between the two also. The Basin and Range Province is a landlocked, intracontinental back-arc rift (Scholz *et al.* 1971; Eaton 1982,1984) and the Kuttung Volcanic Chain was probably sited in a similar rift but it, according to palaeogeographic reconstructions of the Kuttung area in the Lower Carboniferous (Roberts and Oversby 1974; Roberts and Engel 1980), was a mere 30 km inland from the sea in the east.

4.13 DISCUSSION AND CONCLUSIONS

There is a complete absence of basaltic rocks in the Lower Carboniferous volcanics in the Hunter Valley, as was also noted by McPhie (1987) in the Upper Carboniferous in the northern part of the New England Orogen. This indicates that, by Carboniferous times, the typical basaltic-andesitic compositions of island arcs (Pearce and Cann 1973, Floyd and Winchester 1975, Ewart 1982), and which are evident in the Devonian volcanics (Marsden, 1972; Cawood,1983; Leitch and Willis, 1982) were no longer being generated. It is suggested that, by early in the Carboniferous, the continental crust under the Kuttung volcanoes had thickened to about 40 km , as it is below the Cenozoic ignimbrite-producing calderas, in the western USA at present. Furthermore, the dacites and rhyolites were most likely derived from an andesitic-basaltic magma that was generated in the subduction zone which fractionated assimilated crustal rock on its way to the surface. Nguyen (1976) also endorses this suggestion, in that he proposed that the dacites in the Hunter Valley were derived primarily from a partial melt of mantle peridotite, which assimilated crustal material on its rise through the continental crust, and the rhyolites were differentiations from this melt.

The average elemental abundances of the four upper Carboniferous ignimbrites in the Currabubula section (McPhie 1987) are plotted on nearly all of the diagrams in this chapter by stars. These upper Carboniferous ignimbrites also plot as high-K rhyolites and they are similar to the Lower Carboniferous rhyolites in this study (Fig.4.2), especially in terms of trace element abundances (Fig. 4.5). It was proposed by McPhie (1987) that the Late Carboniferous ignimbrites were emplaced no closer than 50 km from the sea on an arc flank well above sea level, analogous to the north Chilean Andes. However, the continental crust under the Chilean Andes is 50 - 70 km thick (Lomnitz, 1962) and there is no evidence to support that such a thickness occurred in the New England Orogen (under the Kuttung Volcanic Chain). The chemistry of the ignimbrites along the length of the chain in both Lower and Upper Carboniferous times is not compatible them having been derived from a magma originating from such a crustal depth and there is no evidence, such as the eroded remains of a (fold-mountain) cordillera like the Andes, in either the structure or sediments in the Tamworth Belt. No lithologies, other than volcanic (and granitic), have been found in the sediments that were washed off the arc, so that there is no evidence for the existence a folded, metamorphosed basement, like that in the Andes (James 1971) and recently released Bouger gravity maps of the Hunter Valley (Fig 1.7) reveal no abnormal thickening of the crust along the axis of the volcanic chain (Chapter 3).

Therefore, while McPhie's approach in comparing the Upper Carboniferous volcanics to the modern Andes in the matching of the lithofacies between the two is applicable and commended , I think, the association with the Andes leads to a false impression of the actual geography of the Kuttung Volcanic Chain. The Kuttung Volcanic Chain in the Lower Carboniferous was sited within a ensialic back-arc basin, as all modern large-scale ignimbrite-producing volcanoes are, and this suggests that it was possibly 'lower' ground rather than high.

Finally, it should be noted that all of the glassy parts of ignimbrites in the Hunter Valley, analysed to date, show considerable differences in chemistry from the equivalent lithoidal parts of the same ignimbrite. Principally, the glasses have significantly lower K_2O, Ba, and Rb, and higher Sr and much higher water, all of which is considered be the consequence of alteration, leaching, and hydration due to the effect of percolating ground waters. Lipman (1965) noted a similar trend in the glasy parts of ignimbrites in southern Nevada, although Na_2O rather than K_2O was the main element leached. The crystalline lithoidal parts of ignimbrites are therefore, considered to be compositionally closer to the original compositions of the magma. Thus, the glassy parts of ignimbrites should not be used for classification purposes and analyses of them are quite unacceptable as a basis for theories of petrogenesis.

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CHAPTER 5

GEOLOGY OF THE NERONG VOLCANICS IN THE PORT STEPHENS DISTRICT, NEW SOUTH WALES, AUSTRALIA

5.1 ABSTRACT

This paper presents a new map of the proximal facies of the Nerong Volcanics which crop out in the Port Stephens District, New South Wales. The current literature contends that eight different ignimbrites crop out in the district and that, together with interbedded sediments, they have a total thickness of nearly 2 km. However, detailed chemical and mineralogical analyses of ignimbrites in virtually every outcrop in the district distinguish only three different ignimbrites in the district: two rhyolites named, respectively Port Stephens ignimbrite and Fly Point ignimbrite, and one dacite, named Nelson Bay ignimbrite. The Port Stephens District lies on the closure of the Girvan Anticline so that the general dip in the whole area is southwards. A set of NNE-SSW and WNW-ESE normal faults creates many fault blocks that repeatedly step the ignimbrites back up to the surface in the south, and an orthogonal joint set (N-S and E-W) hosts numerous Tertiary basalt dykes.

The ignimbrites are intensely welded and all exhibit both glassy and lithoidal lithologies. The glassy lithology occurs in narrow lenses, normally near the base of the flows and results from extreme welding. The crystals are set in an isotropic glass matrix which in thin section shows little evidence of the the original shard texture. The bulk of the ignimbrites is the lithoidal rock and although it is less intensely welded than the glassy variety, it is sufficiently

welded so that the shards in the matrix are stretched and deformed around clasts and crystals.

The glassy lithology contains well preserved, 'fresh' crystals matrix chemistry is altered by hydration and leaching of K_2O. The lithoidal ignimbrite is not hydrated and its analyses give a much better indication of the original chemistry.

5.2 INTRODUCTION

Lower Carboniferous ignimbrites extensively crop out in the Port Stephens District. They outcrop around much of Port Stephens harbour, which is a large drowned river valley harbour (Ly 1978). Sussmilch and Clarke (1928) first mapped these ignimbrites as toscanite, rhyolite and andesite lava flows. Their rock names have persisted in the literature to this time, except that the name toscanite has been replaced by rhyodacite, and the lava flows have been redefined as ignimbrites (Matson 1975; Nguyen 1975; Nashar and Brakel; 1977). Engel (1962) included the entire volcanic sequence in the Port Stephens District as the Nerong Volcanics, which he defined from a type section in Nerong Forestry Road cuttings, about 30 km north of Port Stephens.

The interpretation of the stratigraphic succession of the Nerong Volcanics in the Port Stephens District has changed little since Sussmilch and Clarke (1928) first described it as a succession 6315 ft (1950 metres) thick, including 3 rhyolite flows, 3 toscanite flows, and 2 andesite flows. Furthermore, to date, all of the published geological maps of the district show little structure of the area which gives the impression of their being a thick succession of Nerong Volcanics with an uncomplicated structure. This apparent structural simplicity of the area contrasts markedly with the rest of the Carboniferous succession in Tamworth Belt, which is intensely faulted (Leitch 1974; Roberts and Oversby 1974; Roberts and Engel In press). In fact, the stratigraphic succession in the Port Stephens District is dipping shallowly southwards, is much thinner than its recorded thickness, and repeatedly brought back to the surface by a network of faults. A detailed chemical, petrographic and structural analysis of the ignimbrites and sediments in the Port Stephens District was carried out.

5.3 THE STUDY AREA

The area considered in this study (Fig. 5.1) is confined between latitudes 32°35′ and 32°48′ south, and longitudes 151°55′ and 152°15′ west, and it is largely contained within the Port Stephens (9332-IV-S) and Morna Point (9332-III-N) New South Wales 1:25,000 topographic sheets with some extensions into the adjoining Karuah, Clarencetown and The Branch sheets.

5.4 PREVIOUS WORK

The relationship of the geology of the Port Stephens district to Carboniferous Kuttung Series of the Hunter River District was first considered by Sussmilch and David (1920). Sussmilch and Clarke (1928) were the first to detail the lithologies of the volcanic rocks in the Port Stephens District. Since these pioneering work the geology of the Port Stephens District has not been reconsidered in any detail and their map was the principal basis for the geology of the Port Stephens District as presented by Engel (1962) and the current Newcastle 1:250,000 geology sheet. An unpublished Geological Survey of New South Wales Report by Matson (1975) improved the structural details of the Carboniferous sedimentary succession in the northwestern part of the Port Stephens District, but the rest of the area was still shown as mapped by Sussmilch and Clarke (1928).

Professor Nashar of Newcastle University maintained an active interest in the geology of the Port Stephens District throughout her career. Nashar and Catlin (1959) described the dykes in the Port Stephens District and the geology of Port Stephens formed a significant part of both her book on the geology of the Hunter Valley (Nashar, 1964) and a paper on the textures of ignimbrites in the Hunter Valley (Nashar and Brakel, 1977) which featured photomicrographs of some Port Stephens ignimbrites.

Chemical analyses of some of the ignimbrites from the Port Stephens District have been presented in a number of petrologic and petrogenetic studies of the Hunter Valley, including Nashar (1969), Wilkinson (1971), and Nyugen (1976) and Jakes (1970) and Jakes and White (1972).

The Pleistocene and Holocene sands that occupy large part of the Port Stephens District have been described by Ly (1978).

5.5 REGIONAL GEOLOGICAL SETTING

The Port Stephens District is situated at the southern-most end of the Tamworth Belt, as defined by Korsch (1977), in the southern part of the New England Orogen (Day *et al 1978)*. The Tamworth Belt which formed in the Devonian and existed until the Permian (Roberts and Engel, 1987), was situated between the Kuttung Volcanic Arc on its westernside and a slope and basin province on its easternside above an east facing subduction zone. The belt was a region of shelfal, fluvial and shallow marine, sedimentation and onto it fed the detritus and primary products of the Kuttung Arc. The Nerong Volcanics are a product of this arc.

The Hunter Fault forms the western boundary of the Tamworth Shelf and now defines the border between the shelf and the Permo-Triassic Sydney Basin succession. However, it dies out west of the Port Stephens District (Fig 5.1, Inset) but major north-south faults that break up the Tamworth Shelf in its southern parts continue into the Port Stephens area (Fig 5.1, Inset). The Tarean Fault, for example, truncates the

Carboniferous succession on the western side of the Port Stephens District, it will be shown that other major faults, near-parallel to the Tarean Fault, occur throughout the Port Stephens area.

The Port Stephens District is situated on the southern closure of the shallowly southward plunging Girvan Anticline (Fig. 5.1, Inset). The Girvan Anticline is flanked by the Myall Syncline in the east and by the Medowie Syncline in the west. The Nerong volcanics are exposed in the limbs of all of these NNW. trending folds but in the Port Stephens area the strike swings, to become east-west as the Girvan Anticline closes.

The inferred source of the ignimbrites in the Nerong Volcanics has been named the Port Stephens Volcanic Centre (Chapter 3) and its location has been determined to be about 5 km southeast of Morna Point. The ignimbrites in the Port Stephens District were deposited from pyroclastic flows that flowed north from this centre, so that the ignimbrite facies in south of Port Stephens are the most proximal. They become more and more distal as one moves northwards along the limbs of the major folds.

5.6 <u>THE GEOLOGY MAP</u>

The revised geology map of the Port Stephens District (Fig. 5.1) shows there is a simple outcrop pattern in the Port Stephens area with Lower Carboniferous rocks (Fig 5.2) in part mantled by Pleistocene and Holocene dune and beach sands. Carboniferous sedimentary rocks (Conger Formation and Wootton Beds) are exposed in the core of the Girvan Anticline and they strikes across the northern part of the area, and the Nerong Volcanics crop out over most of the remainder.

The dominant outcrops in the Port Stephens District are of a mostly pink, porphyritic rhyolitic ignimbrite which has been named the Port Stephens ignimbrite (Chapter 3). It is very indurated and resilient and tends to control the topography of

FIGURE 5.1

Geology map of the Port Stephens area. See Fig. 5.2 for key to geological units. The blank (uncolored) parts of the map are Pleistocene and Holocene sands which mantle the Carboniferous strata.

Inset shows the map area with respect to its regional structural setting. GA=Girvan Anticline, MyS=Myall Syncline, MoS=Medowie Syncline, TF=Tarean Fault, WRF=Williams River Fault, MCF=Majors Creek Fault, HF=Hunter Fault, SB=Sydney Basin. Cross hatching shows the outcrop of the Nerong Volcanics.

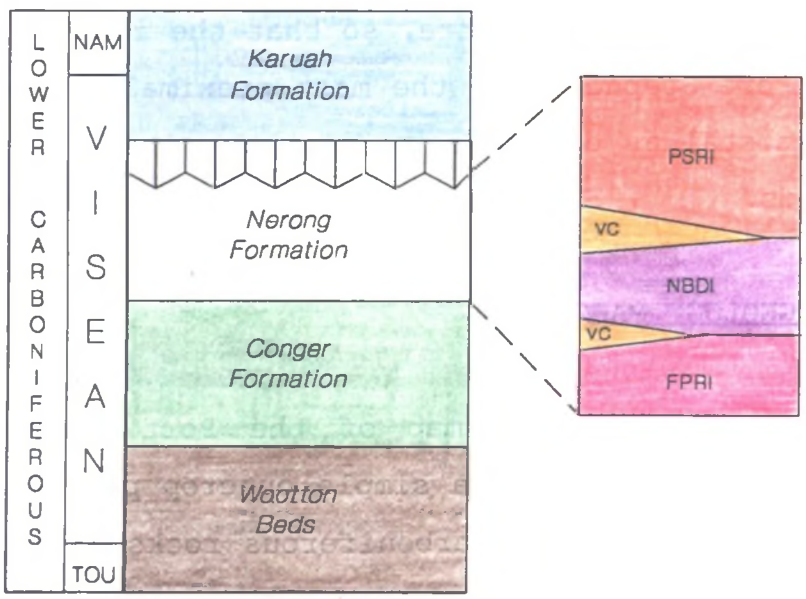


FIGURE 5.2

Stratigraphic column of the Lower Carboniferous strata that outcrop in the Port Stephens area. This is also the key to the Geology Map (Fig. 5.1). The Nerong Volcanics consists of PSI = Port Stephens rhyolitic ignimbrite, NBDI = Nelson Bay dacitic ignimbrite, FPRI = Fly Point rhyolitic ignimbrite, and VC = volcaniclastic sands.

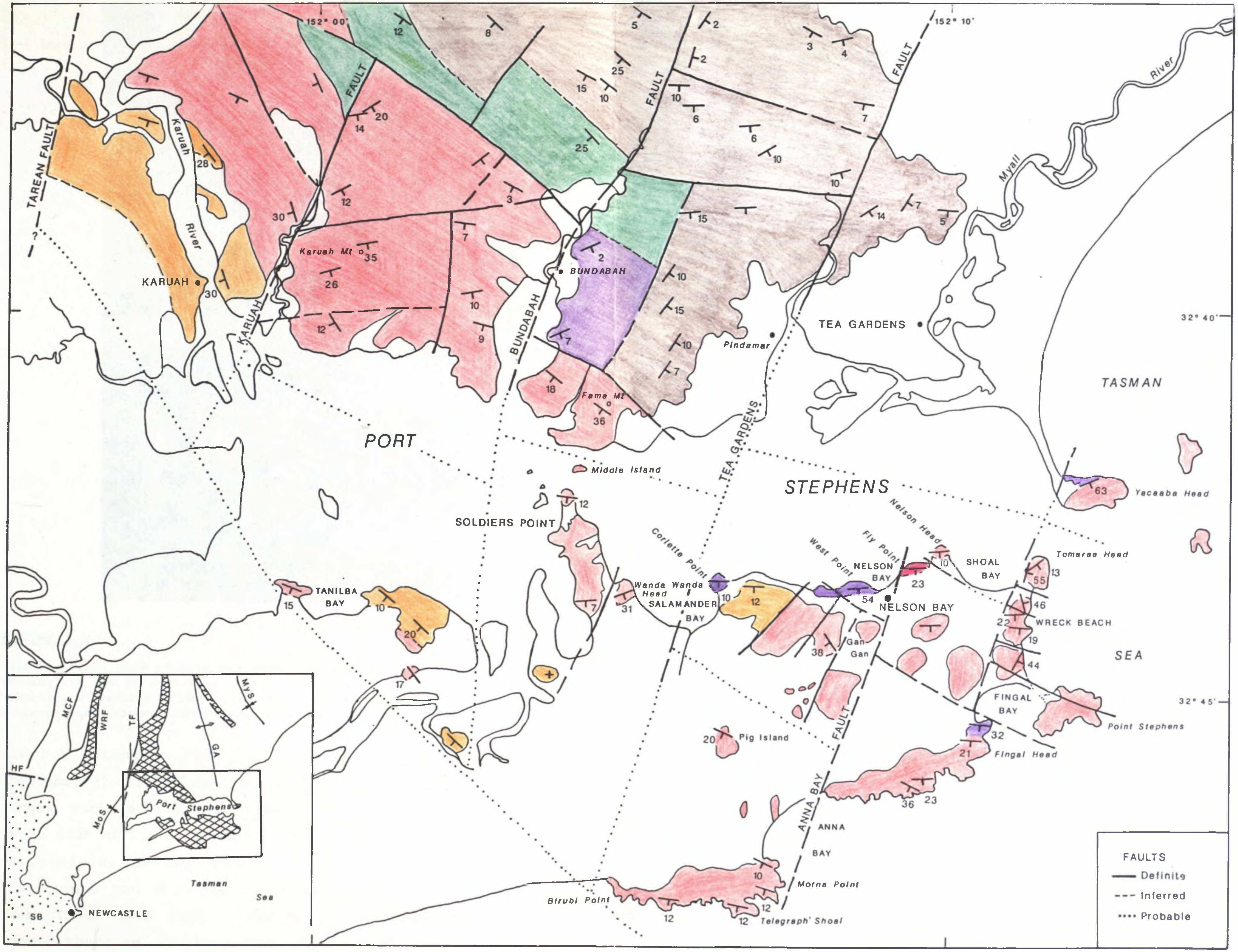

152° 00'
152° 10'
TAREAN FAULT
FAULT
FAULT
FAULT
Karuah River
KARUAH
KARUAH
Karuah Mt
BUNDABAH
BUNDABAH
TEA GARDENS
Pindamar
TEA GARDENS
Myall River
TASMAN
SEA
PORT
STEPHENS
Fame Mt
Middle Island
SOLDIERS POINT
TANILBA BAY
Wanda Wanda Head
SALAMANDER BAY
Corlette Point
West Point
Fly Point
Nelson Head
NELSON BAY
NELSON BAY
Gan Gan
SHOAL BAY
Tomaree Head
WRECK BEACH
FINGAL BAY
Point Stephens
Fingal Head
Yacaaba Head
Pig Island
ANNA BAY
ANNA BAY
FAULT
Morna Point
Birubi Point
Telegraph Shoal
32° 40'
32° 45'
MCF
WRF
TF
MYS
GA
HF
MoS
Port Stephens
Tasman Sea
SB
NEWCASTLE
FAULTS
Definite
Inferred
Probable

FIGURE 5.3

Oblique aerial view towards the north, of the entrance to Port Stephens showing the row of conical-shaped hills, which are formed of the Nerong Volcanics. Yacaaba (219m) is the hill on the northern side of the entrance and Tomaree (165m) is on the south.

the Port Stephens District. On the northern side of Port Stephens, it forms moderately dipping dip slopes and strike ridges, such as Karuah Mt. (246m) and Fame Mt. (143m). On the south side of Port Stephens, the ignimbrite forms a number of steep-sided conical peaks (Fig. 5.3), which have the Pleistocene and Holocene beach and dune sands lapping onto them. These sands tend to reduce the steepness of the slopes around the base of the peaks. The highest peaks are Yacaaba

(219m), Tomaree (165m) (Fig. 5.3) and Gan Gan (161m). In some places, massive parts of the Port Stephens ignimbrite have a distinct rounded, granite-like outcrop (Fig 5.4).

A grey porphyritic dacitic ignimbrite named the Nelson Bay ignimbrite (Chapter 3) crops out in small isolated cliff sections on Corlette Point, West Point, and at the southern end of Fingal Bay, and it forms the flat ground around Bundabah, where it is near horizontal. Sussmilch and Clarke (1928) claim

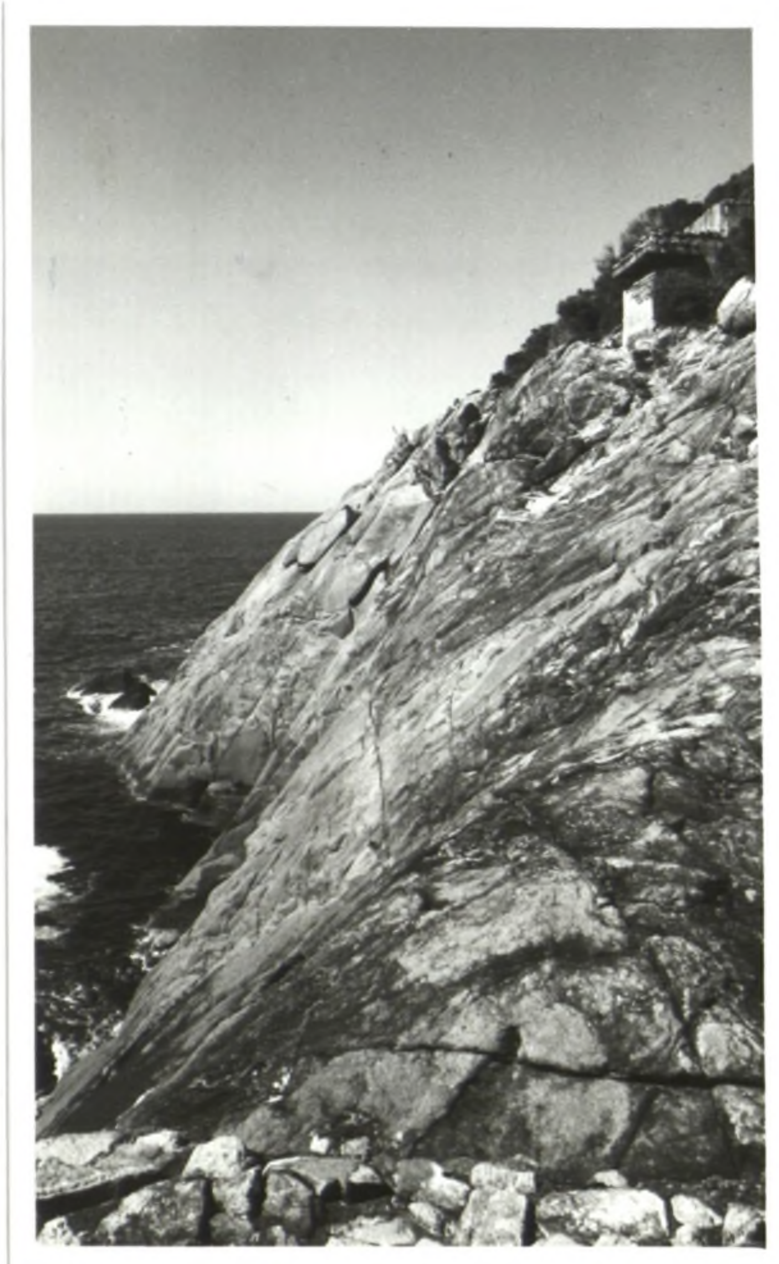


FIGURE 5.4

'Granite-like' outcrop which has formed on a massive part of the Port Stephens rhyolitic ignimbrite, on the northern side of Tomaree Head. Concrete bunker is a W.W.II gun emplacement (G.R. Port Stephens 237802).

that the island on which Point Stephens is located is entirely their equivalent of the Nelson Bay ignimbrite but Matson (1975) and I, both of whom could not arrange a trip to the island, contend from distant observations using field glasses that the nature of the outcrop on the island is more typical of the Port Stephens (rhyolitic) ignimbrite.

An single outcrop of a thin, pumice lenticle-rich rhyolitic ignimbrite crops out on Fly Point and in a small outcrop just above sea level on the northernside of Yacaaba Head. It is informally referred to as the Fly Point ignimbrite in this paper, although it is not considered in any detail.

The sedimentary lithologies in the core of the Girvan Anticline tend to produce a subdued, undulatory relief.

5.7 STRATIGRAPHY

The stratigraphy of the Port Stephens area is summarised in Figure 5.2. The Karuah Formation, which disconformably overlies the Nerong Formation elsewhere, does not crop out in the Port Stephens area and it is therefore not described here. The derivation of the names of the stratigraphic units and their definitive descriptions were detailed in Engel (1962) and updated descriptions of them are to be presented in Roberts and Engel (In press). Only a brief description of the sedimentary units is presented here.

5.7.1 Wootton Beds

The representative section of the Wootton Beds (Engel, 1962) occurs in the Booral-Myall Lakes region about 30 km north of Port Stephens. However it crops out extensively in the core of the Girvan Anticline and it encroaches into the northern part of the Port Stephens area. It has a thickness of at least 1,400 m and it consists predominantly of fossiliferous mudstone with interbedded quartz-rich volcanogenic sandstones.

In the Port Stephens area, the fossil assemblages are confined to the *Schellwinella cf. burlingtonensis* and *Orthotetes australis* Zones (Matson, 1975) and the top of the Wootton Beds is taken as being at the top of the *Delepinea aspinosa* faunal Zone (Roberts and Engel, In press). Thus, the Wootton Beds range in age from late Tournaisian to late Viséan.

Bedding is well developed in the Wootton Beds and good structural measurements can be obtained from them.

5.7.2 Conger Formation

This unit was defined by Campbell (1961) as a sequence of coarse clastic sediments on the western flank of the Girvan Anticline, about 15 km north of Port Stephens. The Conger Formation conformably overlies the Wootton Beds, it has a maximum thickness of 1,070m (Roberts and Engel, In press) and it consists predominantly of shallow marine and terrestrial, quartz-feldspar-lithic sandstone with lenses of boulder conglomerate. The clasts in the sandstone and conglomerate are similar, which are predominantly glassy, silicic volcanic rocks. Roberts and Engel (In press) cite that the Conger Formation contains fossil assemblages from the upper part of the *Delpinea aspinosa* Zone, which dates the formation as late Viséan.

5.7.3 Nerong Volcanics

The Nerong Volcanics were defined by Engel (1962) from a type section on the eastern limb of the Girvan Anticline, on Nerong Road where it crosses the Nerong Range (Grid Reference, 182063 to 190072, Buladelah 1:25,000 sheet), approximately 30 km due north of Nelson Bay. The type section was originally described as

Top	Ignimbrite	100 ft (30 m)
	Toscanite	550 ft (170 m)
	Lithic arenite	200 ft (60 m)
	Toscanite	300 ft (90 m)
	Andesite	200 ft (60 m)
	Conglomerate	100 ft (30 m)
Base	Toscanite	950 ft (290 m)

THICKNESS (m)	LITHOLOGY	OUTCROP LOCATION	NEW NAME
Unknown	Cherts and tuffs		
95	Rhyolite Flow (Morna Point Flow)	Morna Point	PSRI
3	Cherts (with *Racopteris*)		
9	Tuff		
110	Tuffaceous Conglomerate with small Rhyolite Flow (No.2 flow)	Tanilba Bay area	PSRI
15	Tuff		
50	Rhyolite (No.1 flow)	Fingal Head	PSRI
185	Tuffaceous Sandstone with plant fossils		
250	Conglomerates and tuffs		
350	Strata (no outcrops)		
150	Toscanite Flows		PSRI
180	Strata (no outcrops)		
125	Toscanite Flows	Soldiers Point	PSRI
230	Strata (no outcrops)		
60	Toscanite (Nelson's (Sic) Head Flow)	Nelson Head	PSRI
95	Conglomerate (with large Boulders)		
6	Andesite (No.2 flow)	? Nelson Bay	NBDI
9	Conglomerate		
30±	Andesite (No.1 flow)	West Point	NBDI
Unknown	Conglomerate		

TABLE 5.1

The stratigraphic column for Port Stephens of Sussmilch and Clarke (1928). Their measurements have been converted to metric and a column has been added to indicate the location of the outcrops from which their succession was compiled, and another to indicate the new names; NBDI = Nelson Bay (dacitic) ignimbrite, PSRI = Port Stephens (rhyolitic) ignimbrite.

However this sequence is now recognised to consist wholly of ignimbrites, and they are interbedded with lesser amounts of volcaniclastic sediments. Roberts and Engel (in press) state that in the 820 m type section of the Nerong Volcanics

"the dominant ignimbrite is rhyodacitic and occurs in compound units up to 300m in thickness. The only major variation in volcanic composition is the development of a hornblende andesitic ignimbrite (60 m) approximately 320m above the base of the formation."

They also add

"Lithological sections of the Nerong Volcanics share common development of rhyodacitic, dacitic and hornblende andesitic ignimbrites, occasional pyroxene andesite flows, vitric and lithic tuffs and variable amounts of coarse sandstone and conglomerate."

These general descriptions convey the complexities that exist in the stratigraphy and correlation of different sections of the Nerong Volcanics. As in all volcanic terrains, these pyroclastic units are discontinuous, either because they did not reach a particular place or they have been eroded after being emplaced.

The stratigraphic succession in the Port Stephens District was derived by Sussmilch and Clarke (1928) (Table 5.1) and it has never been seriously reviewed. Their measured 1900 m thickness of the Nerong Volcanics in the area is accepted to this day. Matson (1975) considered it to be an overestimate but agreed that it is thicker in the Port Stephens District than it is in the type section.

However, the Sussmilch and Clarke (1928) stratigraphic column was derived from a rather convoluted traverse from Nelson Bay, south to Morna Point. It zig-zagged to Corlette Point, to near Tanilba Bay and Fingal Head as Sussmilch and Clarke (1928) assumed continuity of strike and dip between the areas of outcrop. The new geological map (Fig. 5.1) shows that faults disrupt the sequence throughout the area and that continuity between isolated outcrops are seldom demonstrable (see Structure 5.8.3). In their stratigraphic column (Table 5.1) there are several repetitious sequences in the succession (e.g. toscanite-conglomerate, andesite-conglomerate etc.) and each of these repetitive sequences have been described from localities on different fault blocks. As a consequence, the same ignimbrites and associated strata occur more than once in their succession and their derived thickness of the exposed Nerong Volcanics in the Port Stephens area is grossly exaggerated.

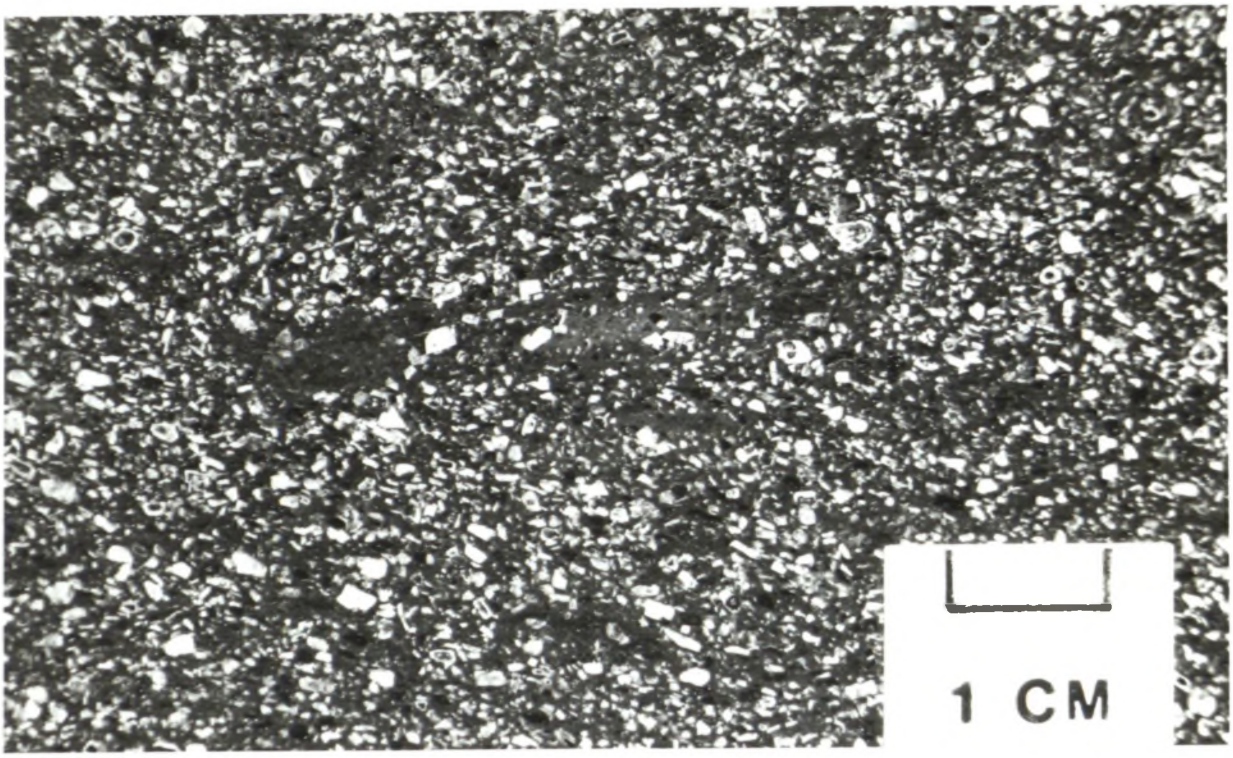
The Nerong Volcanics in the Port Stephens area have been found to include only three ignimbrite units (Fig 5.2). At the base of the succession, the Fly Point (rhyolitic) ignimbrite is approximately 10 m thick and it outcrops in a small fault sliver on Fly Point, resting on sediments . It would have been

FIGURE 5.5

Macroscopic appearance of the Nelson Bay (dacitic) Ignimbrite. The darker lens-shaped feature in the centre is a flattened, glassy pumice clast (fiamme). Plagioclase is the obvious white crystals and hornblende are the black prismatic ones (MU 36578, G.R. Port Stephens 191794).
Note that the crystals in the fiamme, a true sample of the erupted material, are much sparser than in the matrix. Thus it is likely that the matrix in this ignimbrite has been depleted of fines (vitric components) to a substantial degree.

FIGURE 5.6

This is the only known exposure of the disconformable contact (black line) between the Port Stephens (rhyolitic) Ignimbrite (upper unit) and the Nelson Bay (dacitic) Ignimbrite in the Port Stephens District, at the southern end of Fingal Bay (G.R. Morna Point 221753). Contact surface dips 21° -> 187°.


1 CM

impossible to position the Fly Point ignimbrite in the succession except for a very small outcrop of apparently the same unit, at sea level on the northern side of Yacaaba Head, lying directly under the Nelson Bay ignimbrite. At Tanilba Bay and Corlette Point, the Nelson Bay (dacitic) ignimbrite (Fig. 5.5) lies on conglomeratic volcaniclastic sediments. The Nelson Bay ignimbrite has only limited exposure in the Port Stephens area but it is at least 165 m thick at the southern end of Fingal Bay. There the Nelson Bay ignimbrite is disconformably overlain by the Port Stephens (rhyolitic) ignimbrite (Fig.5.6). At Corlette and the Tanilba Bay area the Nelson Bay ignimbrite is overlain by conglomeratic sediments. The Port Stephens ignimbrite (Fig. 5.7) is the most widespread of the three units in the Port Stephens area. Its greatest uninterrupted thickness (190 m) is exposed on Yacaaba Head.

The thickness of the sediments interbedded with the ignimbrites in the Port Stephens District is open to conjecture

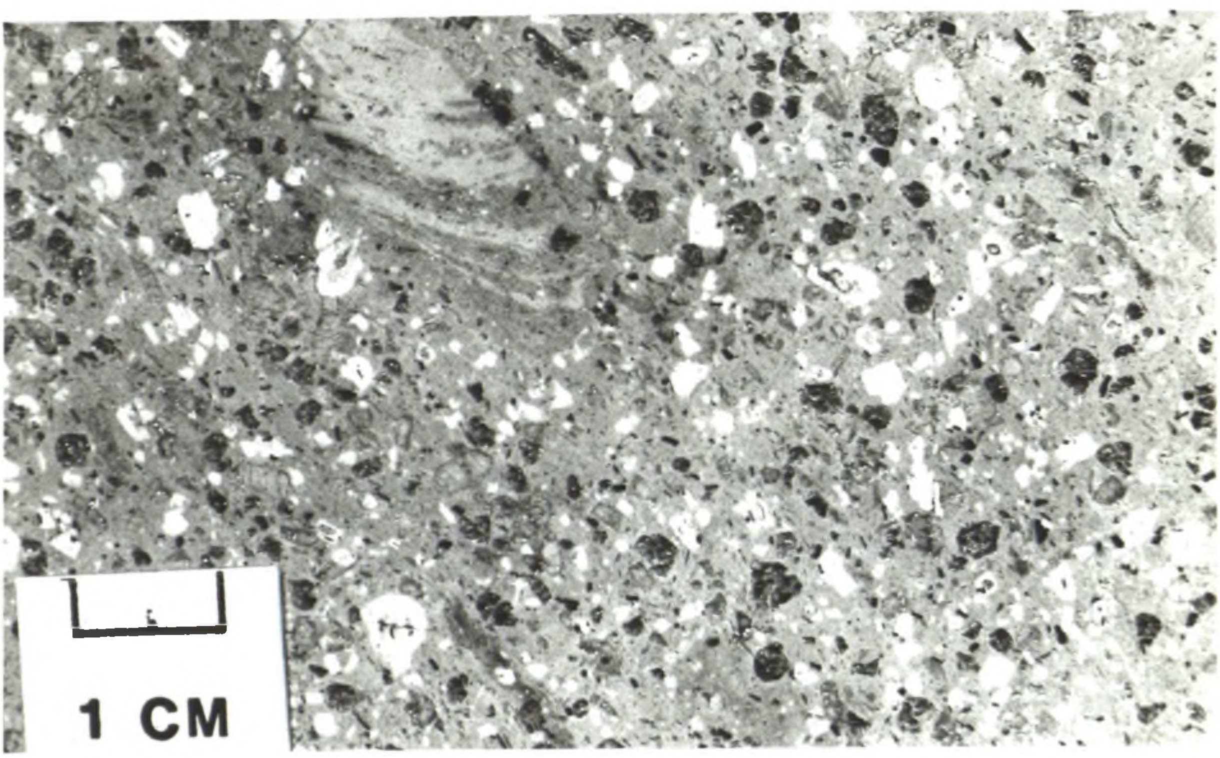


FIGURE 5.7

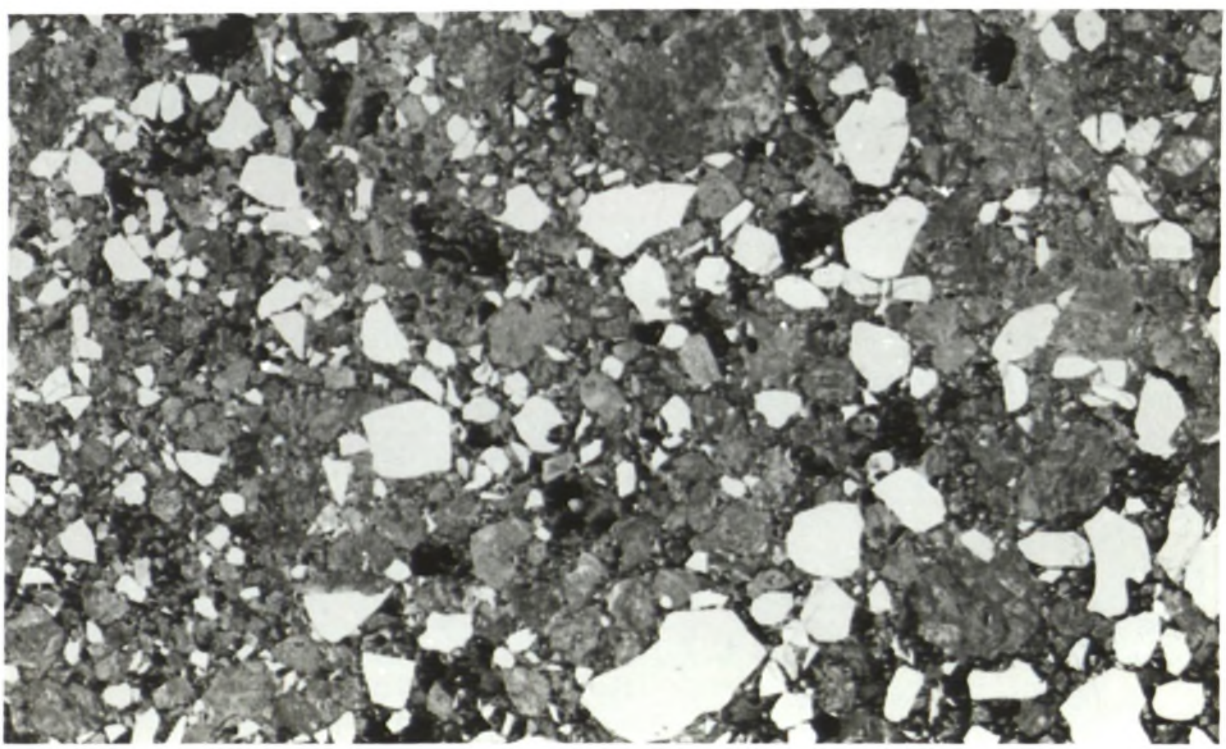
Macroscopic appearance of the Port Stephens ignimbrite. Phenocrysts are quartz (dark colour), orthoclase (large white) and plagioclase (smaller white. prismatic), and biotite. Note the small flow-banded rhyolite clast. (MU 36568, G.R. Morna Point 175717).

FIGURE 5.8

This road cutting at Corlette (G.R. Port Stephens 166795) exposes volcaniclastics (conglomerate, sandstone and shales) that lie between the Nelson Bay Ignimbrite and the Port Stephens Ignimbrite. Basal polymictic conglomerate unit (approx. 5 m thick) contains clasts of silicic volcanics and silicified volcaniclastic sandstones. The open fabric and massiveness of the conglomerate implies rapid or mass movement emplacement.

FIGURE 5.9

Photomicrograph of a typically quartz- and lithic-rich volcaniclastic sandstone in the Nerong Volcanics which are interbedded with the ignimbrites. This one is present below the Nelson Bay Ignimbrite near Bundabah (MU 36624, G.R. Port Stephens 119855, Plane Polarised Light, Image Length = 13mm).



as no outcrop exposes their full thickness. The thickest outcrop of the sediments between the Nelson Bay and Port Stephens ignimbrite is at least 60 m and it occurs in a road cutting within the settlement of Corlette (Fig 5.8) (which is near Corlette Point). This sedimentary unit thins rapidly southwards (towards the source of the ignimbrites) and at south Fingal Bay it is absent, so that the two ignimbrites are in direct contact. The sediment thickness between the Fly Point ignimbrite and the Nelson Bay ignimbrite is indeterminable but it is known that its thickness also varies from nil at Yacaaba Head to at least 2 m at Fly Point. At least 1200 m of volcaniclastic sediments overlie the Port Stephens ignimbrite in the Karuah area. The diagnostic characteristics of all of the sediments in the Nerong Volcanics is that they contain abundant quartz and feldspar (Fig. 5.9), and the lithic components are dominantly silicic lavas, ignimbrites and granite.

In an attempt to correlate the succession in the Port Stephens District with the succession in the type section of the Nerong Volcanics (Engel, 1962) the ignimbrites in the type section were sampled. The 'andesite' (sample MU 36594) and the overlying 300 ft. 'toscanite' (sample MU 36557) in the lower part of the type section proved to be mineralogically and chemically identical to the Nelson Bay (dacitic) ignimbrite and Port Stephens (rhyolitic) ignimbrite, respectively (Chapter 4), and these correlations reflect the continuity of these two ignimbrites between the two localities. The Fly Point ignimbrite appears not to have reached this far north.

5.8 <u>STRUCTURE</u>

5.8.1 Methods

In the Port Stephens District, geologists are faced with the problem of massive ignimbrites which lack bedding from

FIGURE 5.10

This outcrop of the Nelson Bay (dacitic) ignimbrite on West Point shows the pock marks of weathered out pumice clasts and a preferred parting along the plane of flattening (= pseudo-bedding). (G.R. Port Stephens 194795)

which measurements can be made to interpret the structure of the area. The determination of 'bedding', as defined by a foliation, in the ignimbrites has been the key to unraveling this structure. The foliation in ignimbrites is normally defined as the plane that contains the primary flow lineation, although some rheomorphic ignimbrites exhibit a secondary flow foliation (Wolff and Wright 1981).

The Nelson Bay (dacitic) ignimbrite and the Fly Point (rhyolitic) ignimbrite both have a bedding (foliation) defined by the strong alignment of flattened pumice clasts , which on weathered surfaces of outcrops appear as elongated pockmarks (Fig.5.10). These ignimbrites also have a tendency to split along this plane of flattening. Unfortunately they have very limited outcrop. Most of the outcrop in the district is Port Stephens (rhyolitic) ignimbrite which is so massive that its dip could not be determined in the field. The foliation plane

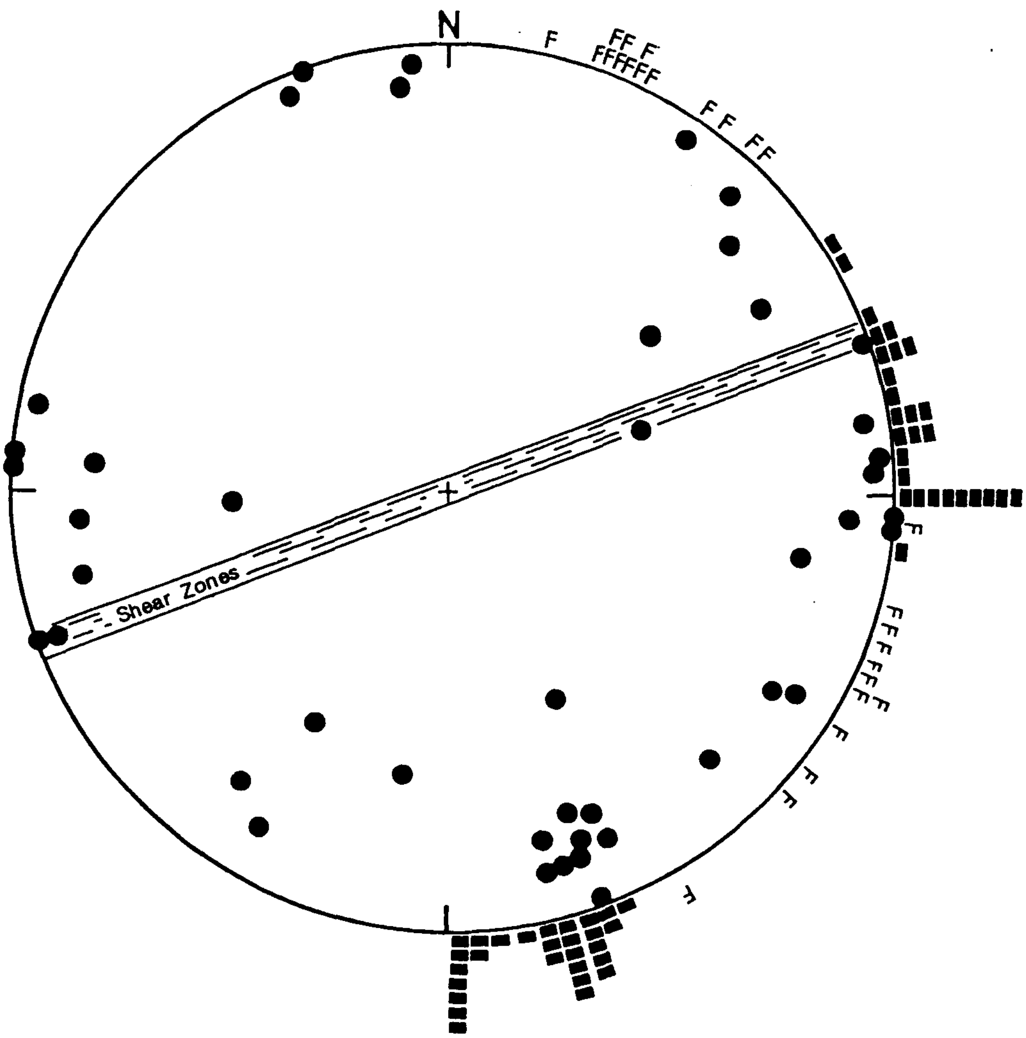


FIGURE 5.11

Stereo-plot of joint surface poles (filled circles), and strikes of faults (F's) and strikes of dykes (filled rectangles). Note the correspondence between joints and dykes.

was determined in the laboratory from sawn orientated samples (Appendix III). In the Morna Point area, some outcrops of the Port Stephens ignimbrite display crude columnar joints and a preferred parting normal to these joints, approximates the foliation orientation determined on the sawn orientated samples.

5.8.2 Folding

The Port Stephens area is on the closure (nose) of the Girvan Anticline, an asymmetric fold that plunges to the south at a shallow angle. As a consequence, the strike of the beds in the Port Stephens area swing from a NW-SE direction on the western side of the map to E-W near the coast. Outcrops along the closure extend to the islands off the entrance to Port Stephens. North from the islands, outcrops are present on the eastern limb of the anticline for about 15 km (Fig 5.1, Inset).

In the Port Stephens area, the beds generally dip at angles less than 20°, except where there is local steepening adjacent to faults. For example, on both Yacaaba and Tomaree Heads, along the southern side of the port from Fingal Bay to Yacaaba Head, and at other scattered localities the dips are 44° - 63°, steeper than the normal <20° dips over most of the District.

5.8.3 Faulting

The new lithological correlations and structural data presented here reveal that numerous faults occur in the Port Stephens area. Although, the area is no more faulted than other parts of the Tamworth Shelf succession. Faults have been determined principally from truncations in bedding and changes in strike, both of which commonly correspond with stream courses and topographic lows. Some lineations were seen on air photos, especially on the northern side of the Port. Direct evidence of faulting is limited. Minor shear zones of crushed rock, about 1 metre wide, occur at the Nelson Bay end of West Point, on Fly Point, and on Morna Point, all with the same orientation. However, this orientation (Fig.5.11) does not correspond with the principle directions of the determined faults.

Only faults that can be placed with a degree of certainty are shown on the geological map (Fig.5.1). A surprising finding was the unsystematic nature of dips in the hills of the Nerong Volcanics such as Yacaaba, Tomaree and Gan Gan, and in isolated outcrops at Pig Island and Wanda Wanda. Each hill or isolated outcrop seems to be a part of a separate fault bounded block. the Port Stephens area it seems likely that almost every hill

Most faults shown on the geological map (Fig. 5.1), south of the Port are inferred as the the Carboniferous volcanics are masked by a mantle of the Quaternary sands. However, the faults shown must exist, although their precise position and orientation cannot be determined with any certainty. There is no doubt that other faults, which are not shown, are also present.

There are two main orientations of faults in the Port Stephens area (Fig. 5.11). The principal faults trend NNE (020^{o} to 040^{o}) (e.g. the here named Anna Bay, Tea Gardens, Bundabah and Karuah Faults). The second set of faults trend WNW (280^{o} to 300^{o}) and mostly branch from, or terminate against the principal faults. The principal NNE-trending faults have the same trend as the major faults in the southern part of the New England Orogen [e.g. the Tarean, Williams River and Majors Creek Faults (Fig. 5.1, Inset)], as mapped by Roberts and Engel (1987). The displacement of the Port Stephens ignimbrite between Morna Point and Fingal Head by the Anna Bay Fault, indicates that it is a normal fault, downthrown on its eastern side by at least 1.9 - 2.1 km.

Roberts and Engel (1987) postulated that folding of Girvan Anticline (and associated folds) was initiated in the Lower Permian but the most intense folding episode occurred in the Late Permian and again in the Triassic. The major NNE-trending faults outside the Port Stephens area are parallel to the axes of the regional folds. Thus, Cary and Osborne (1938) and Osborne (1950) proposed that these faults were related to the compressional folding episode, which no one disputes. However, in the Port Stephens District, in the northwest corner of the geological map (Fig. 5.1), the Tarean Fault truncates the western limb of the Girvan Anticline Furthermore, related NNE-trending faults in the area cut across the regional fold. This indicates that these NNE-trending faults, in this southernmost part of the New England Orogen, occurred after the regional folding episode. Possibly they are related to relaxation (extension) after folding.

The continuous outcrop of the Port Stephens ignimbrite over virtually the entire Port Stephens District and its southwards dip, indicates the WNW-trending faults are a set of normal faults that have produced a series of fault blocks that step down to the north. Perhaps the most significant of the WNW-trending faults is the one inferred to branch from the Tarean Fault that extends from just south of Karuah, through Tanilba Bay to Birubi Point. The sudden disappearance of the gently dipping Port Stephens ignimbrite along this line requires downward displacement to the south.

An apparently related set of normal faults, with an easterly orientation, branch from the major north-south fractures in the Stroud-Gloucester Syncline (the northern extension of the Medowie Syncline). Lennox and Wilcox (1985) contend that they were active in the Late Permian. The

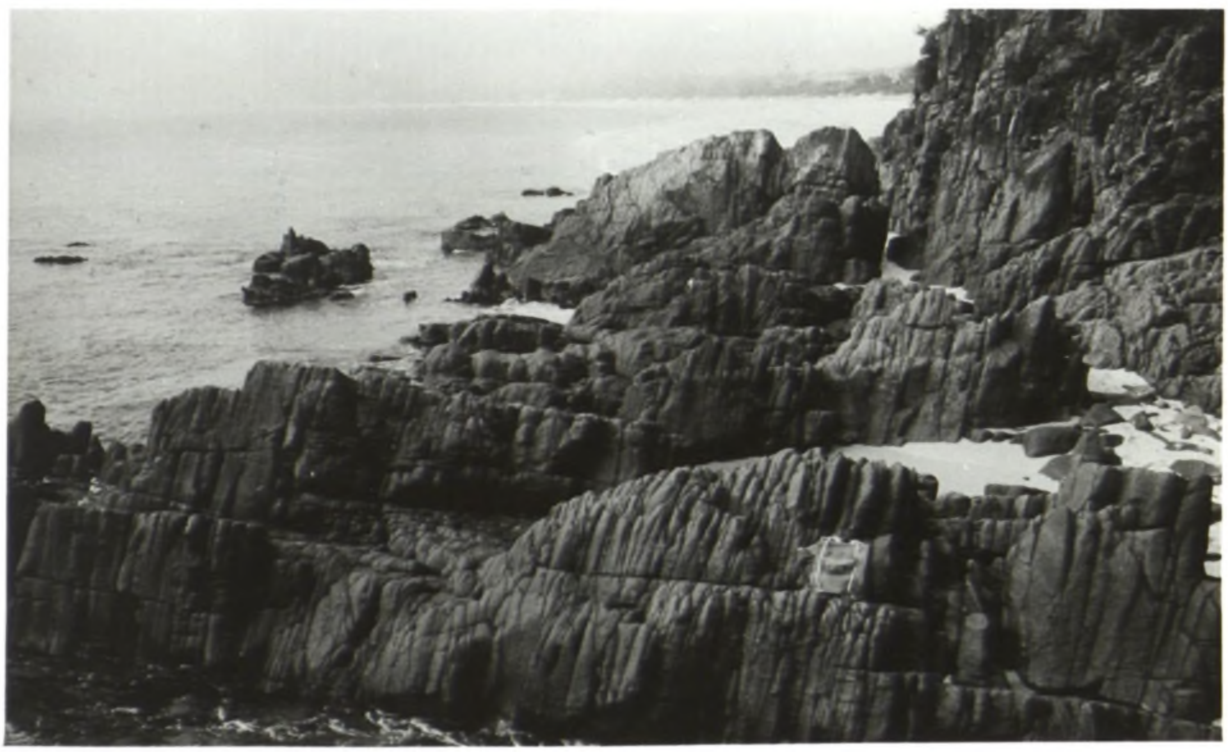


FIGURE 5.12
Steeply dipping, closely spaced joints in the Port Stephens (rhyolitic) ignimbrite on Nelson Head. The more horizontal parting is near to bedding but it is an unreliable source for bedding measurements. Pack scale is 60cm tall (G.R. Port Stephens 213803).

southeasternmost part of the Hunter Fault also has the same trend as the WNW faults. The Hunter Fault dies out west of the Port Stephens area (Roberts and Engel 1987) (Fig. 5.1, Inset), although it is suggested that the WNW faults in the Port Stephens District may be an extension of the Hunter Fault and related to the movements of it.

5.8.4 Joints and Dykes

At least one dominant set of orthogonal joints and a probable second set are present in the Port Stephens District (Fig. 5.11), and are particularly well developed along the southern side of Port Stephens (Fig. 5.12). One joint surface of the dominant set strikes between 350° and 010° and dips mostly between 80° and 85° south. The other surface is less variable in orientation. It strikes between 060° and 075° and dips vary only slightly on either side of vertical. Three shear zones in the Port Stephens area, each about 1 m wide occur in this joint plane (Fig. 5.11). A second set of orthogonal joints, less well defined on Figure 5.11 but conspicuous in the field, has one surface that strikes between 030° and 040°, and dips around 80° SW. The other surface strikes between 310° and 330°, and ranges in dip 20° either side of vertical.

Nashar and Catlin (1959) listed strike measurements of 60 Tertiary basalt dykes, which intrude the Nerong Volcanics throughout the Port Stephens area. They are particularly numerous in the Morna Point area (Fig. 5.13). The dykes vary in width from a few cm to about 5 m and they strike in two orthogonal directions, 070° to o90°, and 160° to 180°. As shown on Figure 5.11, the dykes strike in the same two directions as the dominant joints. This suggests that the dominant joint set had formed prior to the intrusion of the Tertiary dykes and the second joint set after.

The dominant joint set and dykes are tangential to the strike of the faults, although one direction is perpendicular and the other parallel to the strike of the beds. This implies

FIGURE 5.13

An east-west striking Tertiary basalt dyke (1.5-2 m wide) on the north side of Boat Harbour, Morna Point. The dyke is slightly sinuous but overall it is parallel to the prominent north-striking joints. Pack as scale, is 60 cm tall. (G.R. Morna Point 174718)

that these joints formed at the same time as the folding. It is generally believed that the dykes were intruded at the margin of the Australian continent at the time of the initial opening of the Tasman Sea about 80 m.yr ago.

5.9 CHEMISTRY AND MINERALOGY

Although the 'lava flows' of Sussmilch and Clarke (1928)

	Nelson Bay Dacitic Ignimbrite (i)	Nelson Bay Dacitic Ignimbrite (ii)	Port Stephens Rhyolitic Ignimbrite (iii)	Port Stephens Rhyolitic Ignimbrite (iv)
No of Analyses	4	2	8	5
SiO_2	65.95	64.30	75.50	75.23
TiO_2	.68	.71	.23	.22
Al_2O_3	16.22	16.30	13.57	13.62
Fe_2O_3	2.27	2.61	.87	.92
FeO	2.05	2.13	.49	.35
MnO	.08	.11	.03	.04
MgO	1.77	2.15	.24	.24
CaO	4.33	4.08	.58	.75
Na_2O	3.67	3.72	3.63	3.51
K_2O	3.23	2.95	4.99	5.08
P_2O_5	.15	.16	.03	.02
Nb	6	7	11	11
Zr	160	162	179	167
Y	26	24	39	30
Sr	412	422	168	165
Th	14	14	26	25
Pb	14	13	25	21
U	3	3	8	6
Rb	116	113	219	219
Ga	19	19	14	17
Zn	68	63	41	36
Cu	19	19	5	4
Ni	9	10	3	3
Cr	21	19	4	2
V	97	90	4	5
Ti	4192	4125	1578	1502
Ba	453	444	802	729
K/Rb	218	212	188	192

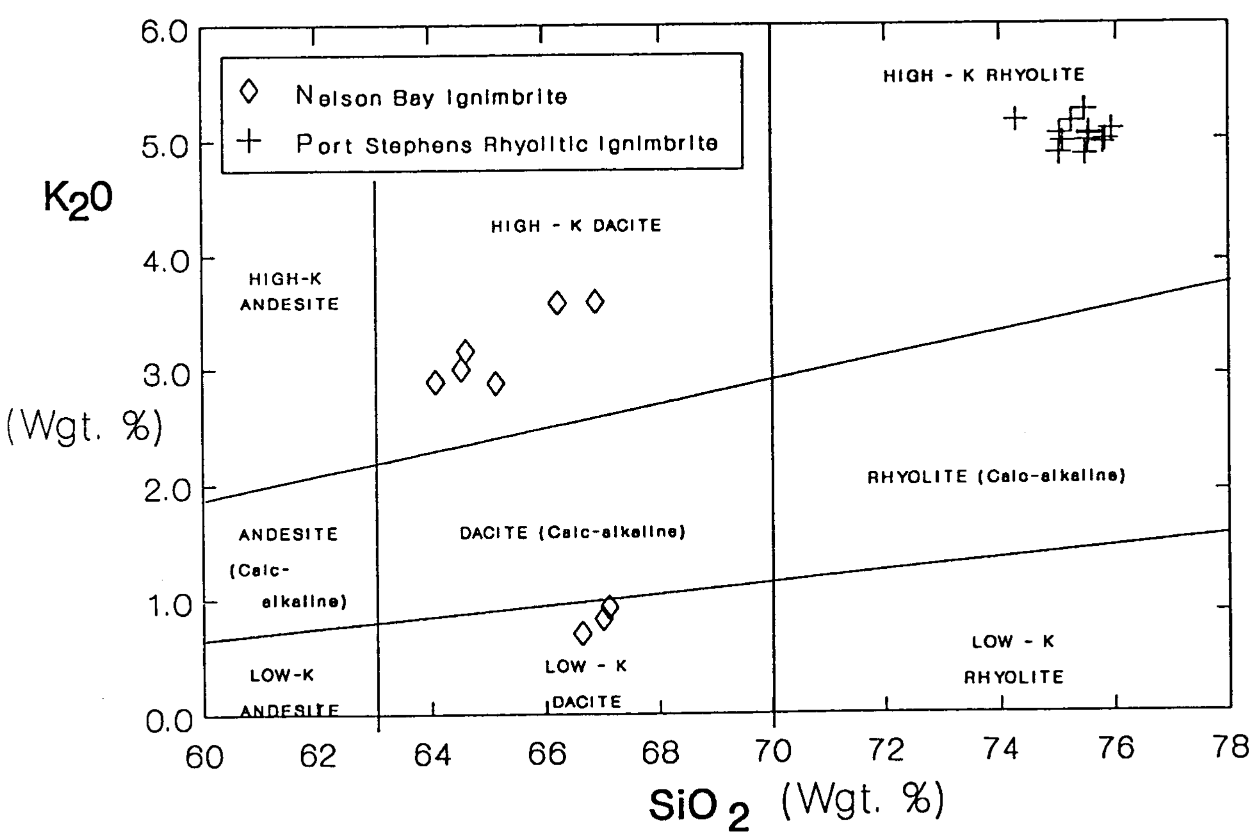
<u>TABLE 5.2</u>

Average major and trace element, whole rock chemistry of the Port Stephens and Nelson Bay ignimbrites from different parts of the Port Stephens area. **(i)** from around Nelson Bay **(ii)** at Fingal Bay **(iii)** from around Port Stephens **(iv)** from around Morna Point. Glassy analyses have been excluded.

are now recognised as ignimbrites, the compositional names they gave these units persist in the literature today. However, the chemical analyses they presented differ substantially from those obtained in this study (Table 5.2 and Appendix VII), so that their rock names are also now considered inappropriate.

5.9.1 Nelson Bay Ignimbrite

Sussmilch and Clarke (1928), Engel (1962), Nashar (1969), and Matson (1975) have all described the mapped outcrops of the Nelson Bay ignimbrite as andesites, and Roberts and Engel (In Press) state that andesites occur in the Nerong Volcanics. However, these 'andesites' are chemically high-K dacites (Fig. 5.14) and mineralogically hornblende-hypersthene dacites. Sussmilch and Clarke (1928) regarded the 'andesites' at south



<u>FIGURE 5.14</u>

Plot of K_2O against SiO_2 and the classification of the Nelson Bay ignimbrite (diamonds) and the Port Stephens ignimbrite (crosses) using the subdivisions of Irvine and Baragar (1971). The three very K_2O poor analyses of the the Nelson Bay ignimbrite are the glassy lithologies which are preferentially leached of K_2O. All of the other analyses represent lithoidal lithologies.

	Specimen MU Number	36579	36588
	Location	*Nelson Bay*	*Fingal Bay*
	N	1811	1925
CRYSTALS	Quartz	0.1	0.1
	Plagioclase	29.1	31.3
	Hornblende	8.4	7. 3
	Hypersthene	3.8	2.0
	Biotite	0.9	0.6
	Opaques	2.9	3.2
	Rock Frags	Present	Present
	Matrix	54.8	55.5

TABLE 5.3

Modal compositions of the Nelson Bay (dacitic) ignimbrite from two different localities.

Fingal Bay as being part of a lava cone stratigraphically above, and different from, the 'andesites' cropping out around Nelson Bay at West Point and Corlette Point (Table 5.1). However, analyses of several samples from each of these localities are virtually identical in both major and trace element chemistry (Table 5.2), and mineralogy (Table 5.3). Thus, all outcrops of dacitic ignimbrite in the Port Stephens area and all of the 'andesites' in the Nerong Volcanics are parts of the Nelson Bay ignimbrite.

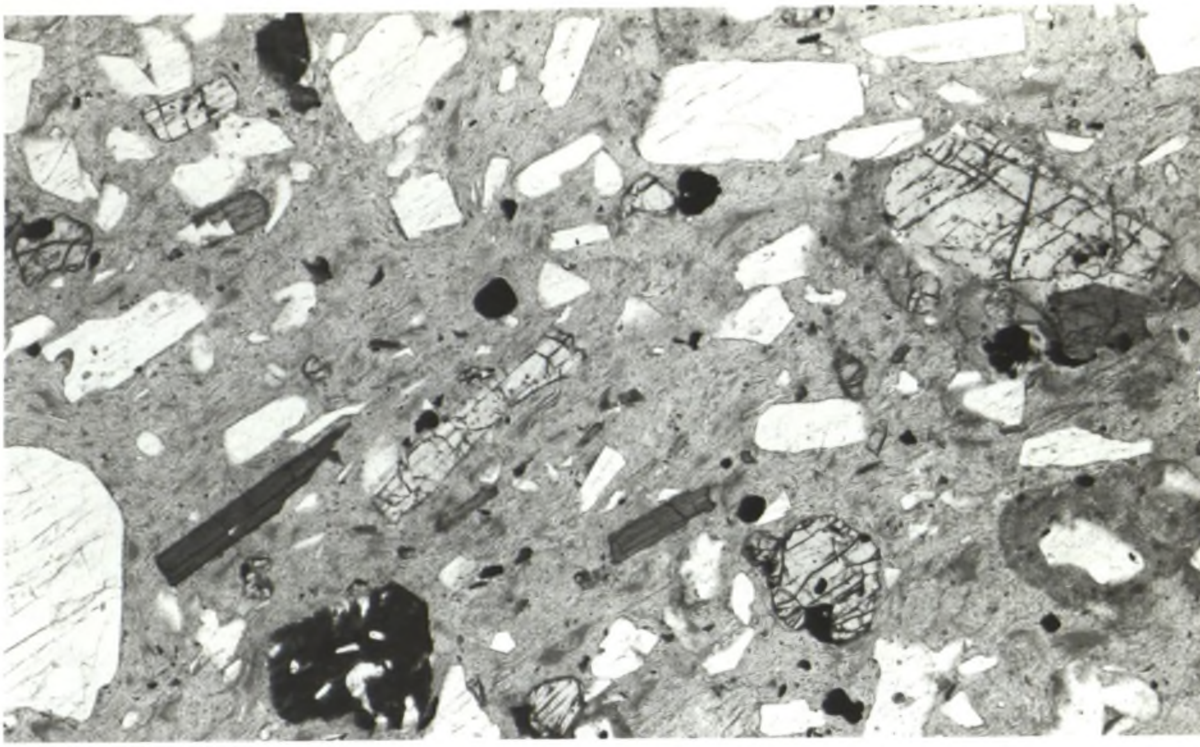
There are two lithological types of the Nelson Bay ignimbrite, glassy and lithoidal. The glassy lithology is the densely welded part of the ignimbrite and it occurs in lenses within, and subordinate to the lithoidal rock at West Point, Corlette Point, and on the flat ground east of Bundabah. It is surprising that of the two different lithologies it is the glassy variety that has fresh, well preserved crystals while chemically it is hydrated and depleted in mobile elements,

FIGURE 5.15

Photomicrograph of a sample of the glassy lithology of the Nelson Bay Dacitic Ignimbrite showing fresh plagioclase, hornblende and pyroxene crystals in a densely welded, deformed shard-rich matrix. (MU 36582, G.R. Port Stephens 157793, Image Length = 6mm)

FIGURE 5.16

This hypersthene crystal in the Nelson Bay Ignimbrite is being replaced by chlorite. Only the outer shell of this crystal is chlorite, but virtually all of the other hypersthenes in this particular specimen, and this ignimbrite are now chlorite-filled pseudomorphs after hypersthene. The hornblende beside the hypersthene is less altered. (MU 36558, G.R. Morna Point 225761, Plane Polarised Light, Image Length = 4.5 mm).



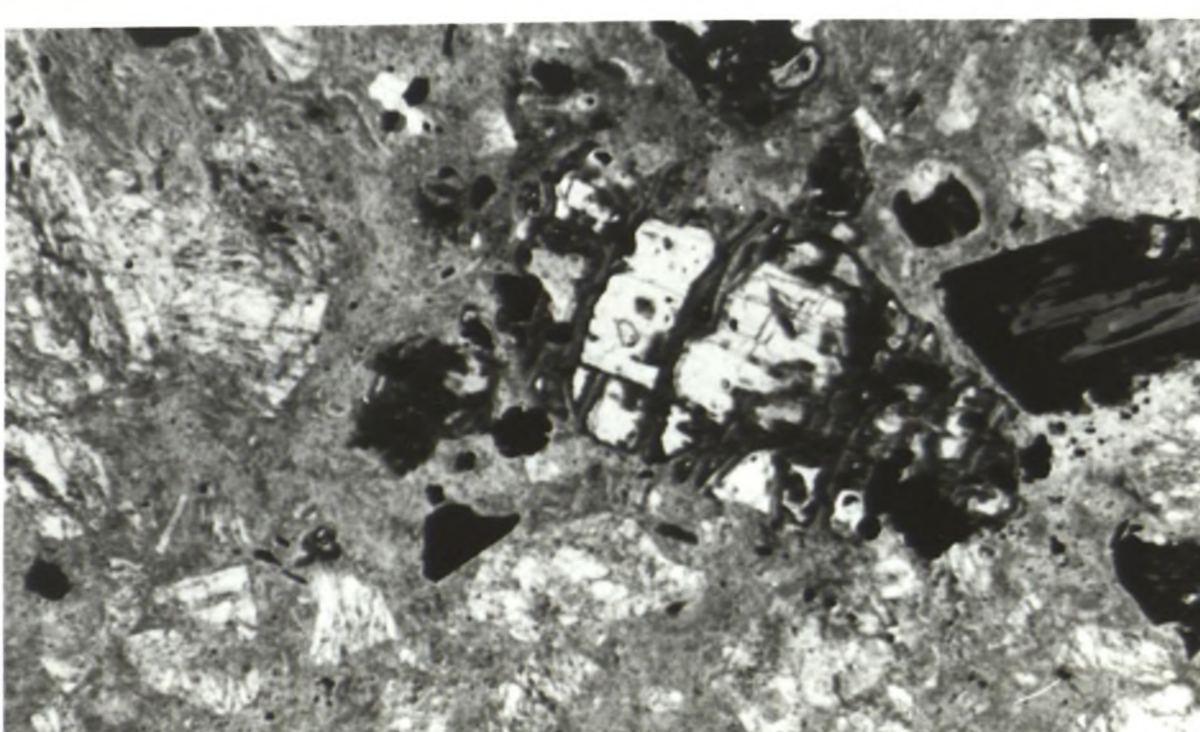
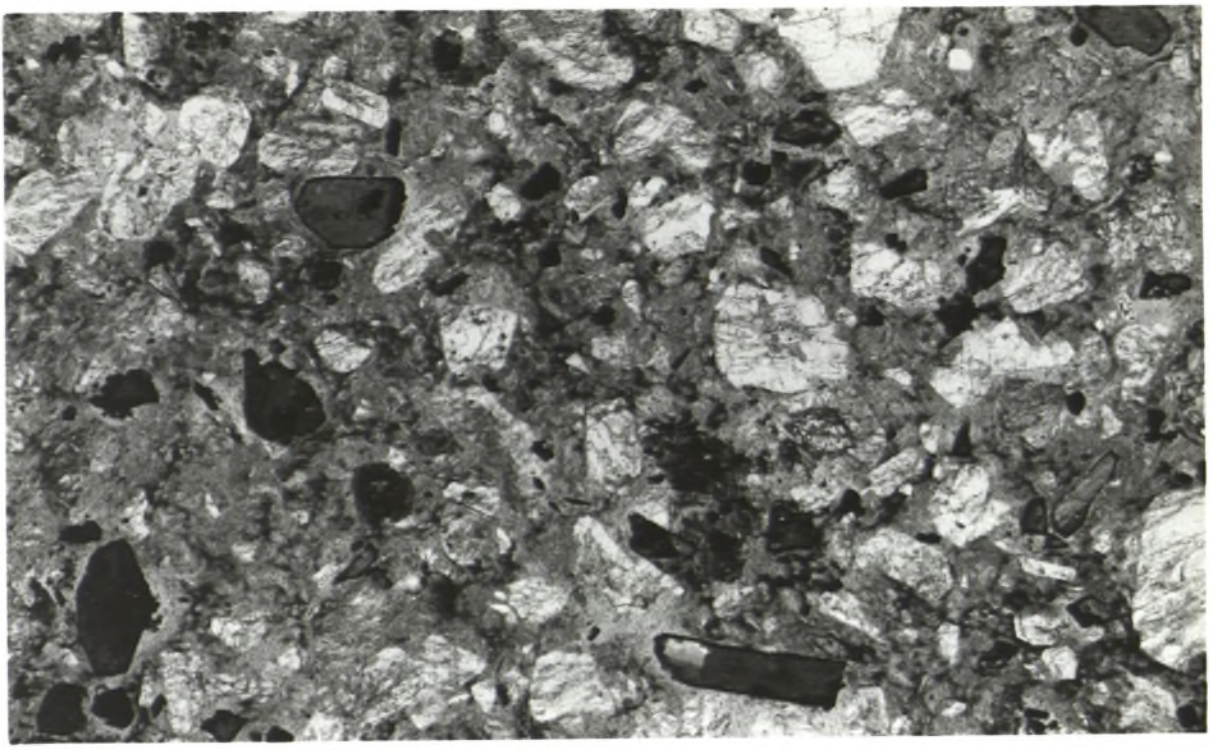


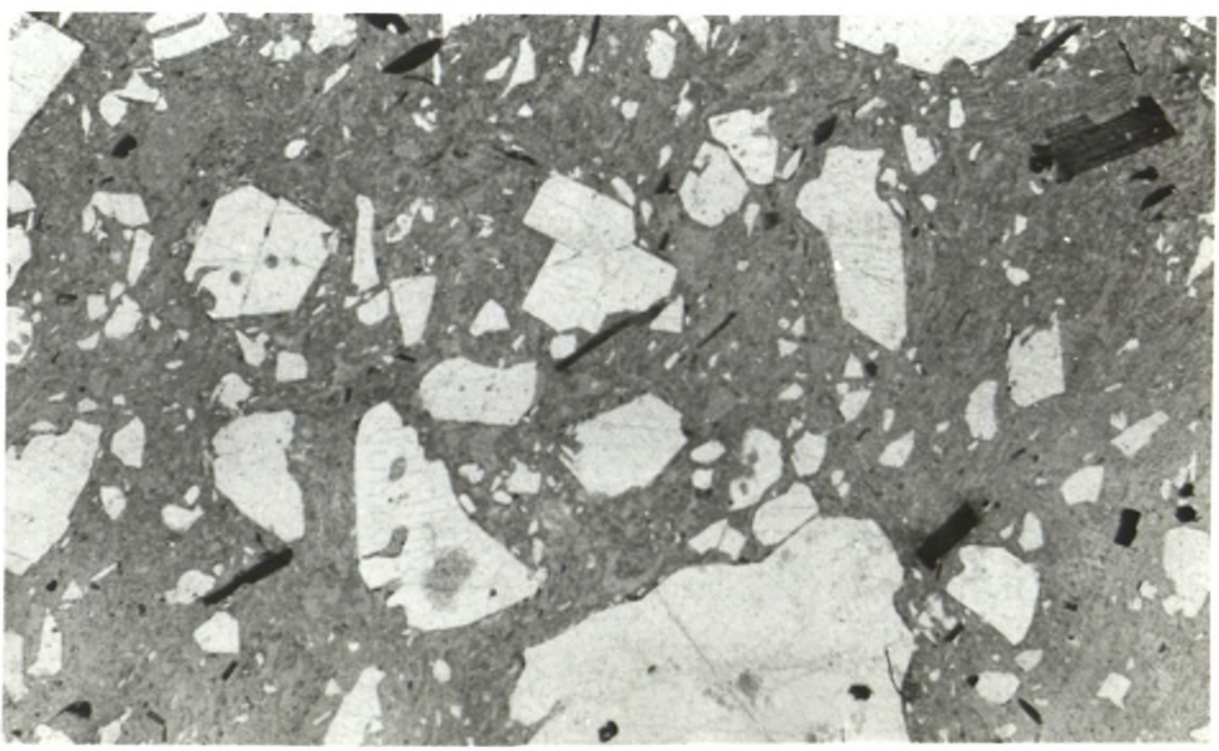
FIGURE 5.17

Photomicrograph showing the normal character of the lithoidal part of the Nelson Bay Ignimbrite with plagioclase, hornblende and opaque mineral phenocrysts set in a devitrified partially sericitised groundmass. Original pyroxene has been replaced by chlorite (intermediate coloured 'crystal' in right-centre) (MU 36578, G.R. Port Stephens 191794, Plane Polarised Light, Image Length = 10mm)

FIGURE 5.18

Photomicrograph showing the typical character of the glassy part of the Port Stephens (rhyolitic) Ignimbrite. Isotropic glass matrix with the original shard texture densely welded and highly deformed about the crystals. Note fragmentation of feldspar crystals, and the quartz crystals are con spicuous with resorption embayments. (MU 36549, G.R. Port Stephens 234788, Plane Polarised Light, Image Length = 10 mm)





especially K_2O (Fig. 5.14) (Chapter 4). The minerals in the lithoidal variety, on the other hand are commonly altered but the alteration seems to have had little effect on the original chemistry as shown by the consistency, and abundance of the mobile elements in the samples analysed. Thus, the lithoidal variety must be used for meaningful chemical comparisons and the glassy type is good for mineralogical comparisons.

In hand specimen the glassy variety is porphyritic with a black obsidian-like matrix. The lithoidal variety has a grey matrix with abundant flattened, glassy pumice clasts (fiamme) (Fig. 5.5). The crystals form 40-50% of the rock (Table 5.3) and in decreasing order of abundance they are plagioclase (An_{40-48}), hornblende, hypersthene, opaques (titanomagnetite, ilmenite), biotite, and embayed quartz (Fig. 5.15). The crystals, plagioclase in particular, are largely crystal fragments (<0.5 mm -2 mm) with unbroken euhedral crystals (up to 4 mm) being less common. The hypersthene in the glassy variety is normally partly chloritised but in the lithoidal variety the hypersthene may be totally replaced so that only chlorite pseudomorphs of it remain. The process of this alteration is captured in Figure 5.16.

The matrix of the glassy variety shows extreme welding that has resulted in the original glass shard-rich matrix being highly stretched (Fig. 5.15), and sometimes transformed into an almost structureless glass which commonly has perlitic fractures. The matrix in the lithoidal variety is at least partially devitrified (Fig. 5.17), but it also shows evidence of dense welding although the original shard texture, when not disguised by the devitrification, tends to be less deformed than in the glassy variety.

5.9.2 Port Stephens Ignimbrite

The unit here named the Port Stephens ignimbrite was identified by Sussmilch and Clarke (1928) as toscanite around Port Stephens from Soldiers Point to Fingal Bay but as

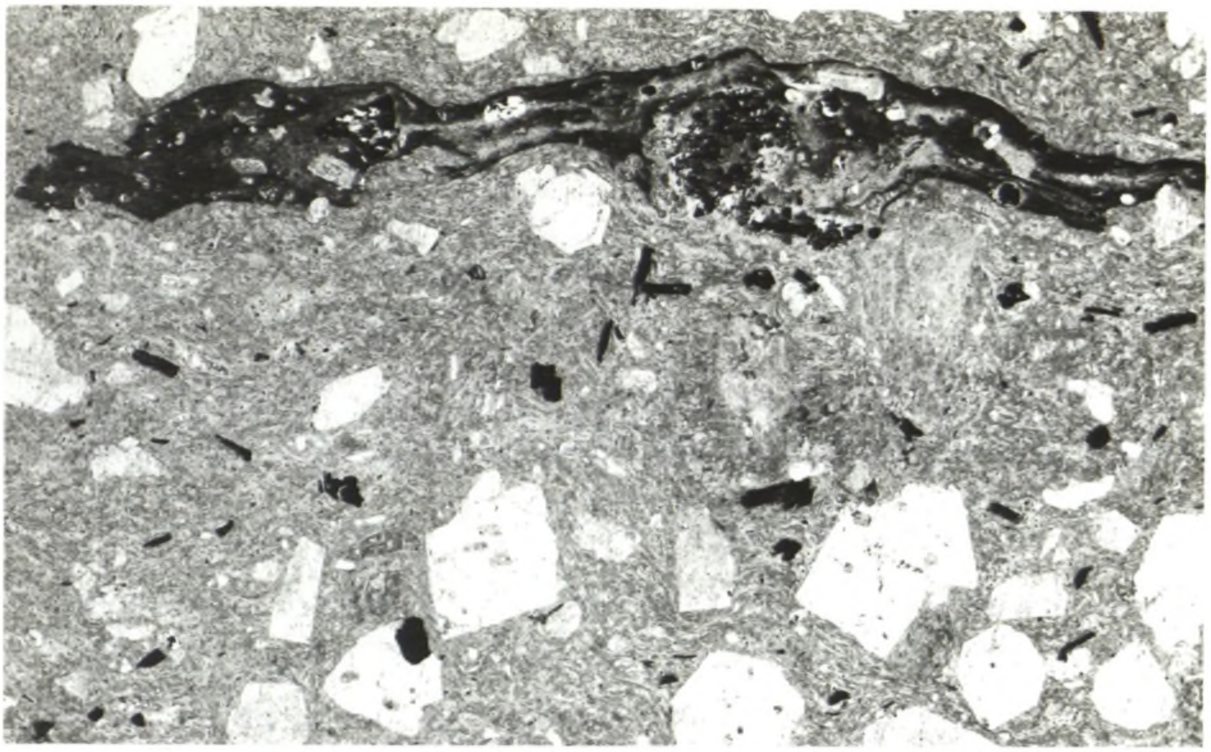


FIGURE 5.19

Photomicrograph of a small now glassy, highly flattened pumice (fiamme) in a lithoidal part of Port Stephens ignimbrite. The matrix is clouded by devitrification and alteration although the original, highly deformed shards are evident (MU 36545, G.R. Port Stephens 185779, Plane Polarised Light, Image Length = 17 mm)

rhyolite in the outcrops from Fingal Head to Morna Point to Tanilba Bay. Matson (1975) renamed the toscanite, rhyodacite, but still reported separate areas of rhyodacite and rhyolite in the Port Stephens area. The chemical data presented here however shows that every analysis of these supposedly different rocks are virtually identical (Table 5.2) (Chapter 4.5) and all have the composition of a high-K rhyolite (Fig. 5.14).

The Port Stephens ignimbrite occurs as both glassy and lithoidal varieties and has the same variation in welding and alteration as the Nelson Bay ignimbrite. The original vitric components (pumice and glass shards) in the glassy rock have been completely deformed and remoulded into the matrix which is now a black obsidian-like, isotropic glass with 'flow' structures that wrap around the crystals (Fig. 5.18). The lithoidal lithology (Fig. 5.7) is normally found with a pink, or grey when fresh, coloured matrix and though it is densely welded the original shards in the groundmass are still identifiable (Fig 5.19). The glassy parts of the Port Stephens ignimbrite occur in irregular shaped lenses towards the base of the ignimbrite unit on Nelson Head (Fig. 5.20), at the northern end of Wreck Beach and at the base of Gan Gan Hill.

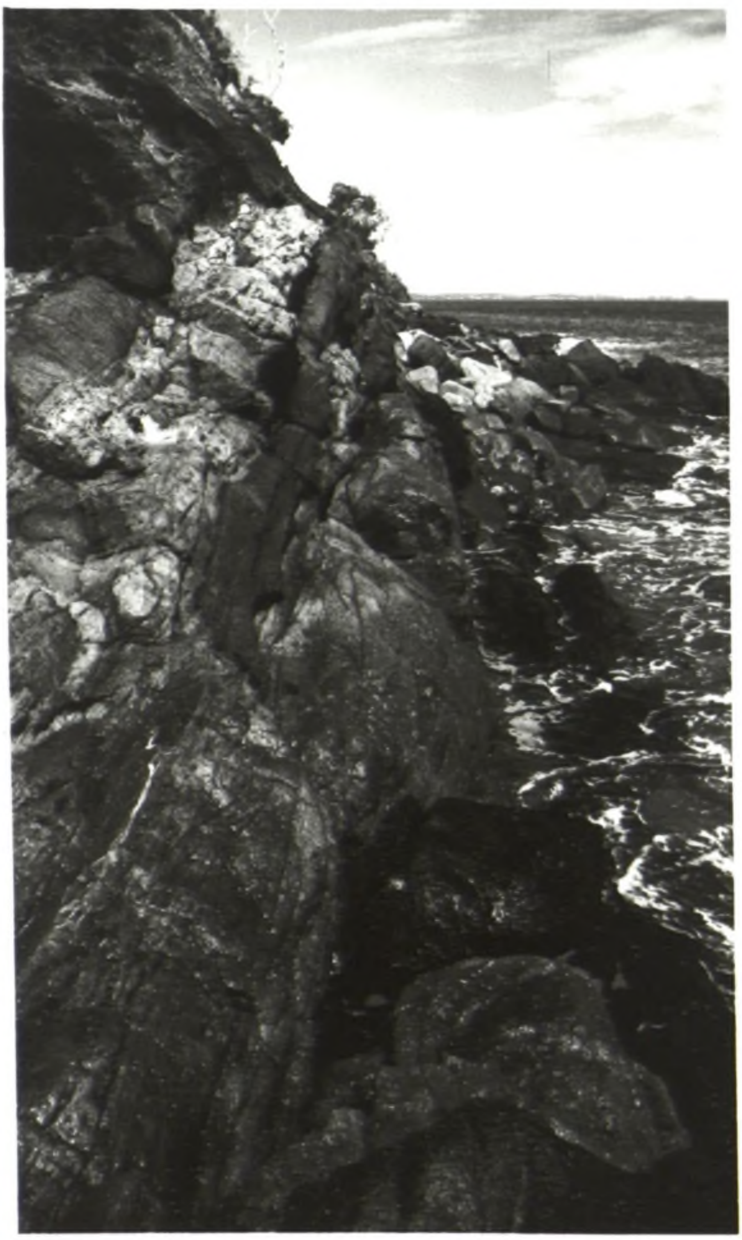


FIGURE 5.20

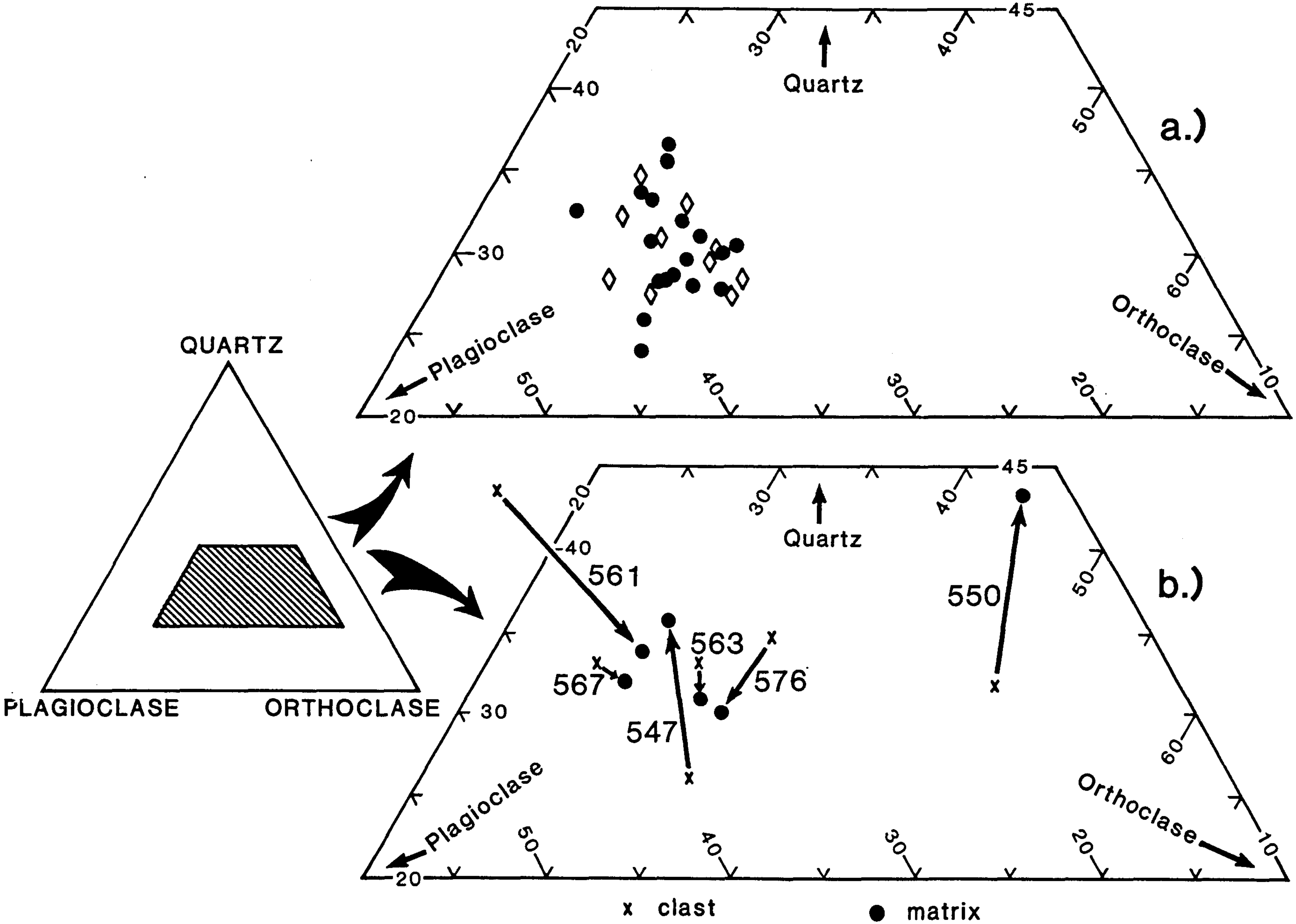
The darker rock in this outcrop of the Port Stephens ignimbrite on Nelson Head, from sea level to the prominent pale layer, is a lens of glassy, densely welded ignimbrite which is enclosed within the dominant lithoidal lithology. (G.R. Port Stephens 213802)

FIGURE 5.21

Ternary diagrams showing the ratios of Quartz, Plagioclase and K-feldspar in the Port Stephens (rhyolitic) ignimbrite.

(a) Total plot of all analyses ignoring clast/matrix distinctions.
Diamonds = samples from south of Fingal Bay
Filled circles = samples from north of Fingal Bay

(b) relationships of clasts with their enclosing matrix in selected samples


QUARTZ
PLAGIOCLASE
ORTHOCLASE
a.)
Quartz
Plagioclase
Orthoclase
b.)
Quartz
Plagioclase
Orthoclase
561
563
567
576
547
550
x clast
● matrix

	Specimen MU Number	36547		36550		36561		36562	36563		36567		36576	
		clast	*matrix*	*clast*	*matrix*	*clast*	*matrix*	*clast*	*clast*	*matrix*	*clast*	*matrix*	*clast*	*matrix*
	N	115	818	513	473	180	839	759	425	645	414	459	367	584
	% of Total	12.3	87.7	52.0	48.0	17.6	82.4	100.0	39.7	60.3	47.4	52.6	38.6	61.4
	Modal %													
CRYSTALS	Quartz	10.4	13.7	10.1	14.8	9.4	13.8	14.9	10.3	10.6	15.0	12.4	12.3	9.3
	Plag	15.7	13.6	6.4	4.4	8.9	15.7	13.2	11.1	12.3	18.6	15.7	12.5	11.1
	Orth	13.9	11.0	15.4	15.0	3.3	11.5	15.0	9.9	11.1	12.1	11.0	12.5	10.7
	Biotite	2.4	2.2	2.7	3.0	1.0	2.6	2.6	2.0	1.8	3.2	1.3	2.0	1.6
	Opaques	0.2	0.1	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.2
	Rock Frags	-	0.2	1.0	-	-	-	0.7	-	0.8	5.8	-	0.5	-
	Matrix	57.4	59.1	64.2	62.6	77.3	56.2	53.4	66.6	63.3	45.1	59.5	59.9	67.1

TABLE 5.4
Comparison of the modal compositions of the *Clasts* and the *Matrix* in samples of the Port Stephens (rhyolitic) ignimbrite.

There it is easily identified as a black obsidian-like rock, in contrasting with the surrounding grey lithoidal ignimbrite. The crystals range up to 5 mm in size and consist of quartz, plagioclase, K-feldspar, biotite, rare hornblende and opaques. The crystals form between 35 and 45% of the rock and quartz (with extensive resorption features), plagioclase (average An_{35}) and K-feldspar form at least 90% of the crystal content. A unique feature of this ignimbrite is that the quartz, plagioclase and K-feldspar crystals occur in approximately equal proportions (Fig. 5.21(a)).

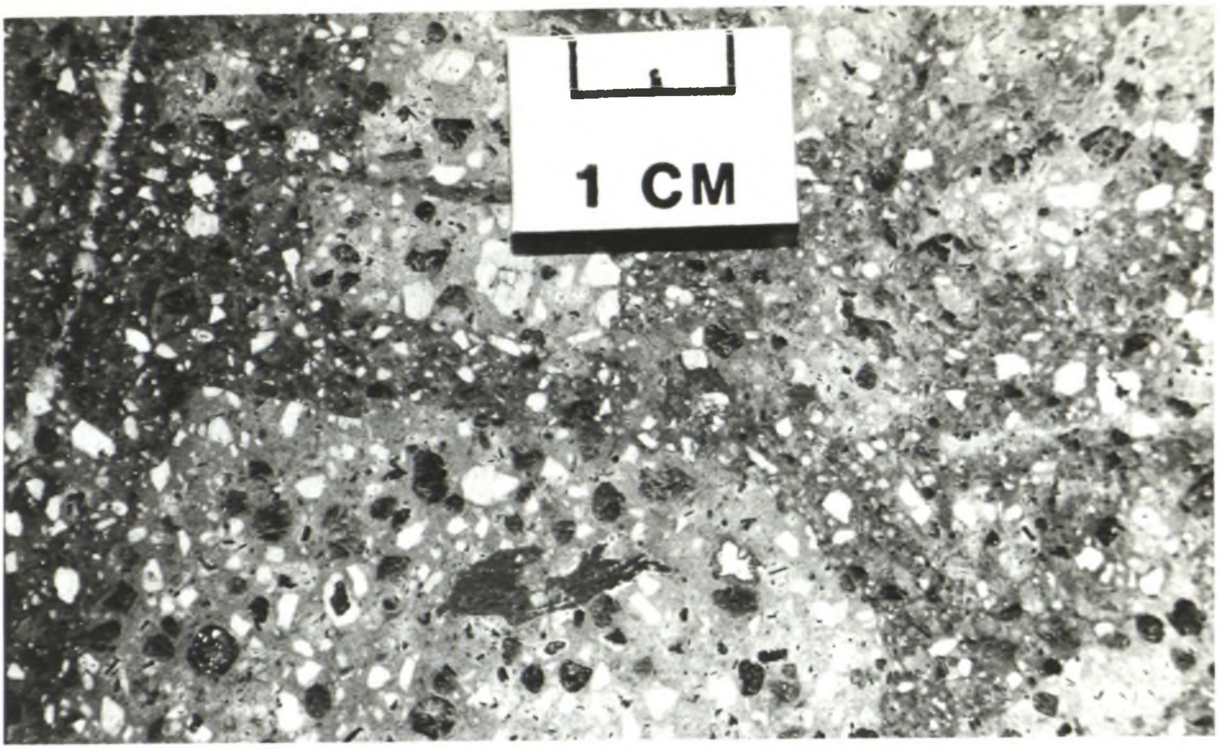
Big blocks of the ignimbrites, collected to determine bedding, revealed a hitherto undescribed feature of this ignimbrite. The Port Stephens ignimbrite invariably looks the same except for rare occurrences of small rhyolitic lithic fragments (Fig. 5.7) and fiamme (Fig. 5.19), although they tend to be microscopic, and the differences between the glassy and lithoidal varieties. But saw cuts perpendicular to the

FIGURE 5.22

Clasts within the co-ignimbrite lag-fall breccia in the basal parts of the lithoidal Port Stephens Ignimbrite. The clasts, considered to be 'clots' of the magma, have almost identical compositions to the matrix enclosing them (Table 5.4). Note that the crystals in the clasts are large and euhedral whereas the matrix contains smaller, broken crystals. (MU 36567, G.R. Morna Point 225796).

FIGURE 5.23

Photomicrograph showing a clast within vitric-depleted matrix in the co-ignimbrite lag-fall breccia in a glassy sample of the Port Stephens Ignimbrite. Note the sharp, straight edges of the flow deformed, deflated pumice-like clasts and the crystal fragment-rich matrix between the clasts (MU 36623, G.R. Port Stephens 213803, Plane Polarised Light, Image Length = 3.5mm)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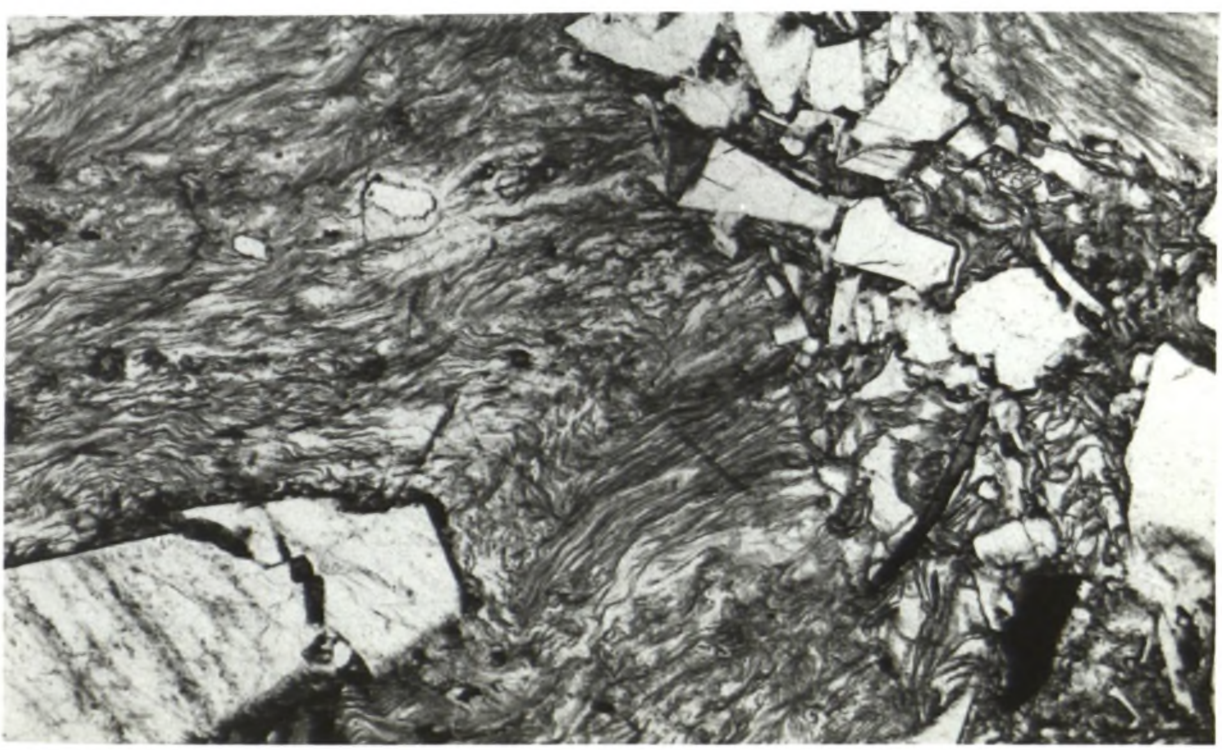

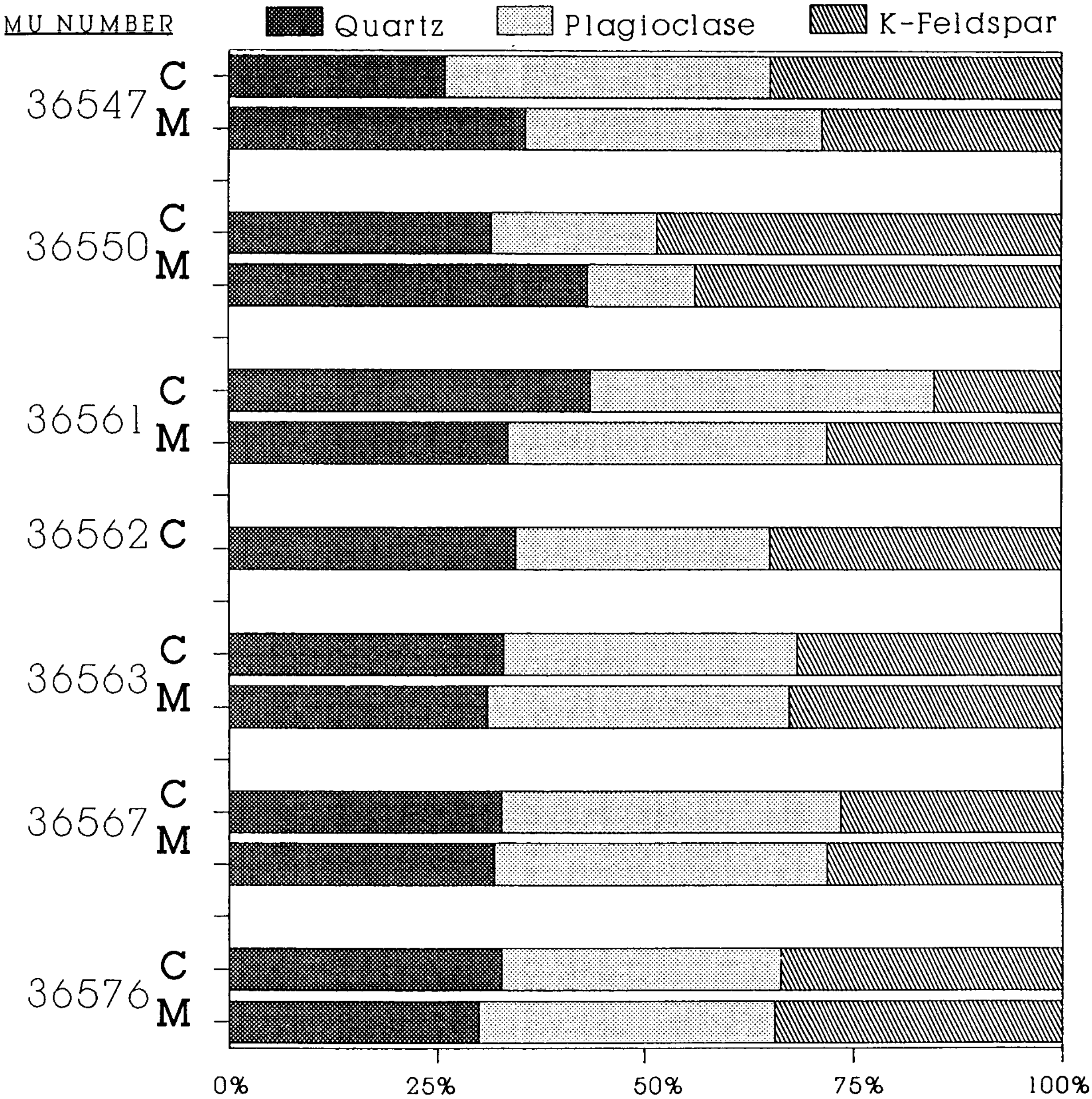

FIGURE 5.24

Bar diagram illustrating the differences (and similarities) of the Quartz:Plagioclase:K-feldspar proportions in the clasts (C) and the matrix (M) (Table 5.4) that encloses them in the Port Stephens ignimbrite.

foliation in seven samples from six separate localities revealed unusual juvenile clasts (Fig. 5.22) in the ignimbrite, making up from 15 to almost 100% of the rock (Table 5.4). Figure 5.21(b)) and Figure 5.24 illustrates the inconsistent slight variations in the proportions of quartz, plagioclase and K-feldspar in the clasts compared with the matrix. All of the samples, except for 36550, in which clasts are quartz rich, have matrices that have very similar quartz, plagioclase, and K-feldspar proportions. The proportions of these crystals within the clasts are slightly more variable than that of the matrix, which tend to contain consistent proportions of them (Fig. 21 (b)) but this may be a function of the clast data being derived from a smaller sample population. The clasts occur in both the glassy and lithoidal lithologies (Fig.5.22 and 5.23) and are characterised by containing whole and generally euhedral crystals set in a glass matrix that has well developed flow structure (Fig. 5.23), which resembles deflated pumice. The crystals in the matrix however are generally fragments of crystals with lesser amounts of whole crystals. In some interstices between the clasts, in the lowermost part of the ignimbrite unit, the matrix is depleted in glass shards (Fig. 5.23).

Sample 36575 (Table 5.4) was taken from the Port Stephens ignimbrite about 3 m above the known base of the unit (above the contact with the Nelson Bay ignimbrite) on Fingal Head, and the other samples containing clasts were taken from the base of the hills of Gan Gan (36561), Tomaree (36562,36563) and from beach level outcrops at Nelson Head (36547), north Wreck Beach (36550), and south Anna Bay (36576). This suggests that the clasts occur in a basal breccia unit in the Port Stephens ignimbrite throughout the southern part of the Port Stephens area, and it also indicates that the base of the Nelson Bay ignimbrite occurs at these locations, which is consistent with the conclusions reached on the stratigraphy and structure that was determined by other means.

As the composition of the clasts is nearly identical to the enclosing matrix of the ignimbrite itself (Table 5.4) probably it is most likely that the clasts are best called 'magma clots. However, the mechanism for the formation of these clasts is debatable, especially since they are unlike any previously described components of ignimbrite breccia units (see Walker 1985), which are normally composed of lithic fragments that are either too heavy to be carried by the flow or have fallen through the flow as a proximal airfall deposit. However, the presence of these clasts only in the basal parts of the flow units indicates that they acted like 'heavy' lithics.

One possible mechanism is that the clasts are simply pumices that never inflated. But the angular, straight edged shapes of most of the clasts and the deflated pumice-like, glassy nature of them (Fig.5.22 and 5.23) suggests that a 'vesicularising' magma had deflated, cooled, solidified and then later been fragmented. Possibly this may have happened as the ignimbrite 'magma' paused in its ascent to the surface at a shallow depth, perhaps due to the loss of the propelling magmatic gases as steam activity on the surface. Here the upper part of the magma cooled, either against the conduit wall or due to the change in confining pressure. Subsequent reinjection of further magma or a renewed build up in gas pressure eventually produced the eruption and the cooled solid parts were broken up and included in the subsequent eruption deposit. As the breccia is confined to the base of the ignimbrite units in the most proximal (Chapter 3) parts of the unit, and as it lacks matrix between the clasts in places, then it has much in common with a co-ignimbrite lag-fall breccia as described by Wright and Walker (1977).

5.10 CONCLUSIONS

The geology of the Port Stephens District is not as simple as the current geology maps of the area show. Before this research it was an 'island' in the Tamworth Belt of the New England Orogen with little apparent structure and it contrasted markedly from the rest of the Belt, which is intensely faulted. However this paper shows that the Port Stephens District is as intensely faulted as the rest of the Tamworth Belt and also that the fault trends (NNE-SSW and WNW-ESE) are consistent.

Previous literature also portrays the Port Stephens District to consist of a thick succession of Nerong Volcanics with a number of thick ignimbrites interbedded with volcaniclastic sediments. However, detailed chemical and petrological analysis of the ignimbrites indicates that only three ignimbrites, two rhyolitic, named the Port Stephens ignimbrite and the Fly Point ignimbrite, and one dacitic named the Nelson Bay ignimbrite, crop out in the District. The Port Stephens ignimbrite crops out over most of the District as it is repeatedly downthrown to the north by movements on the faults. A breccia component at the base of the Port Stephens ignimbrite supports previous statements made that the ignimbrites in the Port Stephens District are close to their eruptive source.

The Port Stephens District is a fault-block terrain, with each fault block forming a separate hill or rocky outcrop of Lower Carboniferous ignimbrites (and sediments) that protrude through mantling Pleistocene and Holocene sands.

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CHAPTER 6

SUMMARY AND CONCLUSIONS

A primary flow induced fabric is preserved in the Lower Carboniferous ignimbrites that crop out in the Hunter Valley, at the southern end of the New England Orogen. It has survived prehnite-pumpellyite low grade metamorphism, gentle folding, and significant faulting. Rheomorphism (secondary flow) due to late stage movement of the ignimbrite down a pre-existing slope is not evident.

Previous flow direction studies of ignimbrites mainly involved measuring crystal and pumice orientations from thin sections. A method was devised to measure the same lineation features on large sawn slabs of the ignimbrite and it proved to be highly successful, as it gives flow lineations that have statistical significance far greater than those obtained in the other studies.

Prior to this study, the oldest ignimbrite from which flow directions were determined was mid-Tertiary and the success of the method used here on Lower Carboniferous ignimbrites indicates that it can be used on almost any ignimbrite, given that it is in a reasonable state of preservation, and within a low metamorphic grade. However, prior to accepting that the method would succeed with any ignimbrite the following tests should be carried out to determine if a primary flow lineation is present. First, from different foliation-parallel saw cuts in the same sample, ascertain whether or not a flow lineation orientation can be duplicated (within $\pm$ 10^{o}). Second, from different samples from the same outcrop, establish with the same 10 degree error limits, if an orientation of a flow lineation can be reproduced in each sample. Third, determine which horizon in the ignimbrite unit gives the most consistent lineations. In this study it was found that the upper few metres of some of the ignimbrites, although indurated, were unwelded and it caused inconsistent lineation orientations and the upper parts of the flow (and outcrops) were therefore avoided for sampling. Previous studies have shown the basal part of some flows can be modified by secondary flow down valley sides.

Six ignimbrites are far more extensive than other units in the Lower Carboniferous succession and by overlapping in places they extend along almost the entire western edge of the southern part of the New England Orogen. Three of these ignimbrites are in the Isismurra Formation in the Muswellbrook-Rouchel District and they have been informally named the Curra Keith, McCullys Gap and Oakfields ignimbrites. Two ignimbrites in the Nerong Volcanics in the Port Stephens District are informally named the Nelson Bay and Port Stephens ignimbrites, and the most extensive ignimbrite is the Martins Creek ignimbrite in the Paterson District.

Strong radial flow patterns are found to be present in each of the ignimbrites and determined flow azimuths indicate that the ignimbrites flowed from vents located south of the present outcrops of the ignimbrites, towards the north and northeast. By projecting the lineations opposite to the determined flow directions (azimuths) until they intersected, probable source areas of the ignimbrites were defined by obvious clustering of the intersection points.

The Curra Keith and McCullys Gap ignimbrites have been determined to have originated from a source located about 4 km north of the township of Muswellbrook while the Oakfields ignimbrites from the same succession probably originated from a source about 12 km SSW of Muswellbrook. Both the Port Stephens and Nelson Bay ignimbrites have been determined to have originated from a source located about 5 km south of Port Stephens and the Martins Creek ignimbrite originated from a source located about 5 km south of the township of Branxton.

The determined ignimbrite sources lie on the western side of the Hunter Fault, which forms the western margin of the southern part of the New England Orogen, where the (younger) Permian Sydney Basin strata now outcrop on the surface. However, in the vicinity of the ignimbrite sources are circular gravity anomalies that indicate that the sources of the ignimbrites are buried below the younger strata.

The circular shape of the negative gravity anomalies in the region of the ignimbrite sources in the Port Stephens and Muswellbrook-Rouchel Districts are best explained by the presence of calderas that are infilled with low density pyroclastics.

An +18 mgal anomaly occurring in the region of the Martins Creek ignimbrite source, in the Maitland District, is also thought to indicate the presence of a caldera, but this caldera has been extensively eroded to reveal its 'roots'. The anomaly is the only one of the three that has been previously modeled, and this model suggested that a 2km thick granodiorite body lay at 2km depth. But, inliers of Lower Carboniferous strata within the Sydney Basin and the anomaly, such as at Mt. View, expose parts of the granodiorite intrusion as well as rhyolite lavas. The intrusion is thus assumed to be the erosion-exposed sub-caldera comagmatic source of the ignimbrites in Maitland District.

The three determined ignimbrite-producing calderas are spaced about 60 km apart and they are at the southern end of a volcanic chain, named the Kuttung Volcanic Chain. This chain lay along the western edge of the New England Orogen during the Lower Carboniferous and the eastern-most of the volcanoes lay between 5 and 10 km west of the present position of the Hunter

Fault. A co-ignimbrite lag deposit at the base of the Port Stephens ignimbrite confirms a proximal location of the ignimbrites in the Port Stephens District.

There are 4 regions in the world today that have a number of 'modern' (Cenozoic) large-scale ignimbrite of similar size to those in the Lower Carboniferous - they are the Basin and Range Province in western USA, western central Andes, the Taupo Volcanic Zone in New Zealand, and southern Japan. Each of these regions contain a number of calderas and they are each in a similar tectonic setting i.e. within ensialic back-arc basins. Thus, it is proposed the Kuttung Volcanic Chain during the Lower Carboniferous was similarly located in a back-arc basin.

The correspondence of the location of the ignimbrite sources with the gravity anomalies indicates that strike-slip and thrust displacement on the Hunter Fault has been less than about 2 km and that only vertical displacement has occurred.

The major element chemistry of the six Lower Carboniferous ignimbrites show many similarities with the four principal areas with 'modern' large-scale ignimbrites. The trace element trends are most comparable with the western USA. The most evolved rhyolites in the USA have almost identical trace element chemistry as the comparable Lower Carboniferous rhyolites and this suggests that the crustal thickness in the region of the Lower Carboniferous calderas was much the same as it now is in Western USA. Thus the Lower Carboniferous crust was in the order of 40 -45 km, which is much the same as it is today.

The Curra Keith, Oakfields and Port Stephens ignimbrites are high-K rhyolites and the Nelson Bay and Martins Creek ignimbrites are both high-K dacites. The M^{c}Cullys Gap ignimbrite is best called a sodic trachyte. The ignimbrites can be distinguished from each other by a plot of V versus Sr. Ni+Cr versus SiO_2 discriminates the rhyolites from the dacites. Zr versus SiO_2 differentiates the Muswellbrook caldera from the Maitland and Port Stephens calderas.

The Port Stephens District is criss-crossed by two sets of previously unmapped faults, one trending NNW and the other WNW, which are consistent with other fault directions in the rest of the southern part of the New England Orogen. Displacements on these faults cause the Port Stephens ignimbrite to crop out almost exclusively throughout the Port Stephens District.

An orthogonal N-S and E-W joint set, intruded by some 60 Tertiary basalt dykes in the Port Stephens District is related to the deformation producing the Girvan Anticline which closes in the district.

APPENDIX I

DEFINITION OF IGNIMBRITE

The North American term is 'ash-flow tuff' while the Greek (English) term is 'ignimbrite'. Although different names are used, the definition of ignimbrite proposed by Sparks *et al.* (1973) is now accepted by most volcanologists worldwide. The definition is

"a pyroclastic rock composed predominantly of vesiculated juvenile material (pumice and shards) showing features indicating a pyroclastic flow origin ..... whether it is welded or not".

It is this definition of ignimbrite that is used in this study.

Ignimbrites are not homogenous rocks, as within a flow unit there can be zonation due both to different degrees of welding, and to vertical variations in grain size (Fig I.1). The Lower Carboniferous ignimbrites in the study area are not preserved in their entirety, as post emplacement erosion has reduced their extent and thickness. Smith (1960) pointed out that the most intense welding occurs in the thickest parts of a flow, especially nearest to source and that welding decreases towards the top, bottom and distal parts of the flow. This pattern similary occurs in the Lower Carboniferous ignimbrites, except that it is now masked by devitrification.

Sparks *et al.* (1973), Fisher (1979) and Sheridan (1979) explained the variations in grain size in ignimbrites in relation to deposition from different parts of a pyroclastic flow. from these authors an idealised model of an ignimbrite eruption has been devised (Fig. I.1). In various outcrops of the Lower Carboniferous ignimbrites in the Hunter Valley some components of the model could be found. An ignimbrite eruption normally begins with the deposition of a plinian pumice airfall unit which forms a basal layer to many ignimbrites (Fig I.2), and it is then followed by the pyroclastic flow. The pyro-

FIGURE I.1

The idealised succession of an ignimbrite eruption (from Sheridan 1979).

FIGURE I.2

A Plinian airfall unit (below hammer handle) mantling a previous uneven surface. This layer consists of bedded coarse pumice lapilli (now lithified) and and an ignimbrite unit overlying it which has the same mineralogy. This indicates that they probably formed in the same event. (site of MU 36487, G.R. Singleton 086476)

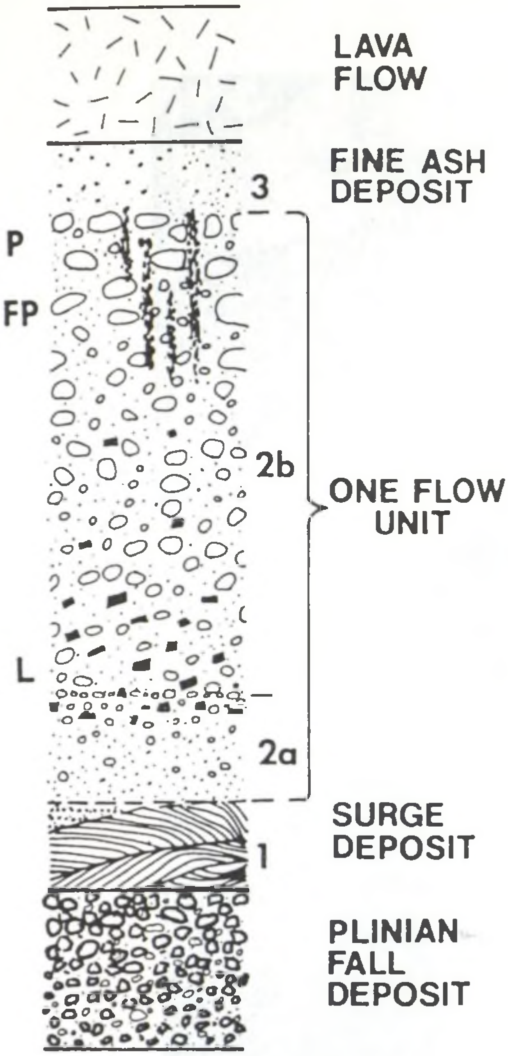

Figure 3. Schematic diagram showing the textural elements of a complete eruption episode. An inversely graded Plinian fall bed is overlain by a surge of deposit of (1) sandwave, massive, or planar facies (Wohletz and Sheridan, this volume). The basal layer of the pyroclastic flow (2a) may show inverse grading, whereas the main part of the flow (2b) has double-grading. Lithic inclusions (L) are concentrated near the base, and pumice fragments (P) are concentrated toward the top. Fumarolic pipes (FP) may be present throughout the flow. Deposits of fine ash (3) from the cloud would occur above the flow unit. A lava flow might cap the sequence. Modified after Sparks and others (1973).

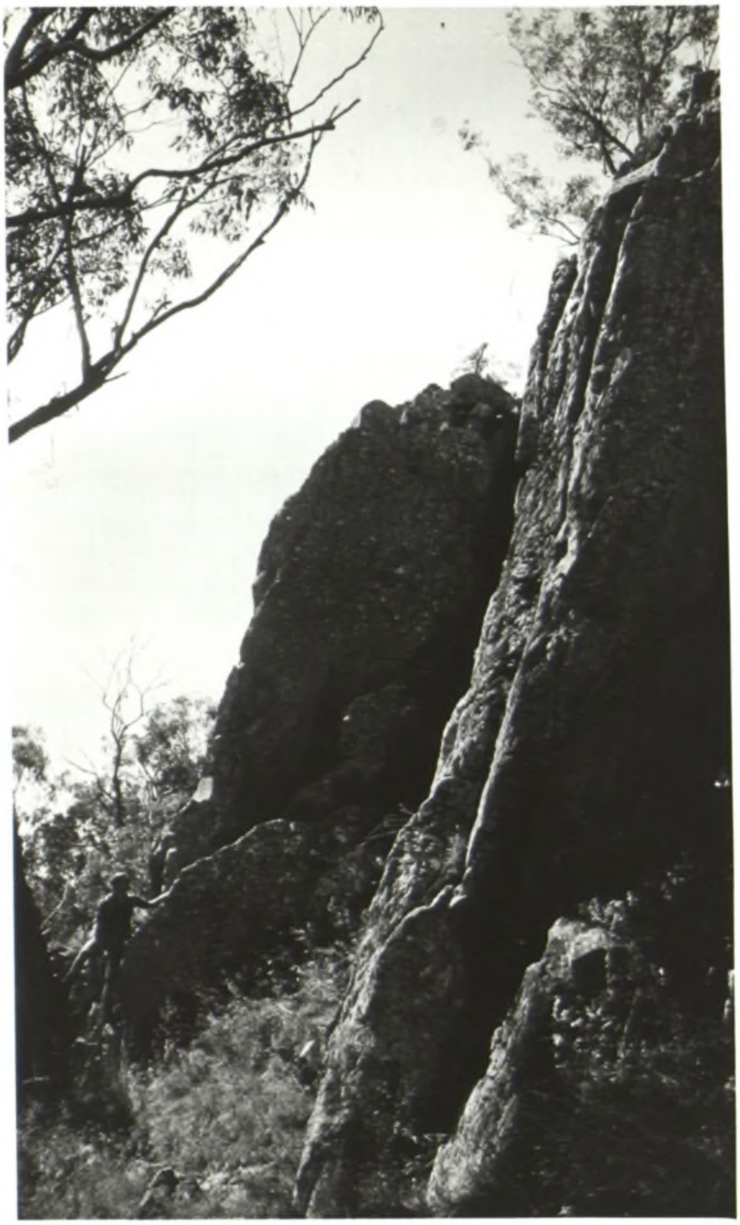

FIGURE I.3

One of the better outcrops of a Lower Carboniferous ignimbrite away from the coast. In this case it is the Martins Creek ignimbrite showing a crude columnar jointing in Layer 2. (site of MU 36524, G.R. Dawsons Hill 251284).

clastic flow lays down deposits from different parts of the moving cloud, forming a stratified deposit. Advancing in front of the flow proper can be a surge cloud which deposits a ground surge layer (Layer 1) that is characterised by low angle antidune cross beds. No trace of a ground surge layer was found anywhere in this study. The main pyroclastic flow deposit (Layer 2) forms the greatest thickness of the ignimbrite (Fig

FIGURE I.4

Basal contact of the Oakfields ignimbrite lying on fluviatile sediments. The prominent horizon from the base to about 0.5 m up is Layer 2a. This layer is depleted in coarse clasts consisting almost entirely of crystals and shards and it grades upwards into Layer 2b which contains abundant coarse pumice lenticles (site of MU 36466, G.R. Dawsons Hill 213244)

I.3) and a thin layer (Layer 2a) at the base of this unit is reversely graded or depleted in the coarse components that otherwise occur in the rest of the flow (Fig. I.4). The final component in the ignimbrite model is a vitric-enriched thin ash (Layer 3), called the ash-cloud layer or the co-ignimbrite ash, which falls out from the expanding ash-cloud above the pyroclastic flow (Fig. I.5).

FIGURE I.5

The distinct near horizontal pale layer seeming to end at the top of the basalt dyke (Tertiary?) contains a thin co-ignimbrite ash (Layer 3), which is here mantling the top surface of the Curra Keith ignimbrite. (site of 36410, G.R. Singleton 086475).

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APPENDIX II

SAMPLE NUMBERS AND LOCATIONS

This is a catalogue of the rock samples that were collected by the author from the Hunter Valley for this study. The *MU* numbers are their reference in the rock collection at Macquarie University and field numbers are the sample numbers used in the authors field notebook. Sample locations are described and detailed by a grid reference from the N.S.W. 1:25,000 topographic map series.

The (*) asterisk alongside the *MU* numbers denote those samples that were not orientated in the field .

Key to Maps Used for Grid References

ABBREV.	1:25,000 TOPOGRAPHIC MAP
A	Aberdeen,9033-I-S
B	Bulahdelah,9333-III-S
C	Camberwell,9133-III-S
CA	Carrowbrook,9133-II-N
CL	Clarencetown,9232-I-N
DH	Dawsons Hill,9133-III-N
E	Elderslie,9132-I-N
G	Greta,9132-I-S
I	Ingar,9133-II-S
M	Maitland,9232-IV-S
MP	Morna Point,9332-III-N
P	Paterson,9232-IV-N
PS	Port Stephens,9332-IV-S
P	Parkville,9034-II-S
RB	Rouchel Brook,9133-IV-S
S	Scone,9033-I-N
SR	Stroud Road,9233-II-N
W	Woolooma 9133-IV-N

MU NUMBER	FIELD NUMBER	GRID REFERENCE	LOCALITY DESCRIPTION

CURRA KEITH IGNIMBRITE (38 Samples)

36401	R1	S.086476	Brushy Hill Quarry,Glenbawn
36402	R2	S.086476	" "
36403*	R2A	S.086476	" "
36404	R3	S.086476	" "
36405	R4	S.086476	" "
36406	R5A	S.086476	" "
36407	R5B	S.086476	" "
36408	R5C	S.086476	" "
36409*	R6	S.086476	" "
36410	R8	S.086475	" " ,south pit
36411	R10	S.088462	Glenbawn Rubbish Tip
36412	R11	RB.134409	Rouchel Brook Rd,Dangarfield
36413	R22A	W.203471	Back Creek,Upper Rouchel
36414	R22B	W.200467	" "
36415	R37	S.093549	Oakey Creek,Gundy
36416	R38	S.092551	" "
36417	R39	S.097552	" "
36418	R50	A.076408	Logans Mt.,Dangarfield
36419	R51	A.073408	" "
36420	R55	A.112392	Rouchel Springs,Dangarfield
36421	R56	A.112392	" "
36422	R57	A.113392	" "
36423	R75	W.141471	Curra Keith Creek,Glenbawn Dam
36424	R76	W.141471	" " "
36425*	R77	W.142471	" " "
36426	R78	W.138471	" " "
36427	R79	W.138471	" " "
36428	R80	RB.183419	The Cottage,Rouchel
36429	R93	RB.168404	" "
36431	R95	RB.123320	Summer Hill,McCullys Gap
36432*	R96	RB.123319	" "
(36433	R116)		
36434	R117	S.041575	Glen Creek,Gundy
36435	R118	S.041575	" "
36436	R137	W.177537	'Nabinabah',Gundy
36437	R141	W.244481	Woolooma
36438	R142	W.238479	"
36439	M11	DH.162282	Rock Lily Gully
36622	R122A	RB.171326	Limestone Creek,McCullys Gap

OAKFIELDS IGNIMBRITE (32 Samples)

36433	R116	S.041575	Glen Creek,Gundy
36440*	R13	RB.129404	Hardyville,Rouchel Brook
36441	R14	RB.135403	" "

MU NUMBER	FIELD NUMBER	GRID REFERENCE	LOCALITY DESCRIPTION

OAKFIELDS IGNIMBRITE (Cont.)

36442	R15	A.075422	Cnr Brushy Hill Rd & Rouchel Rd
36443*	R47	A.083410	Logans Mt.,Dangarfield
36444	R48	A.079409	" "
36445	R52	A.076410	" "
36446	R59	RB.115391	Rouchel Springs,Dangarfield
36447*	R60	RB.116391	" "
36448	R72	W.145470	Curra Keith Creek,Glenbawn Dam
36449*	R73	W.145470	Curra Keith Creek,Glenbawn Dam
36450	R104	RB.122317	Summer Hill,McCullys Gap
36451	R105	RB.122317	" "
36452	R106	RB.122316	" "
36453	R107	RB.122316	" "
36454	R122B	RB.173329	Limestone Creek,McCullys Gap
36455	R123	RB.131367	Sandy Creek,McCullys Gap
36456	R124	RB.131367	" "
36457	R130	A.028432	Segenhoe Mt.,Segenhoe
36458	R135	W.129486	Glenbawn Mt.,East Glenbawn Dam
36459	R136	W.130487	" " "
36460	R138	RB.170399	Spring Gully,Rouchel
36461	R139	RB.170399	" "
36462	M1	DH.129286	'Moonya',Muscle Creek
36463*	M2	DH.129285	" "
36464	M10	DH.161281	Rock Lily Gully,Muscle Creek
36465	M12	DH.158292	Muscle Creek
36466	M16	DH.213244	'Glendoon',Foy Brook
36467	M17	DH.213244	" "
36468	M18	DH.213244	" "
36469	M19	DH.186246	Sawyers Creek,Foy Brook
36470	M20	DH.188244	" "
36471	M24	C.262141	Falbrook-Greenland Road
(36472	R69)		
(36473	PS55)		

McCULLYS GAP IGNIMBRITE (12 Samples)

36474	R49	A.078409	Logans Mt.,Dangarfield
36475	R99	RB.122318	Summer Hill,McCullys Gap
36476	R100	RB.122318	" "
36477	R101	RB.122317	" "
36478*	R131	A.028433	Segenhoe Mt.,Segenhoe
36479*	R132	A.034435	" "
36480	R133	A.034435	" "
36481	R134	A.035436	" "
36482	M3	DH.123286	'Moonya',Muscle Creek
36483	M4	DH.126288	" "

MU NUMBER	FIELD NUMBER	GRID REFERENCE	LOCALITY DESCRIPTION

McCULLYS GAP IGNIMBRITE (Cont.)

36484	M5	DH.126288	" "
36485	M13	DH.130261	Beggary Creek,Muscle Creek

UNNAMED NATIVE DOG MEMBER IGNIMBRITES (21 Samples)

36430*	R94	RB.123320	Summer Hill,McCullys Gap
36487	R7	S.086476	Brushy Hill Quarry,Glenbawn
36488	R12	RB.124404	'Hardyville',Rouchel Brook
36489	R58	RB.115391	Rouchel Springs,Dangarfield
36490*	R70	RB.116390	" "
36491	R74	W.141471	Curra Keith Creek,Glenbawn Dam
36492	R91	RB.169403	Spring Gully,Rouchel
36493	R97	RB.123319	Summer Hill,McCullys Gap
36494	R98	RB.122318	" "
36495	R102	RB.122317	" "
36496*	R103	RB.122317	" "
36497	R140	RB.170399	Spring Gully,Rouchel
36498*	M6	DH.125286	'Moonya',Muscle Creek
36499	M7	DH.161281	Rock Lily Gully,Muscle Creek
36500*	M8	DH.161281	" "
36501*	M9	DH.161281	" "
36502	M14	DH.213248	'Glendoon',Foy Brook
36503	M21	DH.190172	Upper Hebden
36504	M22	DH.190172	"
36505	M23	DH.208166	Yorks Creek,Hebden
36506	M25	C.271143	Falbrook-Greenland Road

HAPPY VALLEY IGNIMBRITE (16 Samples)

36507	R16	RB.196408	'Grenell Park',Rouchel
36508	R25	RB.243398	Davis Creek
36509	R33	RB.144396	'Hardyville',Native Dog Gully
36510	R34	RB.144396	" "
36511	R35	RB.144396	" "
36512	R36	RB.144396	" "
36513	R41	DH.217292	Bowmans Creek
36514	R42	DH.216293	"
36515	R43	DH.216293	"
36516*	R44	DH.216293	"
36517*	R63	DH.251286	'Grenell',Bowmans Creek
36518	R88	RB.158361	'Happy Valley',Dunbar Creek
36519	R89	RB.160360	" "
36520	R129	RB.218351	Stringybark Creek
36533	M26	DH.306207	'Rosevale',Dawsons Hill
36472	R69	DH.255281	Bowmans Creek

MU NUMBER	FIELD NUMBER	GRID REFERENCE	LOCALITY DESCRIPTION
SEDIMENTARY ROCKS			
Scone Area (9 Samples)			
36535*	R53	A.109393	Rouchel Springs,Dangarfield
36536*	R54	A.112392	" "
36537	R61	DH.253283	'Grenell',Bowmans Creek
36538*	R71	W.133463	Curra Keith Creek,Glenbawn Dam
36539	R86	RB.158357	'Happy Valley',Dunbar Creek
36540	R92	RB.169403	Spring Gully,Rouchel
36541*	R114	PV.043578	Glen Creek
36542*	R115	PV.042579	"
36543*	M15	DH.215246	NE of 'Glendoon',Foy Brook
PORT STEPHENS IGNIMBRITE			
From the Port Stephens Area (23 samples)			
36544*	PS4	PS.185779	Gan Gan Hill,Nelson Bay
36545*	PS5	PS.185779	" " "
36546	PS6	PS.213804	Nelson Head,Port Stephens
36547	PS7	PS.214803	" "
36548	PS12	PS.235789	Wreck Beach,north
36549*	PS13	PS.234788	" "
36550	PS14	PS.234787	" "
36551	PS15	PS.234785	Wreck Beach,south
36552	PS21	PS.121814	Soldiers Point
36553	PS24	PS.068874	Karuah Mt.
36554	PS25	PS.069868	"
36555	PS26	PS.066863	"
36556	PS27	B.178089	Booral-Buladelah Road
36557	PS28	B.176085	" "
36558	PS38	PS.234777	Box Beach,south
36559	PS39	PS.234778	" "
36560	PS43	PS.136789	Scott Circuit,Wandawanda Head
36561	PS44	PS.186780	Gan Gan Hill,Nelson Bay
36562	PS45	PS.236802	Tomaree Head
36563	PS46	PS.337802	"
36564	PS48	MP.162757	Pig Island,Nelson Bay Road
36565	PS51	PS.133838	Fame Mt,Bundabah
36473	PS55	B.076055	Conger Hill,Booral
36623	PSE	PS.213803	North Nelson Head
PORT STEPHENS IGNIMBRITE			
From the Morna Point Area (12 Samples)			
36566*	PS9	MP.224798	Fingal Bay,south
36567	PS10	MP.225796	Fingal Head
36568	PS16	MP.175717	NE side of Boat Harbour
36569	PS17	MP.170712	Telegraph Shoal
36570	PS18	MP.149714	Fishermans Bay

MU NUMBER	FIELD NUMBER	GRID REFERENCE	LOCALITY DESCRIPTION

PORT STEPHENS IGNIMBRITE
From the Morna Point Area (Cont.)

36571	PS31	PS.084769	Gibber Pt,Lemon Tree Passage
36572	PS32	PS.084769	" " "
36573	PS33	MP.210743	Snapper Point
36574	PS34	MP.213747	Boulder Bay
36575	PS37	MP.225753	Fingal Head
36576	PS50	MP.174726	Anna Bay.south
36486	PS54	PS.179768	Gan Gan Military Camp

NELSON BAY IGNIMBRITE
From around Nelsons Bay (8 Samples)

36577	PS1	PS.194795	West Point,Nelson Bay
36578	PS2	PS.191794	" "
36579	PS3	PS.190794	" "
36580	PS40	PS.157792	Corlette Point
36581	PS41	PS.157792	"
36582	PS42	PS.157793	"
36583	PS47	PS.234799	Tomaree Head
36584	PS52	PS.249821	Yacaaba Head
36594*	PS29	B.174083	Booral-Buladelah Road

NELSON BAY IGNIMBRITE
From Fingal Bay (4 Samples)

36585*	PS8	MP.221752	Fingal Bay,south
36586	PS11	MP.225753	" "
36587	PS35	MP.226760	" "
36588	PS36	MP.225761	" "

OTHER VOLCANIC ROCKS
from the Port Stephens Area (5 Samples)

36589	PS22	M.828783	Raymond Terrace BMG Quarry
36590	PS23	M.828784	" "
36591	PS30	SR.950177	Stroud Road-Dungog Road
36592	PS49	PS.203798	Fly Point,Nelson Bay
36593*	PS53	PS.250821	Yacaaba Head,Port Stephens
(36594*	PS29)		

SEDIMENTARY ROCKS
Port Stephens Area

36624	BUN4	PS.119855	Bundabah

MU NUMBER	FIELD NUMBER	GRID REFERENCE	LOCALITY DESCRIPTION

MARTINS CREEK IGNIMBRITE
From the Muswellbrook-Rouchel Area (13 Samples)

36521	R62	DH.251286	'Grenell',Bowmans Creek
36522	R64	DH.251286	" " "
36523	R65	DH.251286	" " "
36524	R66	DH.254284	" " "
36525*	R67	DH.254284	" " "
36526	R68	DH.255283	" " "
36527*	R119	RB.240378	'Makathalro',Stoney Creek
36528	R120	RB.240378	" "
36529	R121	RB.240378	" "
36530	R125	RB.236351	Stringybark Creek
36531	R126	Rb.236351	" "
36532	R127	RB.234345	Hilliers Creek
36534	M27	C.290128	Greenland

MARTINS CREEK IGNIMBRITE
From the Maitland - Paterson Area (17 Samples)

36595	MC1	P.708972	Martins Creek BMG Quarry
36596	MC3	P.708971	" "
36597	MC4	P.708969	" "
36598	MC5	P.708969	" "
36599*	MC6	P.707971	" "
36600	MC8	E.541918	Lambs Valley Road
36601	MC10	G.574881	Maitland Vale-Stanhope Road
36602	MC13	E.492932	'Glenalister',Elderslie
36603	MC14	P.767033	Paterson-Dungog Road,Wallarobba
36604	MC15	P.767033	" " "
36605	MC18	P.808921	Old Quarry,Glenoak-Clarencetown Rd
36606	MC19	P.808921	" " "
36607	MC24	CL.864929	E bank of Williams River,Clarencetown
36608	MC25	E.491015	Eui Creek,Glendon Brook
36609	MC26	I.532054	Webbers Creek
36610	MC27	I.430043	Reedy Creek
36611	MC28	CA.399187	Carrow Brook

OTHER PATERSON DISTRICT IGNIMBRITES (10 Samples)

36612	MC7	E.554966	Lambs Valley Road
36613	MC9	E.532907	Lambs Valley Road Corner
36614	MC11	M.616839	Maitland Vale-Stanhope Road
36615*	MC12	E.493948	South Cranky Corner Basin
36616	MC16	M.800867	Carmichaels Creek Bridge,Seaham Road
36617	MC17	M.800867	" " "
36618	MC20	CL.881944	Clarencetown-Glen Martin Road

MU NUMBER	FIELD NUMBER	GRID REFERENCE	LOCALITY DESCRIPTION
OTHER PATERSON DISTRICT IGNIMBRITES (Cont.)			
36619	MC21	P.729957	Black Rock Road
36620	MC22	CL.864899	Mt.Gilmore
36621*	MC23	CL.866903	"
(36622	R122A)		
(36223	PSE)		
(36224	BUN4)		

TOTAL SAMPLES = 224 (185 orientated)

APPENDIX III

SAMPLING AND PREPARATION METHODS, FLOW DIRECTION MEASUREMENTS AND STATISTICAL PARAMETERS

III.1 PREVIOUS WORK

Statistically determined parameters of flow directions have been used in the study of sedimentary rocks for some time after the initial impetus was created by Krumbeins' paper in 1939 on the orientations of pebbles in sediments, but Elston and Smith (1970) were the first to demonstrate that the same parameters could be derived from ignimbrites by showing that there exists a statistically strong preferred orientation of crystals, pumice fragments and glass shards in the ignimbrites in the Valles Caldera, New Mexico. The parameters they obtained had much the same confidence levels as those that have been derived from sediments, and consequently by taking a number of sample localities it was possible to project the flow direction back to a probable source vent or area. After this initial success the same approach was used to determine the flow directions and source of the ignimbrites in the Mogollon Plateau, New Mexico (Rhodes and Smith 1972, Aldrich 1976) and Suzuki and Ui (1982) applied it to the Ata pyroclastic flow in Japan.

III.2 METHODS OF INVESTIGATION

III.2.1 Field Work

Orientated rock samples were collected from the field and they were processed according to the procedure set out in the flow diagram of Fig. III.1

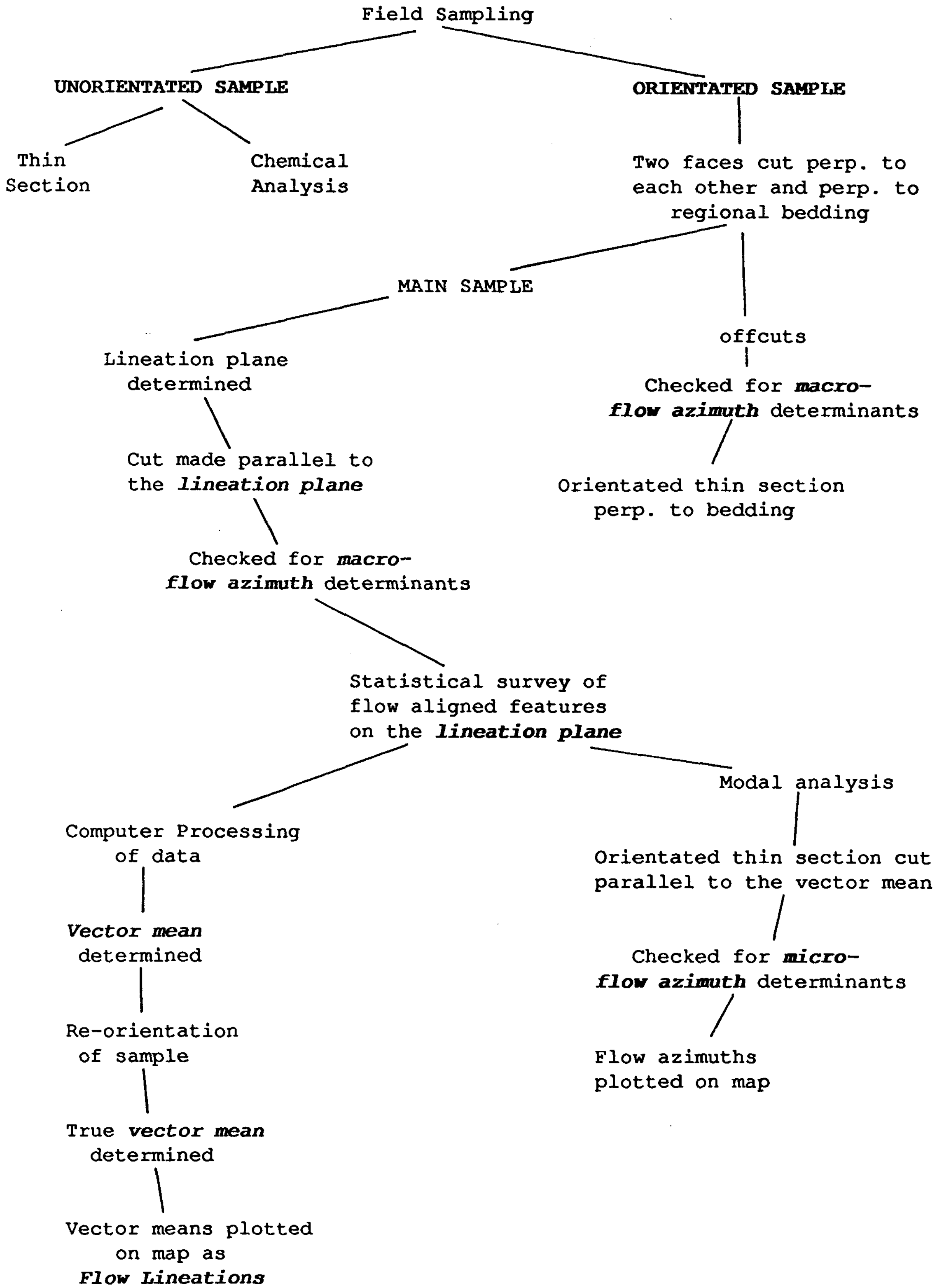


FIGURE III.1

Flow diagram of the procedure followed for the analysis of samples.

FIGURE III.2

The way samples for flow lineation determinations were orientated in the field. Dip, dip azimuth and strike of a flat face was taken.

Samples of the greatest practical size were collected and the sample had to have at least one accessible flat face on it which could be used to orientate the specimen. The orientation of the sample was recorded by drawing on the face the direction of dip and strike of it and measuring its dip (Fig. III.1). A flat surface on the top of a specimen proved to be the easiest to later re-orientate in the laboratory although vertical or near vertical faces, especially those created by columnar joints also proved to be easier to later re-orientate.

At most localities it was impossible to determine "bedding" in the outcrops of the ignimbrites since top and bottom contacts were rarely exposed and weathering of the surface of the outcrops normally masked the fabric of the ignimbrites. This meant that bedding was normally sought from a sedimentary unit as near as possible to the sample site but often the interbedded fluvial sediments were quite massive and bedding was determined from the ignimbrite sample in the laboratory after it had been sawn.

III.2.2 Cutting of the Specimens

Two mutually perpendicular saw cuts were first made close to the edge of a specimen with both being as near as possible perpendicular to the "bedding" of the rock. On these cut surfaces the preferentially aligned, elongated crystals and pumice lenticles were normally obvious and from there it was possible to define the bedding plane that contains the flow lineation. The sample was then sawn along this bedding plane to produce a slab.

II.2.3 Observations

A tally of the orientations of elongated crystals and clasts was made directly from the slab. This was achieved by using a modified binocular microscope which accommodated the sometimes very large specimens (Fig. III.3). This microscope has a hand-cranked mechanical stage which allows a rapid traverse across a specimen in two directions (north-south and east-west), and an ocular which contains a set of parallel lines which rotates about a 0° to 180° gradual. This allowed the orientation of aligned features on the lineation plane to be quickly measured and tallied over a maximum area of 256 sq. cm (16 x 16 cm).

The previous studies of flow lineations using the Elston and Smith (1970) method consisted principally of measuring the alignment of crystals in orientated thin sections. In their study crystals were measured that were at least twice as long as they were wide. However the larger areas of the ignimbrite able to be scanned by using slabs rather than thin sections enables one to be a little more selective of the crystals being measured and only the most elongate, euhedral prismatic crystals, those that would most likely be aligned by the pyroclastic flow, were measured. Pencil-like crystals were

FIGURE III.3

The modified binocular microscope for measuring crystal lineations on slabs of rock up to 16 cm x 16 cm.

preferentially measured and few crystals were measured that did not exceed approximately 3 to 1 in their dimensions.

As well as measuring the orientation of crystals, measurements were also made of elongated clasts (both pumice and lithics), segregated strings of crystals (Fig. 2.7), trends in the eutaxitic groundmasses such as an apparent flow-induced

FIGURE III.3

The modified binocular microscope for measuring crystal lineations on slabs of rock up to 16 cm x 16 cm.

preferentially measured and few crystals were measured that did not exceed approximately 3 to 1 in their dimensions.

As well as measuring the orientation of crystals, measurements were also made of elongated clasts (both pumice and lithics), segregated strings of crystals (Fig. 2.7), trends in the eutaxitic groundmasses such as an apparent flow-induced banding, and any other feature obviously induced by flow were measured. A measurement of each of these features were considered equivalent to a single crystal measurement.

The use of the large slabs and binocular microscope also allows both macro- and micro-scopic observations of the flow lineation which meant that perturbations in the crystal lineations such as in turbulent areas around large clasts could be excluded from the measurements.

III.3 STATISTICAL PARAMETERS

Three main parameters are used to analyse the flow direction of ignimbrites. The direction of the preferred alignment of particles in the ignimbrite is determined by a measure of central tendency which is the **Vector Mean** and the significance (or statistical strength) of the vector mean is assessed by both the **Vector Magnitude** and the **Tukey Chi Square** value.

III.3.1 Vector Mean (V)

There are two major statistical methods of assessing the measures of central tendency in dispersed sets of data; the arithmetic mean and the vector mean. The vector mean is appropriately used for vectors which are scattered about the compass through 360 degrees as it maintains consistency as the data becomes more dispersed, whereas the arithmetic mean fails for widely dispersed data (Potter and Pettijohn, 1963).
(see below for the calculation of the vector mean.)

III.3.2 Vector Magnitude (L)

The vector magnitude is a measure of strength of the Vector Mean. It is readily computed from either individual observations or from grouped data. The calculations for grouped data are as follows;

$$A = x \cos \theta$$

$$B = x \sin \theta$$

$$V = \arctan \frac{B}{A}$$

$$R = \frac{(A^2 + B^2)}{2}$$

$$L = (\frac{R}{n}).100$$

where

θ = mid-point azimuth of the class interval,

V = azimuth of the resultant vector (<u>**VECTOR MEAN**</u>),

x = number of observations in each class interval,

n = total number of observations,

R = length of the resultant vector,

L = magnitude of the resultant vector expressed as a percentage.

For ungrouped data the sines and cosines of each angle are used directly.

The vector magnitude (L) is the measure of the concentration (or dispersion) of vectors about the mean, in the data where the higher the percent magnitude the greater the concentration of vectors i.e. 100% indicates a perfect orientation while 0% indicates a random distribution.

III.3.3 **Tukey Chi Square (X^2)**

The significance of the vector mean in each data set was further assessed by both the Chi Square and the Tukey Chi Square tests. Both tests are based on departures of observed data from a distribution which is completely random where the distribution is expected to have an equal number of observations in each interval. The **Chi Square** test is described in any statistic text as:

$$X^2 = \frac{(fo - fe)^2}{fe}$$

fo = the observed frequency

fe = the expected frequency

(= total observations/no of classes)

The Tukey Chi Square test is the Chi Square test which was modified by Tukey (1954) so that it could be applied to circular distributions of data in which the limits of the angular deviation, 0 and 360 degrees, are in the same direction. It combines the chi square test for grouped data with the calculation of the vector mean.

The formula for the calculation of the **Tukey Chi Square** is as follows;

$$X^2 = C^2 + S^2$$

where

$$C = \frac{x \text{ Cos } 2\theta}{\text{Cos}^2\ \theta} \quad \text{and} \quad S = \frac{x \text{ Sin } 2\theta}{\text{Sin}^2\ \theta}$$

The mathematical derivation and a discussion of the application of the Tukey Chi square test is given by Middleton (1965), and Pincus (1956), Harrison (1957) and Rusnak (1957) describe some of the earliest applications of the Tukey Chi Square test to geological data.

When the Chi Square value shows that an observed distribution does not depart significantly from a uniform distribution then the vector mean is not considered significant and is rejected. It is considered that a 90 percent probability level with 2 degrees of freedom (that equals 4.61) is significant for the data obtained in this study which is in accordance with that proposed by Elston and Smith (1970).

III.4 DATA PROCESSING

III.4.1 Computer Programs

The gathered data was processed using a VAX II computer with two similar Fortran IV programs (Appendix VIII). Both of the programs were adjusted to read the same data file (Appendix VIII).

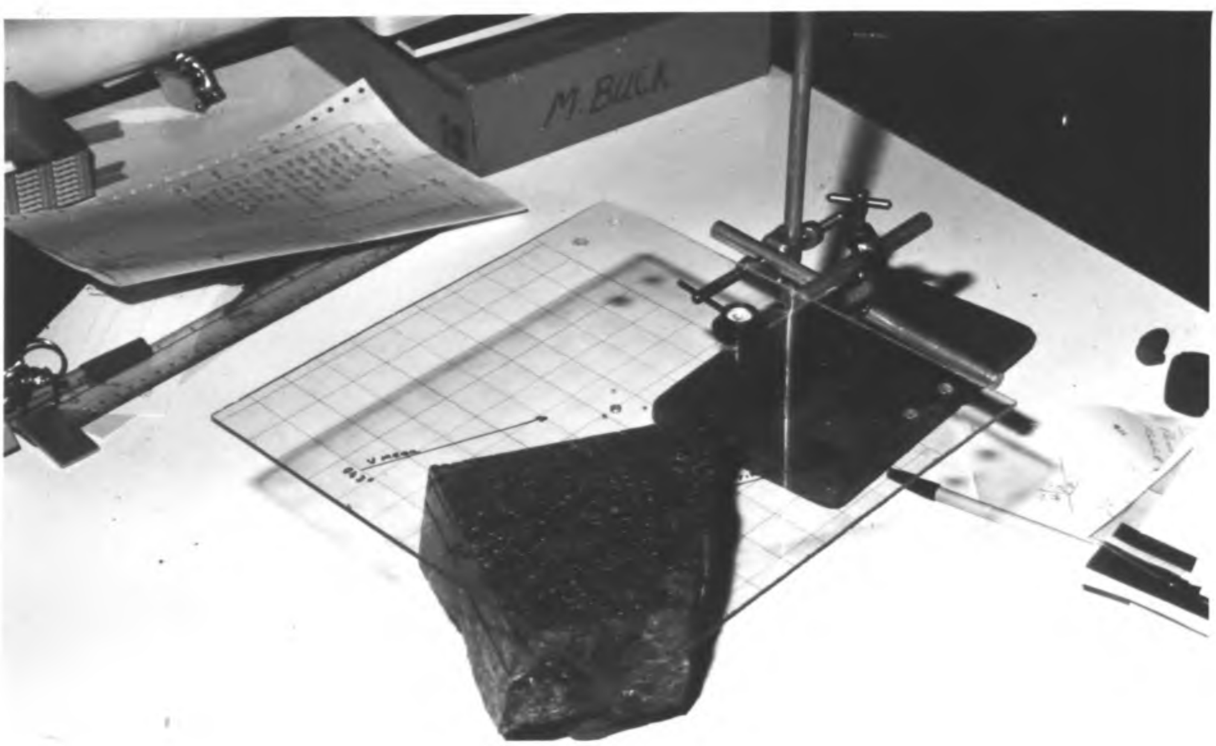
The first program was named FLOWLIN and it is a modified version of the program used by Elston and Smith (1970) and others (Rhodes and Smith 1972, Aldrich 1976). As this program read data from class sets it was modified to first group the individual measurements in the data files of this study into 10 degree intervals and it then calculates the vector mean and the vector magnitude, as well as calculating both the Tukey Chi Square and the standard Chi Square values.

The second program, called ROSE is one that originated from the sedimentologists at Macquarie University to analyse the preferred alignment of clasts in sedimentary rocks from the formulae that are set out in Potter and Pettijohn (1963). The program calculates the same vector mean and vector magnitude as the FLOWLIN program except that it works on individual data points rather than grouped data It also calculates the strength of the resultant vector mean. The ROSE program was modified during the course of my research to make the data input quick, and the output well illustrated. The end result is a program that is distinct from other similar programs in that it processes individual data points rather than grouped data, which are typed in on a VDU, and to illustrate the distribution of the data it plots as a rose diagram that has an option of 5 or 10 degree class intervals.

The vector means that were calculated by each program were always slightly different ($\pm 5^{o}$) because of the grouped data analysis of FLOWLIN versus the non-grouped data analysis of the ROSE program, but the vector magnitudes obtained from each program were identical. The vector means calculated by the ROSE program were the ones used to determine the final flow lineations in this study.

III.4.2 Determination of flow lineation and correction of data for tectonic tilt.

Up to this stage the flow lineation (vector mean) that has been determined is but an arbitrary orientation on the slab. To determine the "true" orientation of the lineation it has to be related back to the field orientated face and to achieve this the sample was first restored to its original configuration with plastecine filling the saw cut along the bedding plane. Then by placing the whole sample on a pedestal of plastecine the orientated face was restored to its original dip using a clinometer. A level, transparent perspex, rectilinear grid was then suspended above the sample (Fig. III.4) and one set of the



<u>FIGURE III.4</u>

This perspex grid allowed the determined flow lineation to be quickly re-orientation according to the field orientation of the specimen. Note leveling bubble to keep grid horizontal and the orthogonal grid which can be aligned with a known direction.

grid lines were orientated in the direction of the strike of the face (and the other in the direction of dip). The top part of specimen was then carefully removed, leaving the rest of the sample held in the plastecine, thus exposing the bedding plane and the orientation of the determined lineation that had previously been drawn on it. The orientation of the lineation was traced onto the perspex and using a protractor its "true" orientation was determined from it relationship to the known orientation of the grid. The orientation of the bedding plane was determined like this as well and its dip was measured with the inclinometer.

After the "true" flow lineation vector mean had been determined for each sample it had to be to be restored to its original horizontal emplacement position since the ignimbrites are both folded and faulted. The lineation vector means for each sample were restored to a horizontal position by rotating the bedding plane around the axis of the fold from which the sample was taken using a stereonet. It is these restored flow lineations (vector means) that are regarded as the flow lineations that formed in the ignimbrites when they were first emplaced. The list of all the flow lineation data determined in this study is presented in Appendix IV and it is this data which is plotted on all of the maps in this thesis.

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APPENDIX IV

FLOW LINEATION STATISTICAL DATA

The (*) asterisk alongside any set of data denotes that it falls below the Chi Square 90% confidence limit and it is therefore rejected.

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI^2	CHI^2
CURRA KEITH IGNIMBRITE						
36401	50	67	022	32.21	12.87	25.69
36402	145	106	020	41.21	36.47	65.85
36404	130	56	025	38.05	15.95	44.29
36405	72	114	021	42.20	39.96	76.74
36406	135	99	070	51.22	52.39	119.36
36407	110	109	042	35.15	26.24	96.27
36408	36	63	352	44.67	23.55	48.71
36410	50	73	025	45.20	28.90	57.93
36411	80	191	044	43.21	72.36	93.32
36412	100	83	042	49.48	38.80	100.25
36413	114	58	090	21.25	4.94	28.90
36414	97	68	315	41.96	25.18	62.24
36415	45	108	008	24.30	12.56	39.00
36416	135	101	066	46.91	42.45	59.57
36417	110	97	040	73.66	12.56	168.92
36418	40	150	018	39.56	46.46	70.56
36419	75	143	047	49.36	69.92	89.99
36420	70	91	322	38.39	26.85	78.12
36421	60	111	047	57.08	72.17	92.51
36422	54	97	044	46.56	41.52	81.33
36423	65	62	058	27.09	8.44	22.77*
36424	42	142	060	37.51	38.34	74.75
36426	45	91	037	72.16	95.96	167.13
36427	50	68	026	39.61	22.17	50.06

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI^2	CHI^2
<u>CURRA KEITH IGNIMBRITE</u> (cont..)						
36428	140	109	030	48.86	49.45	62.91
36429	80	52	052	42.72	18.53	43.54
36431	58	59	094	40.86	19.16	52.36
36434	132	40	356	69.48	38.95	94.10
36435	40	53	010	17.63	3.48	44.47
36436	156	61	023	69.06	57.57	103.36
36437	72	74	101	56.63	42.26	76.32
36438	84	36	073	57.57	22.62	33.00
36439	110	95	106	36.19	23.96	50.33
36622	104	90	088	42.00	31.35	78.40
Total	2952	3118	*Average*	44.68	37.23	71.20
Average	87	92	*S.Dev*	14.49	24.30	34.45
Combined data of samples from the same locality						
36401-08	728	678	029	31.29	132.30	144.01
36415-17	290	306	045	36.10	77.27	106.32
36418,19	115	293	034	38.31	87.68	112.07
36421,22	114	208	045	50.26	109.23	148.17
36423,24	107	204	060	33.22	44.27	77.09
36426,27	95	159	034	57.49	104.55	170.61
36434,35	132	93	356	39.21	28.13	105.91
<u>OAKFIELDS IGNIMBRITE</u>						
36433	63	101	349	42.62	36.84	110.90
36441	45	53	043	61.66	40.23	57.38
36442	85	74	023	35.25	18.04	46.16
36444	68	183	017	22.65	19.16	41.75
36445	40	203	029	19.03	15.00	53.52
36446	64	56	036	62.01	42.08	82.21
36448	40	51	355	56.22	33.17	78.53
36450	78	101	040	41.82	35.60	50.66
36451	54	113	043	32.39	24.59	59.83

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI^2	CHI^2
<u>OAKFIELDS IGNIMBRITE</u> (cont..)						
36452	100	138	030	44.77	55.18	72.00
36453	96	96	022	37.75	27.32	47.63
36454	118	164	045	33.59	32.66	59.56
36455	90	44	046	57.75	27.53	49.45
36456	120	76	032	63.98	62.42	111.11
36457	80	57	358	29.60	10.23	30.47
36458	84	64	348	64.26	54.58	109.25
36459	132	68	007	53.17	38.27	47.41
36460	63	49	090	32.00	9.78	49.82
36461	163	148	075	65.49	126.20	160.43
36462	143	100	043	68.06	94.13	141.20
36464	150	103	056	44.68	39.66	88.01
36465	110	77	096	36.19	23.96	50.33
36466	76	72	046	13.78	2.71	26.50
36467	68	84	020	65.89	69.59	104.57
36468	126	84	028	53.96	49.39	95.57
36469	103	45	034	55.49	27.38	41.00
36470	169	85	034	74.94	93.60	178.22
36471	84	79	090	62.94	63.25	120.37
Total	2481	2467	*Average*	47.57	41.87	77.27
Average	87	88	*S.Dev*	16.78	28.69	39.73

Combined data of samples from the same locality

36450-53	328	448	033	39.76	143.44	191.24
36455,56	210	120	036	59.60	82.47	117.22
36458,59	216	132	355	56.59	79.75	129.14
36460,61	226	197	075	54.67	117.78	169.85
36466-68	270	240	026	43.76	90.88	116.98
36469,70	272	130	034	68.84	122.71	216.82

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI2	CHI2
McCULLLYS GAP IGNIMBRITE						
36474	48	75	043	27.30	10.72	41.40
36475	124	113	030	55.99	69.54	140.12
36476	80	106	026	32.88	23.71	77.74
36477	108	86	038	25.23	11.42	57.58
36480	65	51	343	39.69	16.24	36.88
36481	158	57	329	24.64	6.97	36.79
36482	65	75	067	34.85	17.49	53.40
36483	156	97	066	58.69	64.76	152.59
36484	60	62	057	36.16	15.98	52.39
36485	163	77	116	27.48	12.06	47.60
Total	1027	799	*Average*	36.29	24.89	69.65
Average	103	80	*S.Dev*	12.16	22.76	42.24
Combined data of samples from the same locality						
36475-76	312	305	031	40.26	95.96	202.22
36480,81	223	108	337	30.79	19.88	62.80
36482-84	281	234	065	43.57	89.94	157.85
UNNAMED NATIVE DOG IGNIMBRITES						
36487	98	107	054	30.14	19.85	42.89
36488	47	32	085	37.90	8.71	33.25
36489	45	79	072	21.73	6.56	36.97
36491	60	41	058	74.99	47.62	79.73
36492	130	160	018	31.35	30.63	52.85
36493	58	198	075	19.23	13.03	29.82
36494	45	60	045	54.56	36.43	70.80
36495	95	149	094	25.22	19.42	37.89
36497	75	51	023	41.17	17.66	39.71
36499	169	71	142	24.00	7.67	34.72
36502	132	60	068	53.72	35.10	69.00
36503	97	100	074	68.28	93.68	150.56
36504	81	72	074	54.05	42.52	94.00

SAMPLE NUMBER	AREA (cm2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI2	CHI2
UNNAMED NATIVE DOG IGNIMBRITES (cont..)						
36505	150	31	356	67.75	28.87	69.45
36506	85	46	315	77.00	54.37	84.70
Total	1367	1257	*Average*	45.41	30.80	61.75
Average	91	84	*S.Dev*	20.25	22.88	32.33
Combined data of samples from the same locality						
36503,04	178	172	074	61.17	68.10	122.28
HAPPY VALLEY IGNIMBRITE AND AIRFALL						
36472	90	94	Airfall	9.86	2.80	24.50*
36507	80	39	Airfall	7.49	0.35	19.62*
36508	156	50	051	40.12	15.71	33.52
36509	52	76	040	38.62	22.94	63.74
36510	38	59	029	47.76	26.74	94.46
36511	72	87	048	65.92	74.20	150.31
36512	100	152	035	25.31	18.95	33.65
36513	32	25	305	74.85	27.17	69.32
36514	75	53	024	72.65	55.09	102.89
36515	84	43	295	60.19	30.39	77.98
36518	50	48	028	56.15	29.20	60.75
36519	20	21	040	86.17	30.89	55.29
36520	32	22	084	45.23	9.18	28.73
36533	90	37	348	34.24	8.87	17.97*
Total	971	806	*Average*	53.93	29.11	65.72
Average	69	58	*S.Dev*	18.49	18.74	37.39
Combined data of samples from the same locality						
36509-12	262	374	039	39.64	115.07	222.07
36518-19	70	69	033	55.54	46.32	113.30

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI^2	CHI^2
PORT STEPHENS IGNIMBRITE						
From the Port Stephens Area						
36473	106	66	350	58.82	45.15	88.91
36546	170	93	048	55.99	58.27	122.81
36547	90	53	022	46.14	23.43	68.92
36548	126	82	035	35.41	19.87	55.85
36550	132	19	046	71.21	19.15	52.05
36551	156	87	034	66.36	77.05	129.21
36552	118	103	317	51.24	56.90	100.24
36553	85	49	351	66.62	43.06	76.27
36554	80	58	009	70.50	56.47	82.90
36555	240	89	358	62.98	71.70	117.90
36556	120	59	016	72.98	62.64	140.83
36557	208	80	006	42.87	26.91	63.55
36558	192	89	002	58.56	59.99	95.25
36559	208	102	344	55.43	61.01	104.82
36560	132	86	314	47.98	38.23	52.56
36561	156	94	000	31.41	18.49	57.28
36562	Coarse Breccia - No Lineation Possible					
36563	165	63	009	64.12	50.44	75.57
36564	168	113	302	62.32	85.96	123.23
36565	208	104	331	74.36	116.08	181.23
Total	2860	1489	*Average*	57.65	52.15	94.18
Average	160	78	*S.Dev*	12.45	25.40	35.04

Combined data of samples from the same locality

36546,47	260	146	040	47.15	64.25	150.18
36548-51	414	188	041	50.89	101.42	162.31
36553-55	405	196	000	64.62	163.82	233.77
36556,57	328	139	011	55.39	86.40	156.06
36558,59	400	191	353	54.02	117.17	167.51

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI^2	CHI^2
PORT STEPHENS IGNIMBRITE (Cont.)						
From the Morna Point Area						
36567	Coarse Breccia - No Lineation Possible					
36568	196	92	002	50.56	45.19	77.83
36569	143	68	072	48.27	31.48	63.29
36570	96	61	334	73.87	67.08	135.23
36571	192	104	088	37.14	27.15	56.96
36572	153	92	070	57.09	60.92	143.96
36573	143	94	032	46.84	40.67	103.23
36574	168	93	348	67.55	83.74	142.94
36575	176	97	317	51.06	50.99	89.87
36576	224	90	302	27.59	13.19	34.80
36586	150	70	321	80.48	90.37	154.23
Total	1641	861	*Average*	54.05	51.08	100.23
Average	164	86	*S.Dev*	16.25	24.72	42.18
Combined data of samples from the same locality						
36568,76	420	182	344	21.57	17.51	45.24
36571,72	345	196	278	45.08	75.56	136.85
36573,74	311	187	004	42.48	68.88	82.90
NELSON BAY IGNIMBRITE						
From around Nelson Bay						
36577	162	92	332	60.53	65.57	113.83
36578	169	77	336	66.23	69.48	130.35
36579	160	72	324	75.04	80.81	178.50
36580	192	103	027	85.66	147.74	237.60
36581	108	64	020	62.70	50.70	95.19
36582	96	59	354	52.39	31.62	53.58

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI^2	CHI^2
NELSON BAY IGNIMBRITE						
from around Nelson Bay (cont..)						
36583	120	158	330	26.56	23.07	52.99
36584	192	70	051	52.45	38.34	82.74
Total	1199	695	*Average*	60.20	63.42	118.10
Average	149	87	*S.Dev*	17.85	39.43	63.55
Combined data of samples from the same locality						
36577-79	491	241	330	65.81	205.95	360.30
36580-82	396	226	019	64.13	185.11	291.40
NELSON BAY IGNIMBRITE						
From Fingal Bay						
36586	140	30	343	77.85	37.52	62.40
36587	250	74	325	61.58	54.94	93.84
36588	230	133	328	13.80	5.42	60.40
Total	620	237	*Average*	51.07	32.63	72.21
Average	206	79	*S.Dev*	33.29	25.12	18.76
Combined data of samples from the same locality						
36586-88	620	237	332	35.37	59.94	136.65
MARTINS CREEK IGNIMBRITE						
From the Muswellbrook-Rouchel Area						
36521	90	84	344	47.72	37.48	68.57
36522	104	79	033	65.19	67.95	113.99
36523	44	74	358	78.18	89.33	143.46
36524	75	73	352	51.50	38.43	75.19
36526	90	94	336	60.79	68.27	141.15
36528	108	90	013	46.71	40.88	94.80
36529	45	56	322	30.14	10.51	32.71
36530	110	99	006	49.84	48.84	96.82

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI^2	CHI^2
MARTINS CREEK IGNIMBRITE						
from the Muswellbrook-Rouchel Area (cont..)						
36531	95	96	010	52.53	52.24	78.38
36532	100	97	003	43.35	36.62	75.39
36534	104	52	340	62.70	40.83	60.15
Total	965	894	*Average*	53.51	48.31	89.15
Average	88	81	*S.Dev*	12.77	20.91	33.63
Combined data of samples from the same locality						
36521,22	194	163	012	37.83	46.59	76.74
36524,26	165	167	343	54.74	100.58	170.04
36528,29	153	146	002	30.09	26.81	53.69
36530,31	205	195	008	51.48	102.76	147.92
MARTINS CREEK IGNIMBRITE						
From the Maitland - Paterson Area						
36595	192	85	083	57.18	56.65	107.07
36596	192	76	059	78.99	93.46	161.32
36597	195	132	043	46.76	58.42	106.64
36598	168	84	060	31.18	15.36	44.14
36600	240	151	009	38.45	45.90	95.16
36601	132	66	015	46.98	27.95	63.27
36602	168	145	352	45.60	60.13	158.27
36603	250	134	040	57.07	84.83	124.72
36604	90	80	018	54.72	47.08	86.95
36605	170	128	077	66.86	114.02	203.03
36606	77	107	063	24.83	12.44	36.16
36607	110	123	070	58.28	84.39	136.46
36608	120	86	349	53.29	47.56	88.98
36609	80	97	010	62.55	77.42	120.30

SAMPLE NUMBER	AREA (cm^2)	N	VECTOR MEAN	% VECTOR MAGNITUDE	TUKEY CHI^2	CHI^2
MARTINS CREEK IGNIMBRITE						
from the Maitland - Paterson Area (cont..)						
36610	78	79	346	60.81	58.51	119.91
36611	50	61	350	63.01	48.03	132.87
Total	2312	1629	*Average*	59.91	58.26	111.58
Average	145	102	*S.Dev*	13.65	27.65	43.52
Combined data of samples from the same locality						
36595-98	747	377	060	45.38	157.44	209.03
36603,04	340	214	032	53.25	117.99	139.44
36605,06	260	235	074	47.58	106.33	172.81
MISCELLANEOUS SAMPLES						
Sedimentary Rocks - Muswellbrook and Rouchel Area						
36537	75	36	332	47.27	15.98	52.00
36539	40	51	066	65.46	43.05	79.24
36540	52	99	062	43.47	36.24	88.45
OTHER IGNIMBRITES						
Port Stephens Area						
36589	182	56	076	69.75	53.39	93.14
36590	182	61	017	62.63	48.48	78.57
36591	170	125	023	60.07	91.63	175.82
36592	104	86	322	73.59	91.54	136.28
Paterson District						
36612	132	67	346	31.44	13.19	28.37
36613	88	108	008	69.08	102.01	150.33
36614	195	61	087	35.50	14.20	43.75
36616	156	52	044	56.72	32.08	66.38
36617	156	82	337	69.08	76.90	126.10
36618	98	71	063	48.54	35.95	70.21
36619	60	55	028	42.69	19.48	47.44
36620	165	69	334	54.74	42.62	68.48

APPENDIX V

ROSE DIAGRAMS

(not included in the thesis)

See Fig 3.12 for key to roses

FIGURE V.1

Rose diagrams of the flow lineation data for the Curra Keith Ignimbrite.

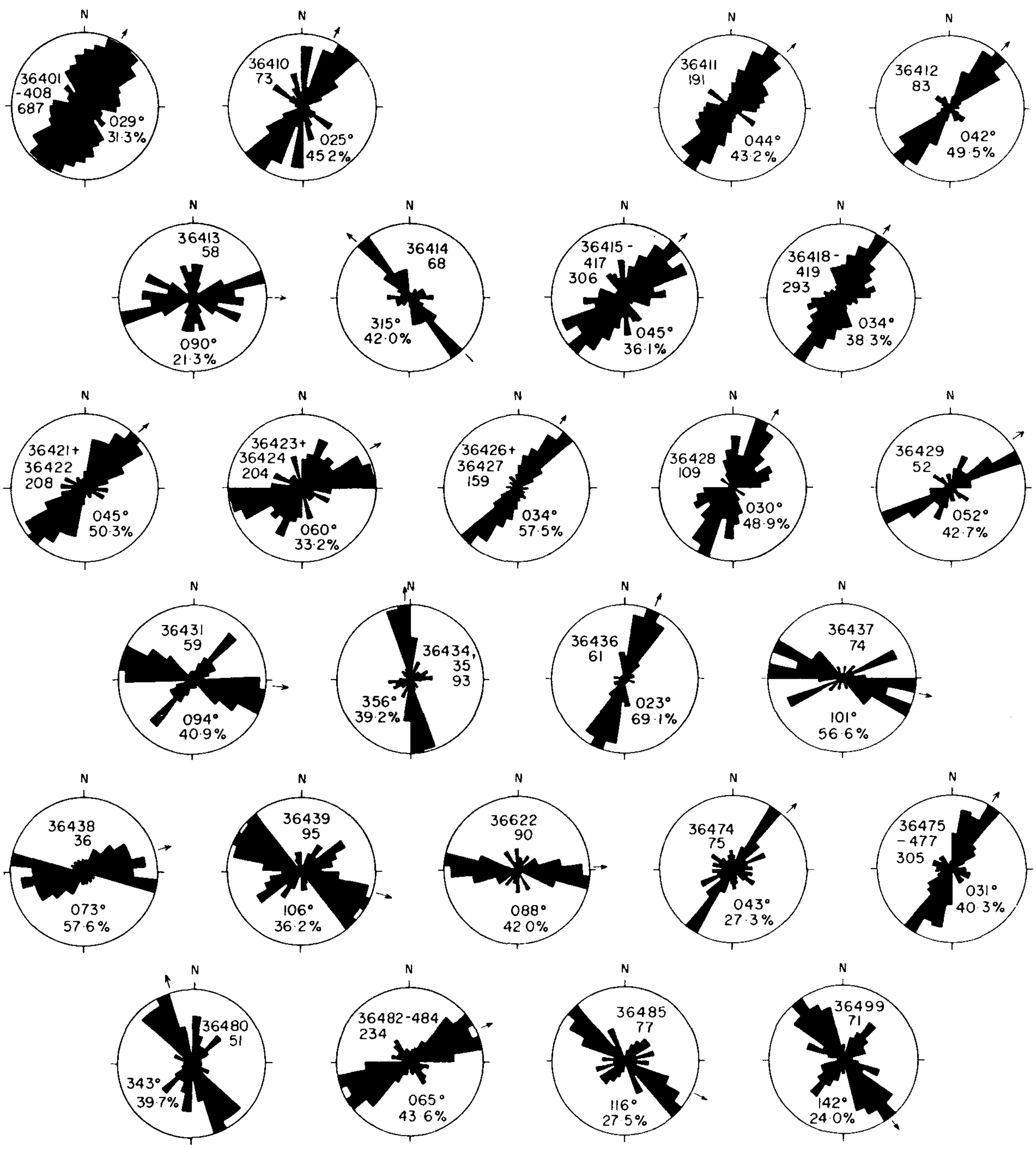


FIGURE V.2

Rose diagrams of the flow lineation data for the Oakfields Ignimbrite.

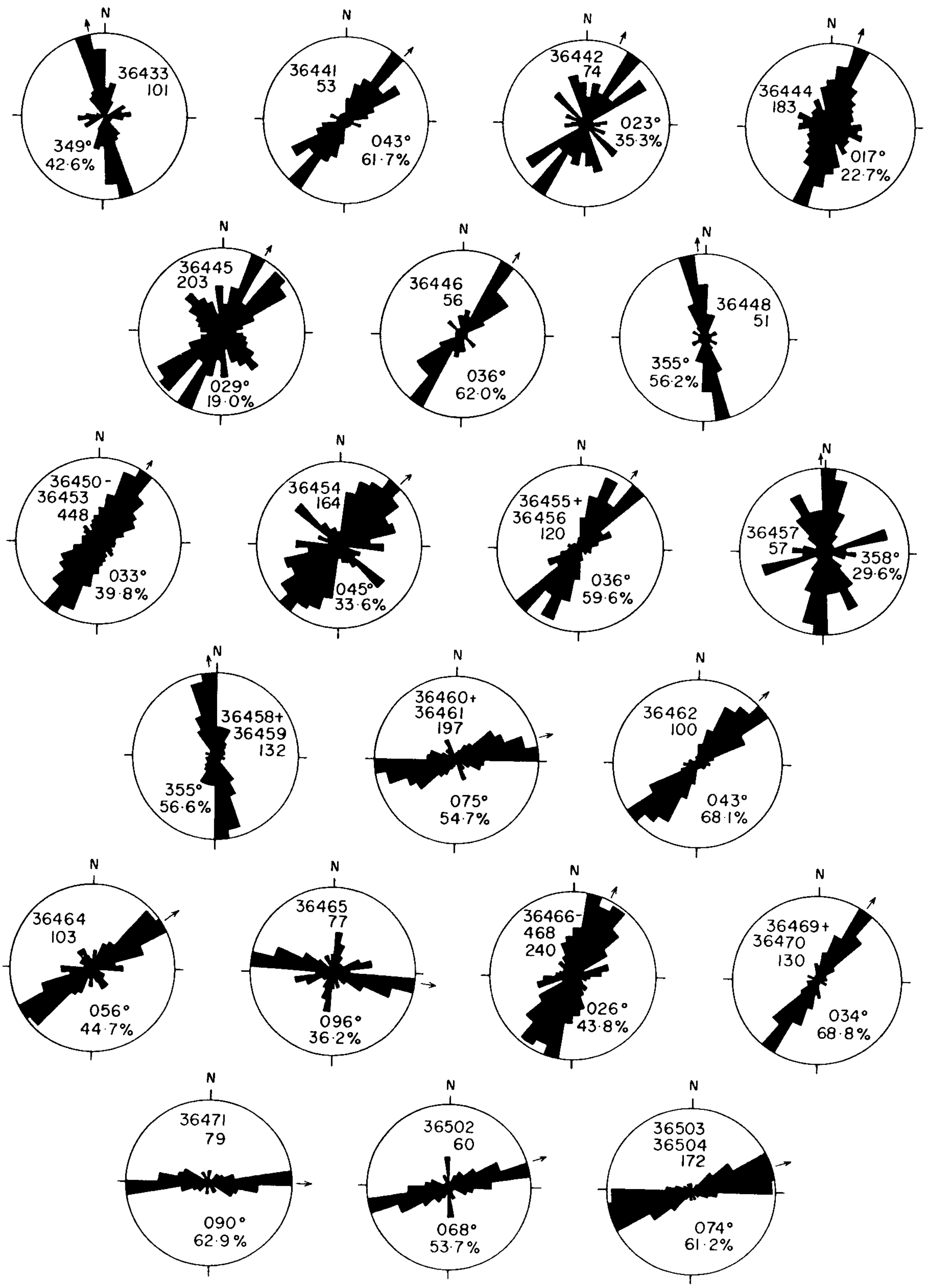
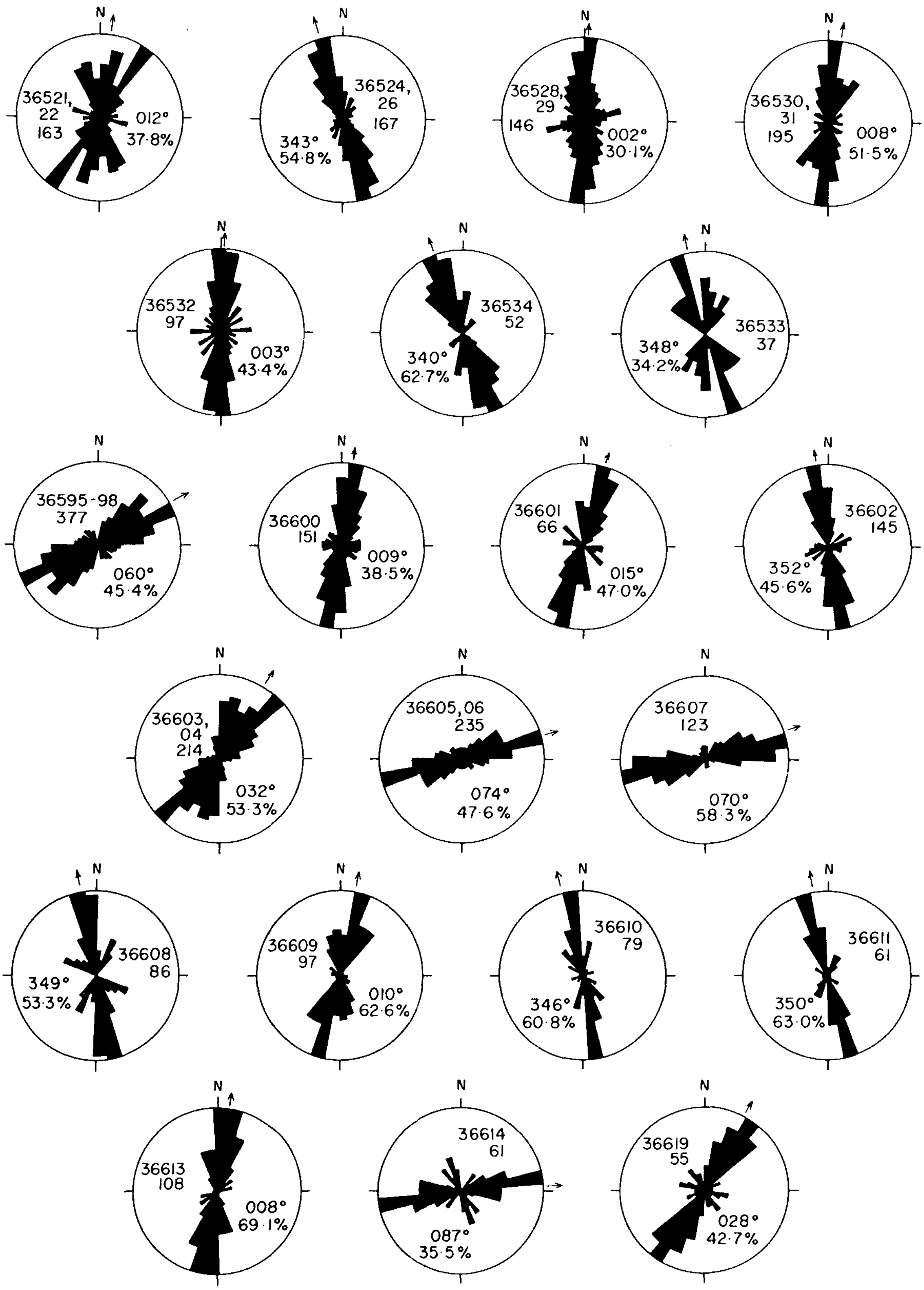


Figure V.3
Rose diagrams of the flow lineation data for the Martins Creek Ignimbrite.



APPENDIX VI

PETROLOGICAL MISCELLANIA

VI.1 FLOW BANDING

Over 400 theses, from several of the Universities in New South Wales, have been written about aspects of the geology of the Carboniferous succession in the Hunter Valley (or southern New England Orogen) and a number of them have described flow banded ignimbrites. Fig. VI.1 shows a typical example of such a "flow banded" ignimbrite and it is easy to see why it may be called such. However, flow banding is only a feature of ignimbrites that have undergone rheomorphism, or secondary flowage and Wolff and Wright (1981) demonstrate that for this to happen the ignimbrite has to be intensely welded so that it acts as a viscous fluid after initial deposition.

The "flow banded" ignimbrites in the Carboniferous succession in the Hunter Valley are not rheoignimbrites, as Wolff and Wright (1981) call them, but they are moderately welded ignimbrites with liesegang bands (Fig. VI.2).

VI.2 CO-IGNIMBRITE LAG-FALL BRECCIA - PORT STEPHENS

Wright and Walker (1977) first defined a breccia within an ignimbrite a co-ignimbrite lag-fall deposit from their observations of the Acatlan ignimbrite in Mexico. To them the coarse lithic-rich deposit at the base of the ignimbrite close to its eruptive vent formed as a lag deposit consisting of pyroclasts that fell to the ground as they were too large and too heavy to be carried away in the pyroclastic flow. They state the significance of a co-ignimbrite lag-fall deposit is three fold:

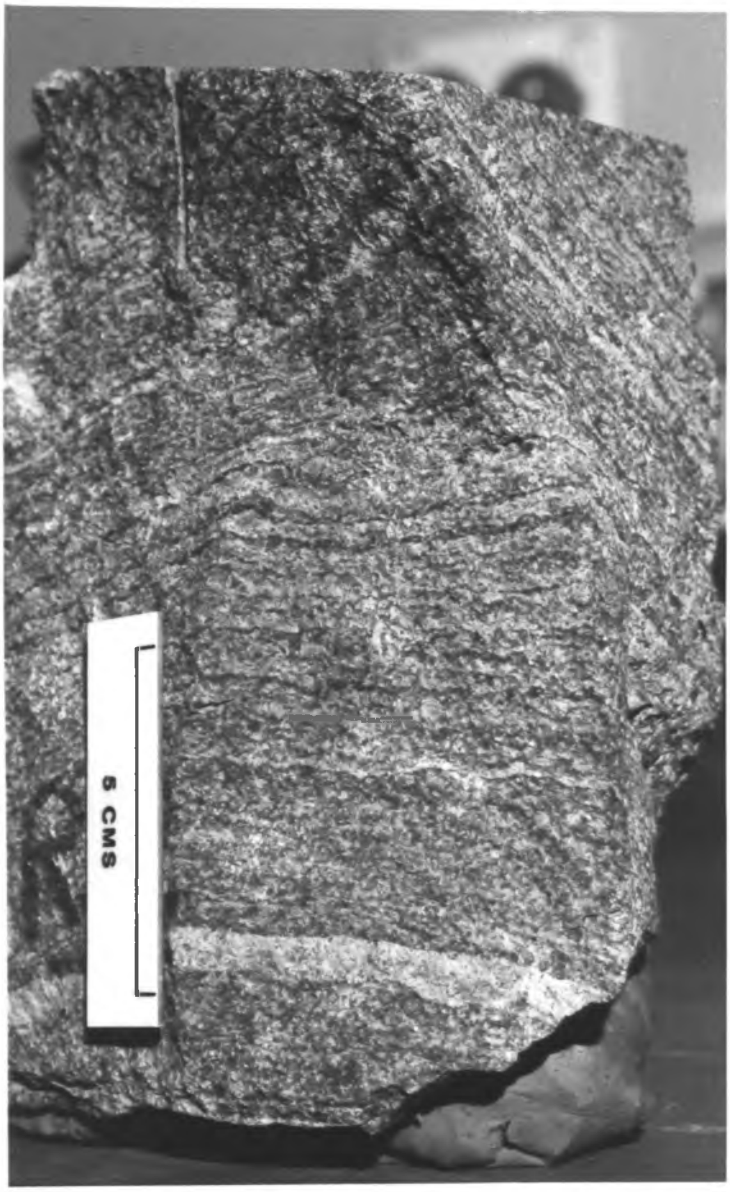
1. It has a bearing on the mechanism of formation of pumice flows.
2. It indicates the existence of a cut-off for material too large and too heavy to be transported by the pumice flows.
3. It narrows down the notoriously difficult search for the position of the ignimbrite source vents.

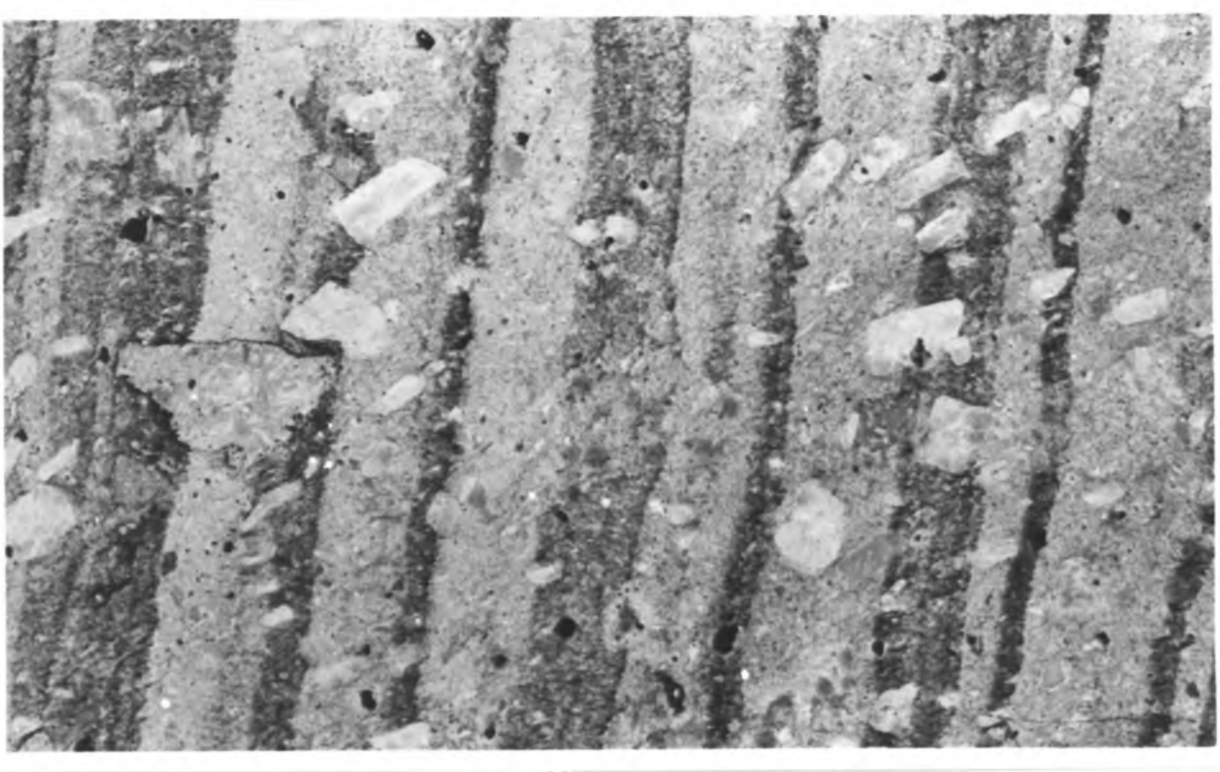
FIGURE VI.1

The deceptive 'flow-banded' Ignimbrite. This kind of banding is common near the base of some of the lower Carboniferous ignimbrites, and here it is the Curra Keith Ignimbrite. In a hand specimen like this it is difficult to tell that this is not a flow banded lava rock, but inspection of a larger outcrop, which is normally unavailable, normally reveals large amplitude, convoluted swirls in the bands quite unlike any flow banding. The bands are in fact a secondary alteration feature similar to Liesegang Bands.
(MU 36403, G.R. Scone 086476).

FIGURE VI.2

Photomicrograph (plain polarised light) of the 'flow banded' ignimbrite in the Fig. VI.1. The bands are Fe-rich and sharply defined, and to me they resemble bands similar to those produced in chromatography. The main feature to discredit a flow banding origin is that, in normal flow banded rocks the phenocryst alignment runs parallel to the bands but here, it cuts across the bands. (MU 36403, Scone 086476, Image Length 17mm)


5 CMS



Similar breccias have since been recognised in a number of localities as a near vent facies of an ignimbrite (Druitt and Sparks 1982; Walker *et al* 1981; Lipman 1976) and Walker (1985) has comprehensively reviewed the origin of coarse lithic breccias near ignimbrite source vents, and since they may be formed by several different mechanisms the term 'co-ignimbrite breccia' is now favoured for any breccia within an ignimbrite.

However, the concept of a co-ignimbrite lag-fall deposit (breccia) seems to best explain the breccia that occurs in the basal metre or so of the Port Stephens (rhyolitic) ignimbrite in the area south of Port Stephens (Fig. 5.22). A detailed description of the formation of the breccia is attempted in Chapter 5.9.2 and Figs VI.3 and VI.4 are given to illustrate other aspects of this, until now unnoticed breccia.

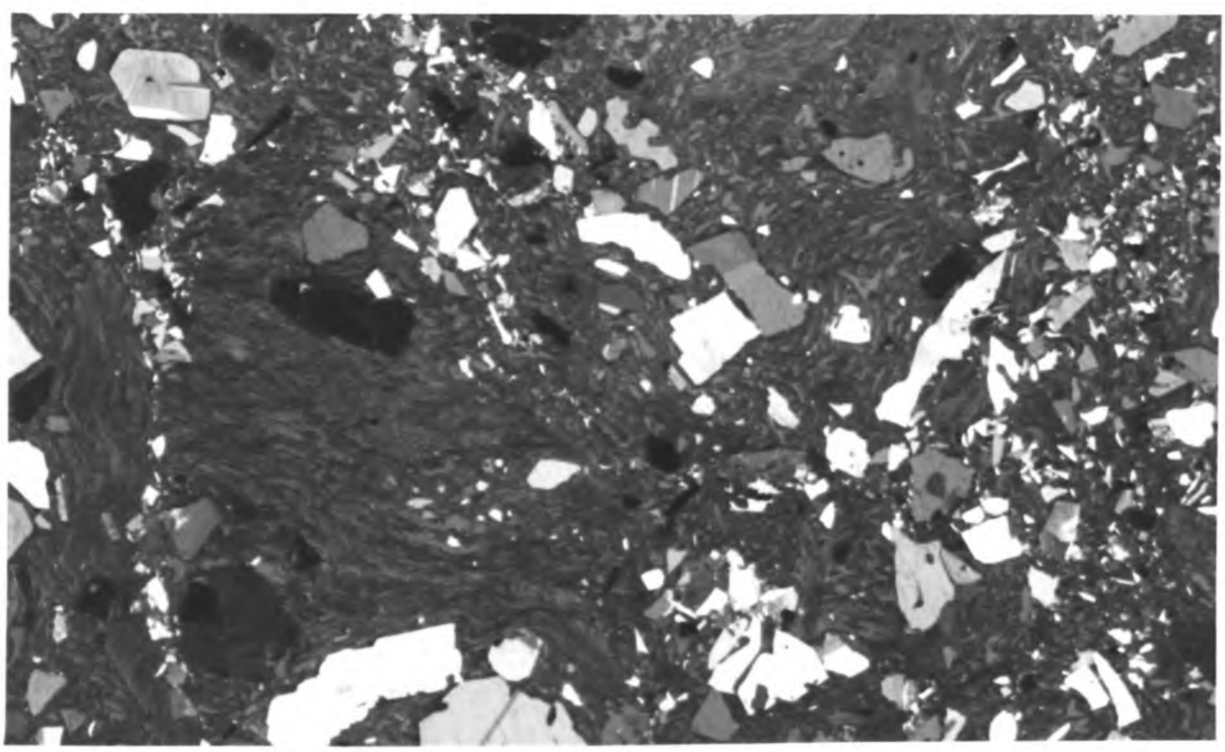


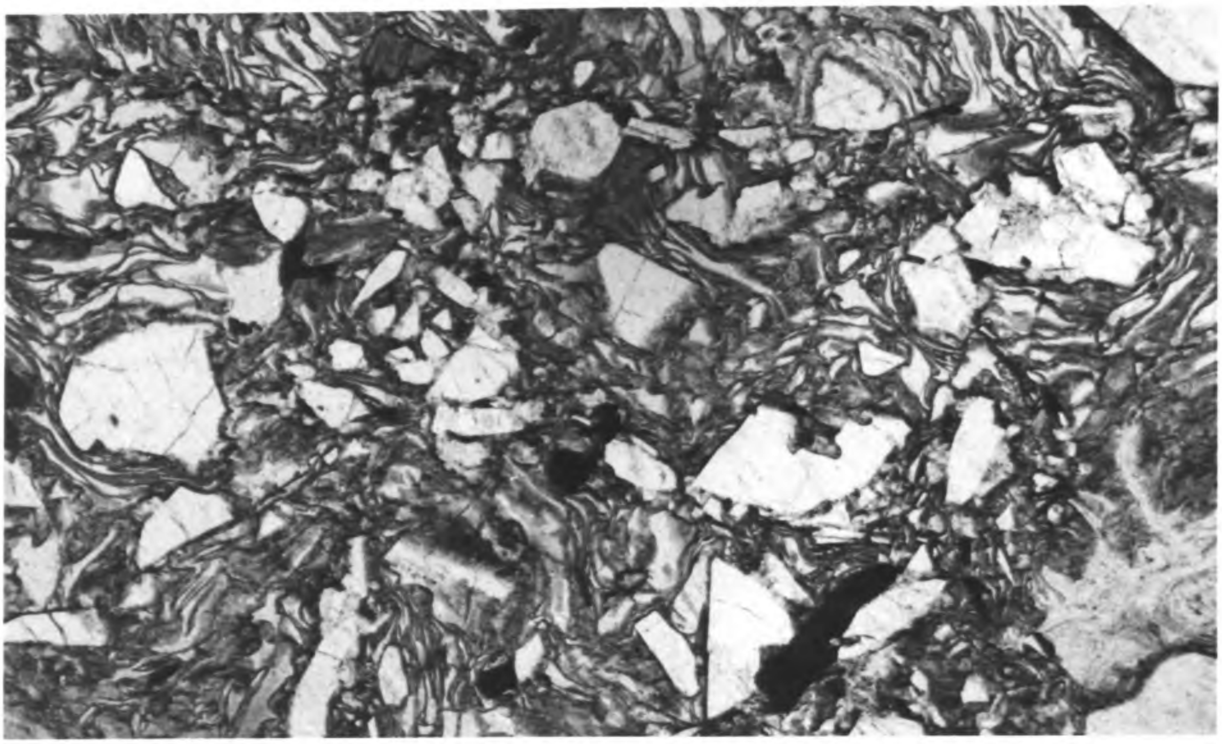
FIGURE VI.3

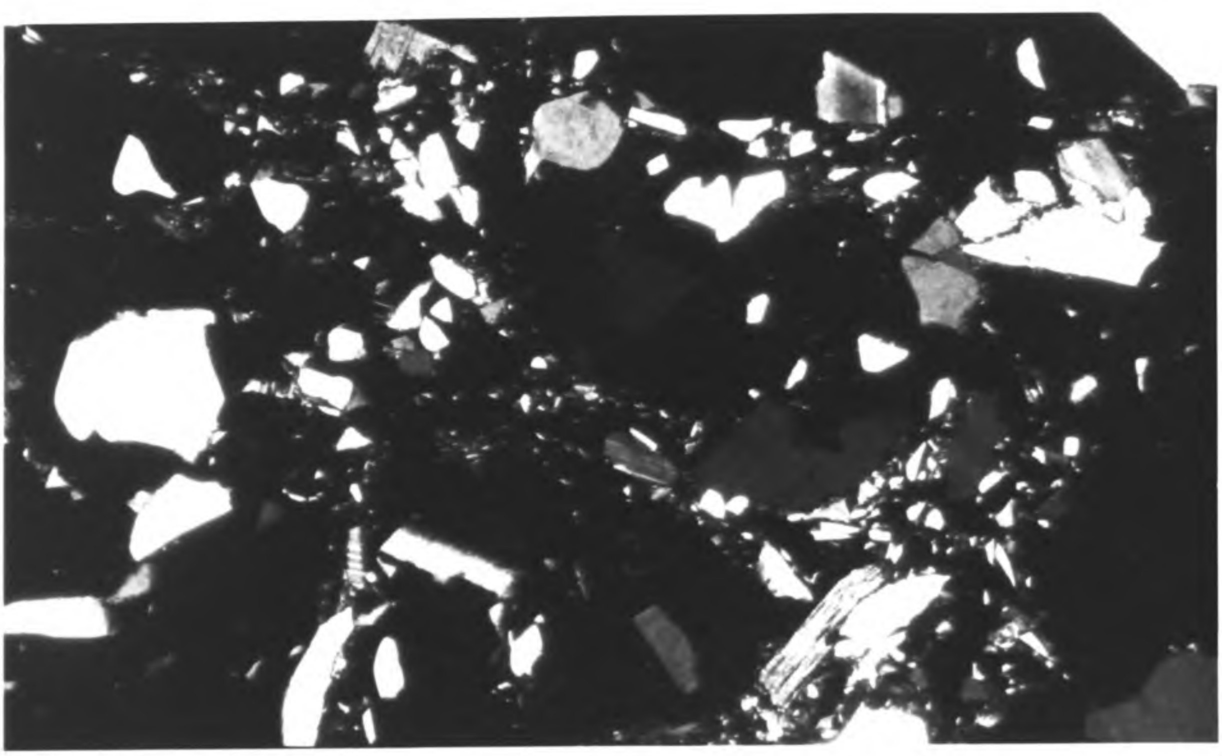
Partial crossed polarised photomicrograph showing the distinct difference between the 'ignimbrite' clasts and the matrix in the co-ignimbrite lag-fall breccia in the proximal facies of the Port Stephens ignimbrite. The clasts have a pumiceous structure but they are poorly inflated and appear to have had the density of normal lithic clasts. (MU 36623, G.R. Port Stephens 213803, Image Length 16 mm).

FIGURE VI.4

A. Plane polarised photomicrograph of the co-ignimbrite lag-fall breccia in the Port Stephens Ignimbrite, illustrating the difficulty in determining that this is in fact a breccia. In this view, it could easily be taken for a partially welded ignimbrite, as the shard-like features in the matrix are deformed about the phenocrysts, except that there is no preferred plane of flattening.

B. Cross polarised photomicrograph of the image above which brings out the nature of the casts that are disguised in the plane polarised view. The phenocrysts in the clasts are large and mostly unbroken whereas, those in the matrix, are small and highly fragmented.
(MU 36623, G.R. Port Stephens 213803, Image Length 4 mm).





VI.3 AIRFALL DEPOSITS

Interbedded with the ignimbrites in the study area are many airfall (tephra) layers which typically now outcrop as a bright haematite red 'cherty' horizons. In fact after the many outcrops I have looked at and sampled over my years with the University of New South Wales on their 3rd year excursion in the Muswellbrook-Rouchel district it is probably a fair statement to make that "all bright red coloured 'cherty' rocks in the Hunter Valley are airfall deposits". These tephra units are normally bedded and they range in particle size from lapilli to the finest ash and Figure VI.5 illustrates many of the typical features of the tephras. No matter what the particle size of the tephra, the particles are generally surrounded by a film of haematite and in some instances the haematite stains the zeolite that has both replaced the original vitric components (Fig. VI.5) and infilled the interstices between the particles. In thin section a characteristic feature of all of the tephra units is the presence of undeformed, randomly orientated glass shards and in many cases 'intact bubbles' (Fig Vi.5) which are not found in the ignimbrites.

The mechanism for the haematite accumulation in the tephra units is envisaged to be the same as that I described for the haematite- stained 'red tephras' between the lava flows on the rhyolite cone of Mayor Island (Buck *et al* 1981). The tephra units would have been porous (and friable) when they were originally laid down whereas the ignimbrites were coherent due to welding and far less porous. Groundwater moves down though the cracks and joints in the ignimbrite extracting iron (and other elements e.g. K_2O) as it goes. The water moves laterally and freely in the intervening tephra horizons where haematite precipitates about the particles and in the pore spaces. The result is that within a short space of time, well before final lithification, the tephra is coloured red.

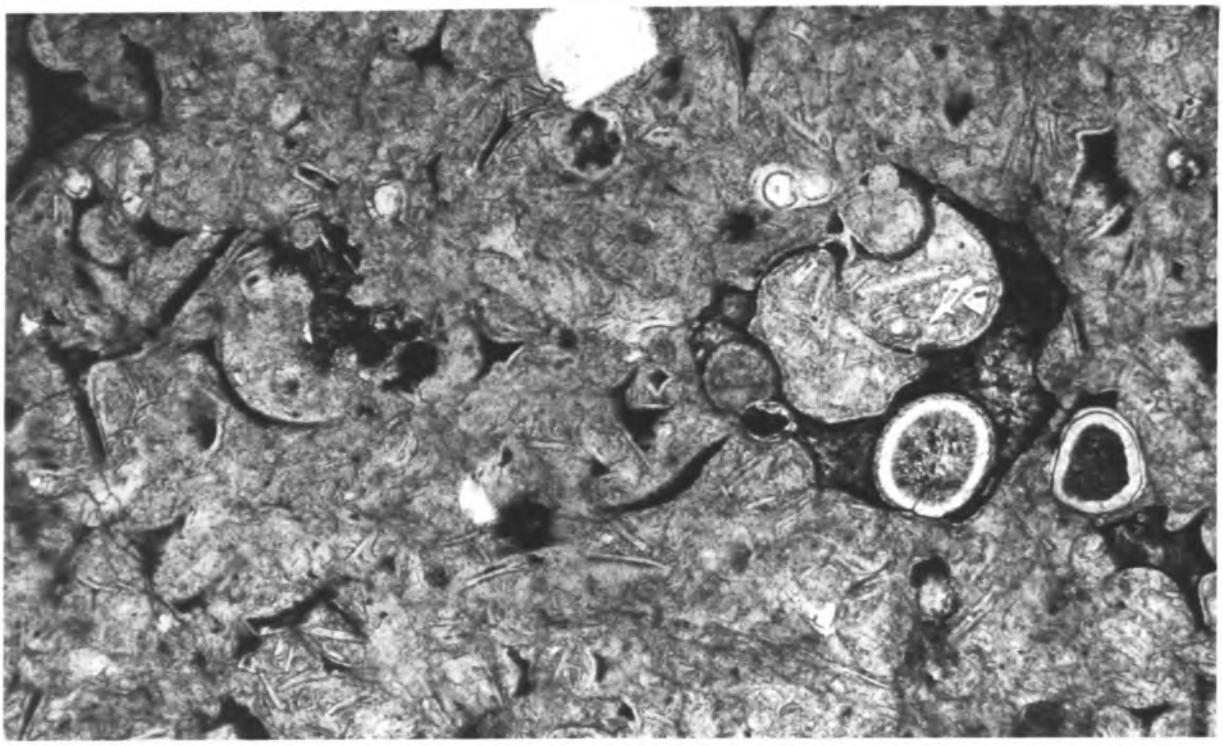


FIGURE VI.5

Photomicrograph of a typical ash-sized tephra unit in the Native Dog Member in the Muswellbrook-Rouchel District. The dark colour is bright red haematite which is staining zeolites that have replaced the original glass shards. Intact bubbles and undeformed shards indicate an airfall origin. (MU 36507, G.R. Rouchel Brook 196408, Image Length = 3.5 mm)

VI.4 REFERENCES

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APPENDIX VII

PREVIOUS CHEMICAL ANALYSES

This is a list of some previously published chemical analyses of the Nelson Bay ignimbrite and the Martins Creek ignimbrite, which compare with the analyses in this study. The data in the analyses marked with an asterisk (*) are considered to be spurious since they depart markedly from the values consistently obtained in this study.

Also included are some analyses of the Port Stephens ignimbrite and the Curra Keith ignimbrite though they have been proven to be wholly inaccurate.

NORMS have been recalculated according to recalculated FeO and Fe2O3 values as per the method used in this study.

DACITIC IGNIMBRITES

Author	Nyuyen 1976	Nyuyen 1976	Jakes 1970	Jakes 1970	Jakes 1970	Nyuyen 1976	Nyuyen 1970	Jakes 1970
Ref.No	**8066P**	**8067L**	**7**	**8**	**10**	**8064L**	**8087L**	**11**
Location	West Point	West Point	West Point	Corlette Point	Fingal Bay	Reedy Creek	Gilmore Mt.	Camberwell
SiO_2	64.40	64.30	63.78	64.44	63.60	66.20	65.60	67.21
TiO_2	.60	.60	.65	.66	.66	.50	.50	.46
Al_2O_3	15.20	16.10	15.03	15.30	15.33	15.80	15.80	14.94
Fe_2O_3	2.04	2.68	1.74	1.54	1.74	1.89	1.80	.40
FeO	1.68	1.82	2.15	2.92	2.32	1.54	1.98	2.69
MnO	.06	.10	.07	.10	.09	.06	.06	.06
MgO	1.55	1.90	1.71	1.98	2.18	1.00	1.50	1.18
CaO	5.00	3.80	4.38	3.38	3.90	2.60	3.00	2.55
Na_2O	3.25	4.00	3.76	3.81	3.55	4.33	4.00	3.73
K_2O	.80	3.20	1.70	2.96	2.68	3.60	3.50	4.03
P_2O_5	.15	.15	.15	.15	.18	.15	.15	.18
Loss	5.90	2.15	4.15	2.75	1.89	2.76	2.38	2.41
Total	100.63	100.80	99.27	99.99	98.12	100.43	100.27	99.84
Zr	200	365 *	177	196	180	230	-	213
Y	-	-	9 *	36	-	-	-	50 *
Sr	525	420	-	393	-	330	-	306
Th	-	-	4	15	14	-	-	19
Pb	-	-	7	-	-	-	-	-
U	-	-	4	4	4	-	-	5
%K	.66	2.65	2.41	2.45	2.22	2.99	2.91	3.35
Rb	105 *	130	-	91	-	205 *	-	155
K/Rb	62	203	-	270	-	145	-	216
Ga	-	-	19	20	-	-	-	4 *
Zn	-	-	62	36	58	-	-	63
Cu	-	-	11	17	19	-	-	21 *
Ni	7	12	7	5	5	10	-	3 *
Cr	9	9	27	15	28	8	-	19
V	70	80	87	89	91	65	-	54
Ba	480	540	675	639	645	570	-	635
Q	28.50	16.79	22.86	19.51	20.16	19.33	19.25	22.24
Or	4.73	18.91	10.04	17.49	15.83	21.27	20.68	23.81
Ab	27.49	33.83	31.80	32.22	30.02	36.62	33.83	31.55
An	23.82	16.53	19.12	15.78	17.99	11.92	13.90	11.47
C	.26	.00	.00	.05	.00	.42	.34	.24
Di	.00	1.10	1.33	.00	.15	.00	.00	.00
Hy	6.83	8.05	6.69	8.64	8.64	5.33	6.95	5.49
Mt	1.62	1.96	1.70	1.94	1.77	1.49	1.64	1.35
Il	1.14	1.14	1.23	1.25	1.25	.95	.95	.87
Ap	.35	.35	.35	.35	.42	.35	.35	.42

Author	Jakes 1970	Jakes 1970	Jakes 1970	Jakes 1970	Jakes 1970	Jakes 1970	R & O + 1972
Ref.No	**12**	**13**	**14**	**15**	**16**	**17**	**0263**
Location	Lambs Creek	Glendon brook	Walla robba	Clarence town	Martins Creek	Martins Creek	Bowmans Creek
SiO_2	66.20	65.87	65.89	65.83	67.99	66.37	69.00
TiO_2	.55	.51	.50	.58	.50	.46	.41
AL_2O_3	16.39	15.20	15.84	15.82	14.70	15.17	14.80
Fe_2O_3	1.71	1.23	1.42	1.21	1.49	1.21	2.25
FeO	2.26	2.57	2.09	2.37	2.34	2.50	
MnO	.08	.07	.05	.07	.06	.07	.05
MgO	1.58	1.45	1.57	1.43	1.14	1.32	1.20
CaO	3.12	3.18	3.08	2.95	3.19	2.83	2.15
Na_2O	3.89	3.70	3.82	3.95	3.19	3.90	4.40
K_2O	3.10	3.48	3.41	3.27	3.72	3.52	4.40
P_2O_5	.13	.13	.12	.14	.12	.12	.11
Loss	1.42	1.58	1.88	1.75	1.48	2.61	1.30
Total	100.43	98.97	99.67	99.37	99.92	100.08	100.07
Zr	227	225	217	221	203	220	-
Y	49 *	-	47 *	-	-	-	-
Sr	422	-	319	-	568 *	420	-
Th	15	17	17	17	15	-	-
Pb	16	-	-	-	2	-	-
U	5	4	4	4	4	4	-
%K	2.57	2.89	2.83	2.71	3.09	2.92	3.65
Rb	160	-	156	-	-	190 *	-
K/Rb	161	-	181	-	-	154 *	-
Ga	19	-	17	-	48 *	-	-
Zn	74	62	64	70	-	-	-
Cu	28	28	28	29	24	-	-
Ni	9	6	4	4	5	12	-
Cr	26	23	10	18	24	10	-
V	68	63	60	88	52	65	-
Ba	656	618	663	658	703	580	-
Q	21.53	21.04	20.71	20.98	25.73	21.07	20.14
Or	18.32	20.56	20.15	19.32	21.98	20.08	26.00
Ab	32.90	31.29	32.31	33.41	26.98	32.98	37.21
An	14.63	14.60	14.49	13.72	14.59	13.25	7.65
C	1.28	.00	.56	.76	.08	.09	.00
Di	.00	.27	.00	.00	.00	.00	2.11
Hy	7.29	6.71	6.82	6.46	6.09	6.51	3.72
Mt	1.73	1.65	1.52	1.55	1.67	1.61	.97
Il	1.04	.97	.95	1.10	.95	.87	.78
Ap	.30	.30	.28	.32	.28	.28	.25

+ Roberts & Oversby (1972)

RHYOLITIC IGNIMBRITES

	Wilko # 1971	Nyuyen 1976	S&C= 1928	S&C= 1928
Ref.No	**R 10**	**8075P**	**III**	**VII**
Locat-ion	Nelson Head	Nelson Head	Nelson Head	Morna Point
SiO_2	70.66	71.80	71.72	74.74
TiO_2	.16	.25	.15	.25
Al_2O_3	12.96	13.30	11.50	11.89
Fe_2O_3	.76	.76	2.30	1.50
FeO	1.15	.66	.63	.27
MnO	.04	.04	.11	.07
MgO	.36	.61	.41	.83
CaO	2.59	1.80	2.56	.74
Na_2O	3.55	3.57	3.40	2.96
K_2O	2.19	2.80	2.53	5.23
P_2O_5	.11	.05	.03	.02
Loss	5.15	5.05	4.81	1.74
Total	100.40	100.69	100.41	100.28
Zr	220	170		
Y	28	-		
Sr	450	280		
Th	-	-		
Pb	45	-		
U	-	-		
%K	2.42	2.32		
Rb	270	150		
K/Rb	90	154		
Ga	20	-		
Zn	-	-		
Cu	-	-		
Ni	5	10		
Cr	5	5		
V	14	18		
Ba	1000	800		
Q	32.58	32.20		
Or	17.19	16.54		
Ab	30.02	30.19		
An	10.84	8.60		
C	.00	1.25		
Di	1.09	.00		
Hy	2.14	2.64		
Mt	.83	.62		
Il	.30	.47		
Ap	.25	.12		

Wilkinson (1971); = Sussmilch and Clarke (1928)

Normative Ratios

	8066P	80671	7	8	10	8064L	8087L	11
OR	8.44	27.29	16.48	26.70	24.80	30.47	30.23	35.63
AB	49.06	48.84	52.16	49.20	47.03	52.46	49.45	47.21
AN	42.51	23.87	31.36	24.10	28.17	17.07	20.32	17.17
Q	46.94	24.15	35.33	28.18	30.54	25.03	26.10	28.66
OR	7.78	27.19	15.52	25.26	23.98	27.54	28.03	30.69
AB	42.27	48.66	49.15	46.55	45.48	47.43	45.86	40.66
A	43.45	52.94	49.37	51.25	49.96	64.16	58.69	64.51
F	39.91	33.09	35.17	33.76	32.56	27.75	29.58	25.69
M	16.63	13.97	15.46	14.99	17.48	8.09	11.74	9.81
A	39.48	32.33	35.29	32.51	33.50	36.59	34.66	35.00
C	38.56	34.42	37.69	32.30	33.77	34.00	32.90	33.47
F	21.96	33.25	27.02	35.19	32.72	29.42	32.40	31.54
QTZ	-	24.5	32.0	29.2	30.3	25.0	26.5	28.4
PLAG	-	57.1	60.9	56.0	56.7	53.4	53.6	45.8
ORTH	-	18.4	7.1	14.8	13.0	21.6	19.9	25.8

	12	13	14	15	16	17	0263
OR	27.82	30.94	30.09	29.08	34.58	31.02	36.69
AB	49.97	47.09	48.26	50.28	42.45	49.21	52.52
AN	22.21	21.96	21.65	20.64	22.96	19.77	10.79
Q	29.59	28.87	28.31	28.47	34.45	28.15	24.16
OR	25.18	28.20	27.54	26.21	29.43	27.78	31.19
AB	45.23	42.93	44.16	45.32	36.12	44.07	44.65
A	55.74	57.76	58.73	59.04	58.16	59.60	71.84
F	31.66	30.57	28.51	29.27	32.24	29.80	18.37
M	12.60	11.67	12.75	11.69	9.60	10.60	9.80
A	37.51	34.02	35.87	36.72	35.89	34.11	28.36
C	31.50	34.63	33.10	32.76	35.47	33.61	36.06
F	30.99	31.35	31.02	30.52	28.64	32.28	35.59
QTZ	30.8	28.6	28.4	28.4	33.2	28.4	23.7
PLAG	37.4	50.3	53.2	54.6	44.1	50.6	44.6
ORTH	31.8	22.1	18.4	17.0	22.7	21.0	31.7

	R 10	8075P
OR	29.61	29.89
AB	51.72	54.56
AN	18.67	15.54
Q	40.82	42.96
OR	21.55	20.19
AB	37.66	36.85
A	74.00	75.83
F	21.88	16.90
M	4.12	7.26
A	39.09	44.96
C	42.80	34.15
F	18.11	20.89
QTZ	37.0	41.5
PLAG	41.9	40.9
ORTH	21.1	17.6

APPENDIX VIII

COMPUTER PROGRAMS

Program 1 calculates vector mean, vector strength, both the Tukey Chi Square and the Chi Square values and the number of samples. It is the same program as used by Elston and Smith (1970) but it has been modified to read non-grouped data on a VDU.

Program 2 has been devised over the years in the School of Earth Sciences at Macquarie University and it plots a rose diagram of the data and calculates the vector mean, vector magnitude and the % magnitude (= vector strength).

PROGRAM 1

```
C       FLOW LINEATION STATISTICAL ANALYSIS PROGRAM
c       AFTER ELSTON & SMITH (1970) AND BORNHURST(1976)
c
C DIMENSION NECESSARY ARRAYS                VAX-11 FORTRAN V3.1-23
        DIMENSION O(20),TH(20),X(20),TO(20),GRAPH(20),TM(6),SS(6),
        1       SD(6),CL(25),NC(20),LAB(40),LAC(40),PCT(25),
        1       BMARG(20),IWR(18),SUM(6),STOR(100,6),OL(100,18)
        DIMENSION BB(500)
        DOUBLE PRECISION TITLE(8),NSLIDE(100),P,FAC,SPEC
        CHARACTER*15 RECORD
        INTEGER ROC(10),COUNT
        DATA SPEC/'TOTAL'/
        DATA SOLID,BLANK/'XXX',' '/,LAB,LAC/40*' ',40*' '/,
        1       LAC(23),LAC(24),LAC(25),LAC(26),LAC(27),LAC(28),
        2       LAC(29),LAC(30),
        2       LAC(31)/'F','R','E','Q','U','E','N','C','Y'/,
        3       BMARG/20*'I**'/
        DATA LAB(1),LAB(20)/ ' 50','25'/,LAC(11),LAC(12),LAC(13),
        1       LAC(14),
        2       LAC(15),LAC(16),LAC(17)/'P','E','R','C','E','N','T'/
C       READ(ROC(I),I=1,10)
C       PRINT HEADING INFORMATION
        ROC(4)=1
        WRITE(6,203)
203     FORMAT('1',90('*'),/,1X,'*',88X,'*')
        READ(1,201)RECORD
201     FORMAT(1A15)
        WRITE(6,204)RECORD
204     FORMAT(1X,'*',18X,'CHI SQUARE AND VECTOR MEAN DATA',39X,'*',
        1       /,1X,'*',88X,'*',/,1X,'*',27X,A15,46X,'*',/1X,'*',
        2       88X,'*',/,1X,90('*')//)
        REWIND 1
        IF (ROC(3).EQ.0) GO TO 221
        WRITE(6,222)
222     FORMAT('1'///)
221     CONTINUE
        COUNT=0
        STO=0
        IF(ROC(1).EQ.0) GO TO 9
        DO29 I=1,18
29      TO(I)=0.0
9       COUNT=COUNT+1
C       READ INFORMATION ON DATA FILE
        READ(1,100)NSLIDE(COUNT)
100     FORMAT(1A6/)
        READ(1,*,END=7778)( BB(I),I=1,500)
7778    DO 9998 I=1,500
        IF (BB(I).EQ.9999 ) GO TO 9994
9998    CONTINUE
        WRITE(6,7777)
7777    FORMAT('I AM HERE',I7)
9994    I=I-1
C       INITIALIZE FREQUENCY STORE
        DO 9996 KK=1 , 18
9996    O(KK)=0
C       ALTER HEMISPHERE FROM 0 - 180 TO 270 - 90
        DO II=1,I
        IF(BB(II).GT.90)BB(II)=BB(II)+180
```

```
                DO WHILE (BB(II).LT.0)
                BB(II)=BB(II)+180
        ENDDO
                DO WHILE (BB(II).GT.180)
                BB(II)=BB(II)-180
        ENDDO
        KK=INT(BB(II))/10+1
        O(KK)=O(KK)+1
        ENDDO
9997    CONTINUE
C       THIS SECTION CALCULATES,PRINTS,AND STORES STATISTICAL DATA
        DO180 I=1,18
180     OL(COUNT,I)=O(I)
99      XX=5.0
        DO 2 I=1,18
        TH(I)=XX/57.29577951
2       XX=XX+10.0
        R=0.0
C       CALCULATE TOTAL OBSERVATIONS (R)
        DO 3 I=1,18
3       R=R+O(I)
        RR=R/18.0
        CHI=0.0
C       CALCULATE CHI SQUARE (CHI)
        DO 4 I=1,18
        CHI=CHI+((O(I)-RR)**2)
4       X(I)=(O(I)-RR)/SQRT(RR)
        CHI=CHI/RR
        SUM1=0.0
        SUM3=0.0
        DO 1 I=1,18
        BVY=TH(I)*2.0
        SUM1=SUM1+(X(I)*COS(BVY))
1       SUM3=SUM3+(X(I)*SIN(BVY))
        SUM2=2.994
        SUM4=2.994
        C=SUM1/SUM2
        S=SUM3/SUM4
        SC=S/C
        THX=0.5*ATAN(SC)*57.29577951
        IF(THX)15,16,16
15      IF(C.GT.0.AND.S.LT.0.) GO TO 200
        THX=360+THX
        GO TO 20
200     THX=90.0+THX
        GO TO 20
16      IF(C.GT.0.AND.S.GT.0.) THX=THX+270.0
C       CALCULATE TUKEY CHI-SQUARE (X2)
20      X2=C*C+S*S
        THF=THX
        A=0.0
        DO 7 I=1,18
        TH(I)=A/57.295777951
7       A=A+20.0
        SUMS=0.0
        SUMC=0.0
        DO 8 I=1,18
        BVX=TH(I)
```

PROGRAM 2

```
                                                    VAX-11 FORTRAN V2.5-66
      DIMENSION IDATV(500), R(0:360), T(0:360), X(0:360)
      INTEGER IF,TYPE
      CHARACTER*16 NAMAR
      CHARACTER*4 SIZE
      RADIAN=ATAN(1.0)/45.0
      read(7,5) NAMAR
5     FORMAT(A16)
      read(7,10) IF,SIZE,TYPE
10    FORMAT(I2,1X,A4,1X,I3)
      I=1
      DO WHILE (.TRUE.)
              read(7,*,END=30) (IDATV(J),J=I,I+9)
30                    DO  LL=I,I+9
                              L=LL
                              IF(IDATV(L).EQ.9999)  GOTO 50
                      ENDDO
      I=I+10
      ENDDO
50    DO  I=0,359,IF
              T(I)=0.0
              DO  J=1,L-1
                      IF((IDATV(J).GE.I).AND.(IDATV(J).LT.(I+IF)))
      1                 T(I)=T(I)+1.
              ENDDO
      ENDDO
      IF(TYPE.EQ.180) THEN
              DO  I=180,360,IF
              T(I)=T(I-180)
              ENDDO
      ENDIF
      TMAX=T(0)
      TMIN=T(0)
      DO  I=IF,359,IF
              IF(T(I).GT.TMAX)  TMAX=T(I)
              IF(T(I).LT.TMIN)  TMIN=T(I)
      ENDDO
      IF(TMIN.EQ.0.) TMIN=1
      call area(1.,1.)
      IF(SIZE.EQ.'LARG')then
               RADIUS=10.0
              call set_window(2.,2.,2.,30.)
      else
              radius=5.
              call set_window(3.,3.,4.,28.)
      endif
      call origin(13.5,13.5)
      call move(0.,0.)
      SCALE=RADIUS/TMAX
      DO  arad=1.,RADIUS
              call circle(arad)
      ENDDO
      IZ=1
      R1=TMIN*SCALE
      call colour(1)
      DO  I=0,359,IF
              R(I)=T(I)*SCALE
              DO  J=IZ,IZ+IF,1
```

```
                        XP=R(I)*SIN((J-1)*RADIAN)
                        YP=R(I)*COS((J-1)*RADIAN)
                        RX1=R1*SIN((J-1)*RADIAN)
                        RY1=R1*COS((J-1)*RADIAN)
                        call vector(xp,yp,rx1*.85,ry1*.85)
                ENDDO
                IZ=IZ+IF
        ENDDO
        call colour(0)
        SC=0.0
        EC=0.0
        CHI=0.0
        S2=2.994
        S4=2.994
        C=SC/S2
        S=EC/S4
        DO  I=1,L-1
                A=2.*IDATV(I)*RADIAN
                SC=SC+COS(A)
                EC=EC+SIN(A)
        ENDDO
        VA=0.5*(ATAN2(EC,SC)/RADIAN)
        IF (VA.LT.0.) THEN
                 IF(C.LE.0.AND.S.LE.0.) THEN
                        VA=360.0+VA
                                         ELSE
                        VA=VA+90.00
                ENDIF
        ELSE
                IF((C.GT.0.).AND.(S.GT.0.)) VA=VA+270.0
        ENDIF
        VM=(SC**2.+EC**2.)**0.5
        VP=(VM/(L-1.0))*100.0
        XP=RADIUS+.5
        call vector(xp,0.,-xp,0.)
        call vector(0.,-xp,0.,xp)
        XP=XP+0.5
        call csymbol(xp,0.,0.5,'E')
        call csymbol(-xp,0.,0.5,'W')
        call csymbol(0.,-xp,0.5,'S')
        call csymbol(0.,xp,0.5,'N')
        call csymbol(0.,xp+1.5,0.5,namar(:iend(namar)))
        call rsymbol(xp+8.5,xp,0.5,'Frequency interval: ')
        call number(,,0.5,float(if),0.,2)
        call rsymbol(xp+8.5,xp-1.,0.5,'Number of samples: ')
        call number(,,0.5,float(l-1),0.,2)
        call rsymbol(xp+8.5,xp-2.,0.5,'CM per reading: ')
        call number(,,0.5,scale,0.,2)
        call rsymbol(xp+8.5,xp-3.,0.5,'Vector mean: ')
        call number(,,0.5,va,0.,2)
        call rsymbol(xp+8.5,xp-4.,0.5,'Vector magnitude: ')
        call number(,,0.5,vm,0.,2)
        call rsymbol(xp+8.5,xp-5.,0.5,'% Magnitude: ')
        call number(,,0.5,vp,0.,2)
        CALL AREA(0.,0.)
        call exit
        END
```

```
************************************************************************************************
*                                                                                              *
*                      CHI SQUARE AND VECTOR MEAN DATA                                         *
*                                                                                              *
*                              R 62   D Ig                                                     *
*                                                                                              *
************************************************************************************************
```

(A)

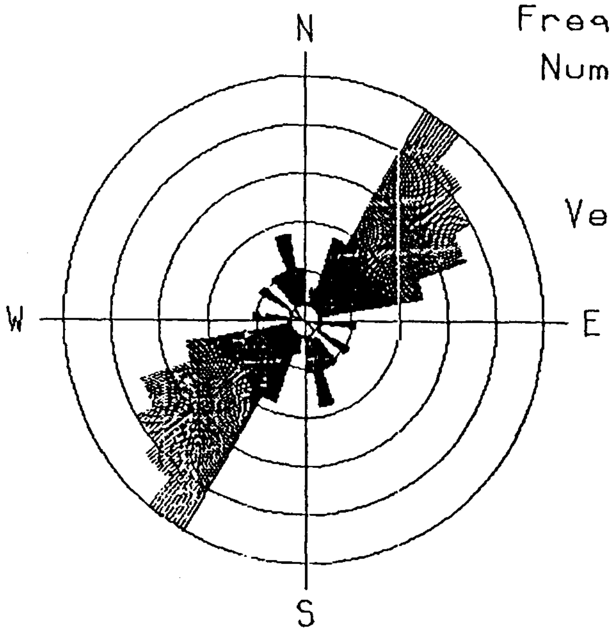
VECTOR MEAN	VECTOR STRENGTH (%)	TUKEY CHI SQUARE	TOTAL OBSERVATIONS	SAMPLE NUMBER
40.65	0.47	37.48	84.00	R 62

CHI SQUARE
68.57

```
R 62  D Ig
10 smal 180
2 16 18 22 22 22 27 27 32 32
32 32 35 35 35 35 36 37 37 38
38 39 42 43 43 45 46 46 47 47
47 48 48 49 50 50 50 51 52 52
53 55 56 57 59 60 60 61 62 62
61 61 64 66 67 71 71 73 74 78
78 79 80 90 92 97 119 121 125 127
140 147 149 150 150 157 161 162 162 163
168 172 178 179 9999
```

(B)

R 62 D Is



Frequency Interval: 10.00
Number of samples: 84.00
CM per reading: 0.36
Vector mean: 45.27
Vector magnitude: 40.08
% Magnitude: 47.72

(C)

(A) The printout from Program 1.
(B) Data file format for both programs on VDU.
(C) The printout from Program 2.