INTRODUCTION

The thesis project investigates a major area of Late Triassic (230-200 Ma) magmatism of southeastern Queensland and adjacent northeastern New South Wales (Fig. 1.1), which corresponds with the 230 Ma initial extension of the Pangean supercontinent and the return after the coal gap to deposition of coal measures after the Late Permian coal gap (Fig. 1.2) (Veevers *et al.*, 1994a). The area of study, the Ipswich Basin, contains a comprehensive volcanic record of this 230-200 Ma extension phase (Veevers *et al.*, 1994a).

1.0 Study Area

The study area encompasses much of the outcropping Ipswich Basin in a 180 x 85 km area centred around Brisbane (Fig. 1.1, inset). Volcanic rocks that occur discontinuously though the area were erupted onto the Palaeozoic basement and form the basal units of the Ipswich Basin. The area has been subdivided into several parts: the Brisbane region in the north, focussing on the Brisbane Tuff; and the area occupied by the Chillingham Volcanics, in the south. Enlarged maps of the Ipswich area, Moreton Island, and Stradbroke Island provide suitable detail of each of these areas. A detailed map of the main area of outcrop of the Brisbane Tuff shows details of the flow lineations and structural data (Fig 2.4). The Chillingham Volcanics have been similarly subdivided so as to provide more detail of the volcanic facies and structure.

Exposure varied from quarries, road cuts, and cliffs in the Brisbane region, to scattered and low outcrop in the rolling hills and cleared pastoral land in the Ipswich area, to limited exposure along water courses and in rare cliffs in the dense rain forest in the Gold Coast - Murwillumbah hinterland.

1.1 Stratigraphic-tectonic setting of the Ipswich Basin

This account is drawn from Veevers et al. (1994a and b).

1.1.1 Along the Panthalassan margin of Gondwanaland

The 230 Ma (Carnian) onset of Pangean extension (Fig. 1.2) includes the start of
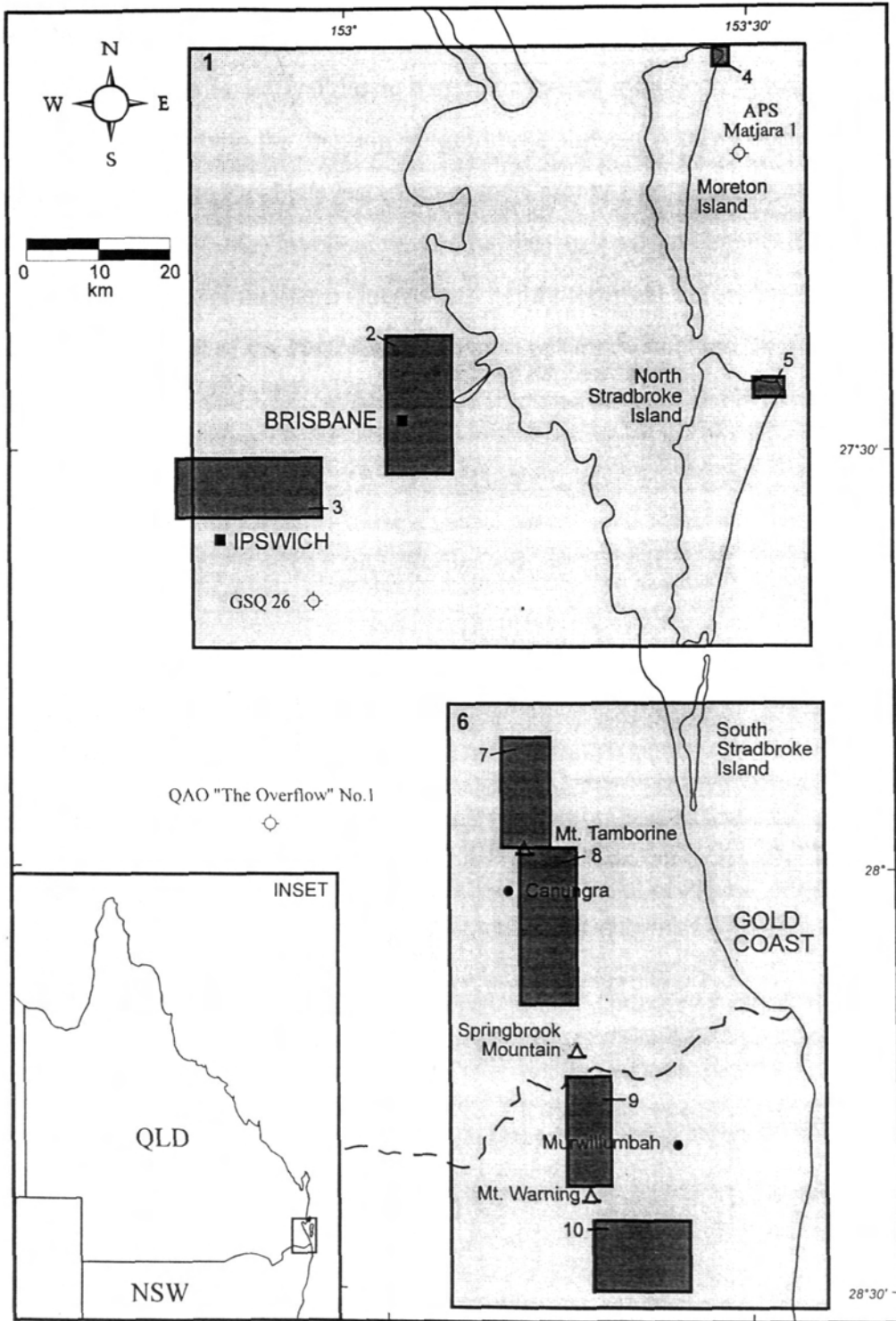
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Figure 1.1 Location of detailed maps. 1 = figure 2.1; 2 = figures 2.4; 3 = figure 4.1; 4 = figure 4.6; 5 = figure 4.8; 6 = figure 3.1; 7 = figure 3.4; 8 = figure 3.5; 9 = figure 3.9; and 10 = figure 3.12.

Veevers *et al's* (1994b) "Stage G" in eastern Australia, represented by the Ipswich Coal Measures, and its felsic and mafic volcanic rocks. Fielding (1996) subscribes this period to the second of his five periods of Mesozoic tectonic activity, namely the "Late Triassic

Extension Phase".

In eastern Australia, Early Triassic magmatic events included the bulk of the New England Batholith with the eruption of ignimbrite sheets (Wandsworth Volcanics) and the main phase of the Rawbelle Batholith in the Cracow-Eungella Mobile Belt. The Middle Triassic (235-230 Ma) involved the preliminary extensional event of the volcanic Esk Trough in southeastern Queensland before terminal deformation (Fig. 1.2) and accompanying uplift of the Panthalassan margin of Gondwanaland, including the New England Fold Belt and adjacent parts of the foreland basin of the Bowen-Sydney Basin.
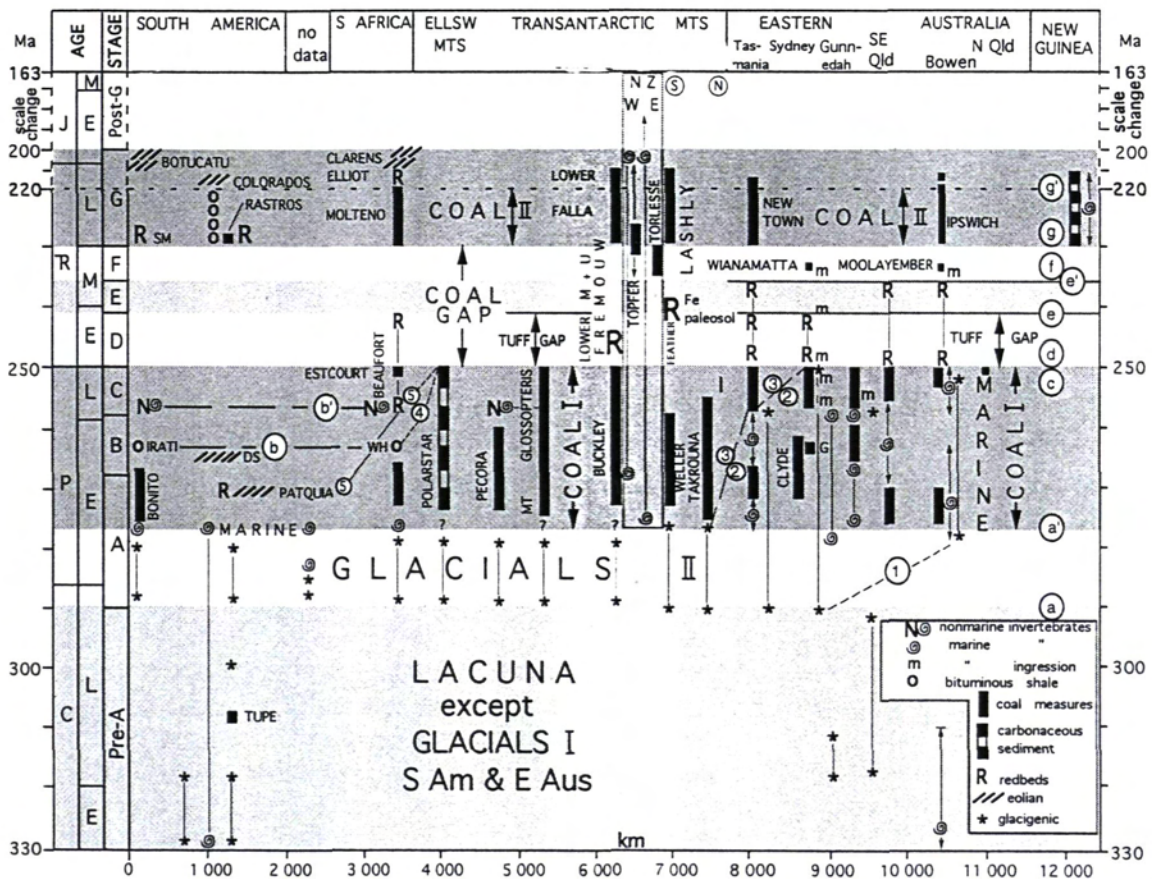

Figure 1.2 Time-space diagram along the Panthalassan margin, from South America to New Guinea during the Carboniferous to Jurassic, showing depositional environments, chiefly the characteristic Gondwanan glacial, coal-forming, and redbed facies, and superimposed marine facies. From Veevers *et al.* (1994b, fig. 3). Ages: J= Jurassic, R=Triassic, P=Permian, C=Carboniferous; L=Late, M=Middle, E=Early. The stages are those proposed by Veevers *et al.* (1994b). The scale on the bottom is the distance along the Panthalassan margin (Fig. 1.3), from South America to New Guinea. Complete details, including abbreviations, are given in Veevers *et al.* (1994b).
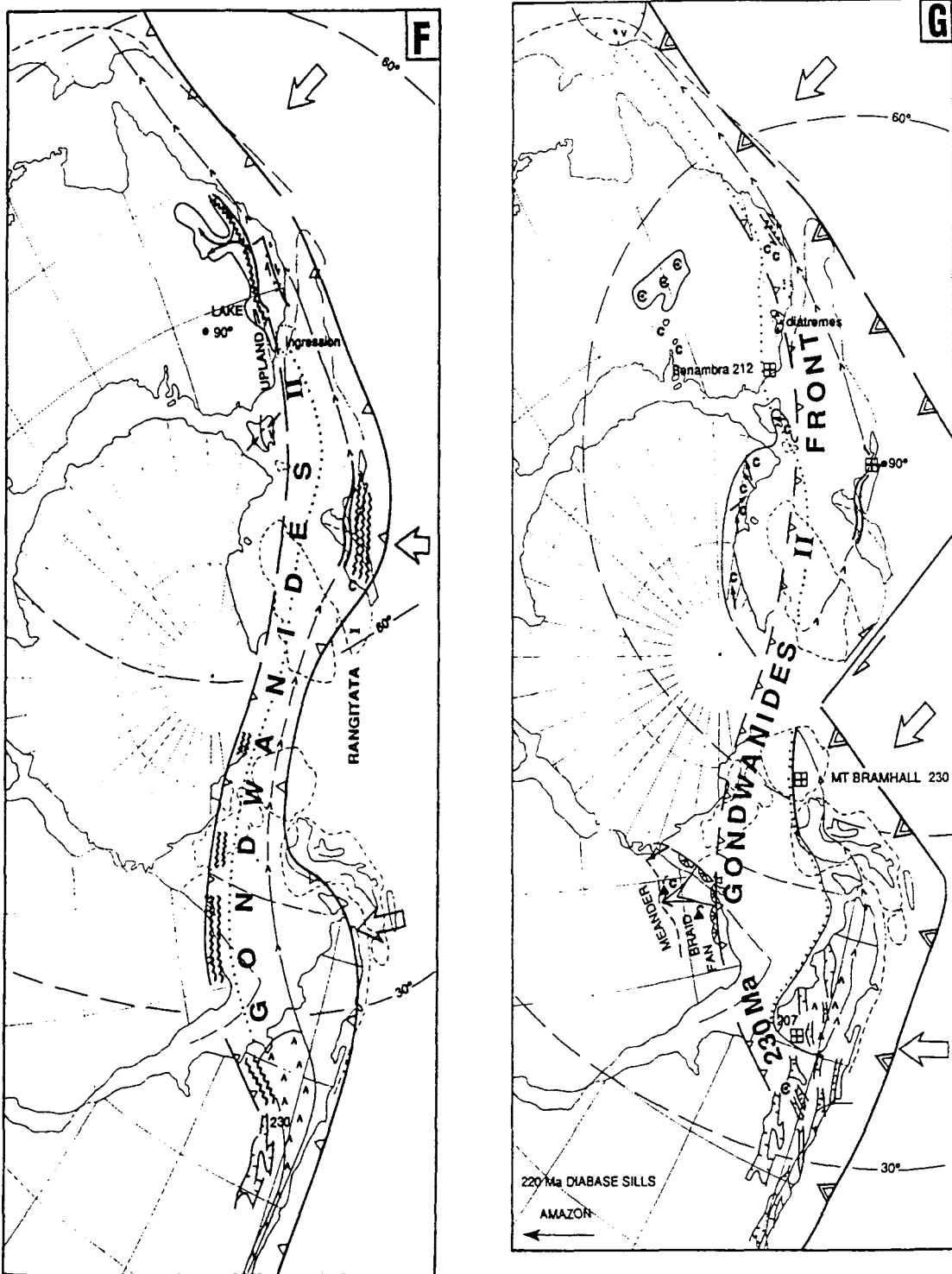
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Figure 1.3 Paleo-tectonic/geographic map of the Panthalassan margin: F (235-230 Ma), with mean pole; and G (230-200 Ma), with pole. The saw-tooth line = deformation, ∧ = felsic volcanics, c = coal, arrows = palaeocurrent vectors. From Veevers *et al.* (1994b, fig. 10 and 11).

The 230-200 Ma extension event marked a continuation of widespread igneous

activity, with local deposition confined to intra-montane fault-bounded troughs,

including the Late Triassic Ipswich Basin which initially accumulated tuff and basalt

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then coal measures, in a return to abundant coal after the coal-free Early and Middle Triassic. Igneous activity elsewhere was widespread (Fig. 1.3). In South America, diabase sills were erupted in the Amazon Basin, and intra-montane rift basins south of 25°S were succeeded by the first part of the Patagonian Chon Aike province of rhyolites and granites, with a date of 207 Ma, and probably extending to the 230 Ma Mount Bramhall intrusion in the Thurston Island block. Storey and Alabaster (1991) interpret the change from Gondwanide compression to lithospheric extension in this region as due to "*a change from shallow to steeply dipping subduction and to a slowing of subduction rates caused possibly by a decreasing age of the subducting plate.*" The postulated shallow dip of the subducting slab (single barbs) in Figure 1.3F passes to a steep dip (double-headed barbs) in Figure 1.3G.

1.1.2 Late Triassic Magmatism in Eastern Australia

Eastern Australia formed a major igneous provience during the Late Triassic (Fig.1.4), with most activity concentrated in southeast Queensland. In addition to the Ipswich Basin, this magmatic activity is represented in Queensland by the Muncon Volcanics (Day *et al.* 1983), Agnes Water Volcanics (Day *et al.* 1983), Aranbanga Beds (Day *et al.* 1983; Stephens, 1986), North Arm Volcanics (Ashley & Dickie 1988; Day *et al.* 1983), and Mount Byron Volcanics (Day *et al.* 1983), together with many plutonic rocks (Table 1.1). Although the majority of these sequences are dominated by felsic rocks, most also contain minor occurrences of mafic rocks as well. In New South Wales, magmatism of a similar age produced the plutons and volcanics in and to the north of the Lorne Basin, including the Werrikimbe ignimbrite.

1.1.3 The Ipswich Basin

The Ipswich Basin is one of the most extensive of the Late Triassic basins in eastern Australia (Fig 1.4), and the Ipswich Coal Measures are the principal fill of the basin, subdivided in the Ipswich area into the Kholo Subgroup and Brassall Subgroup (Fig. 1.5). Volcanism in the Ipswich Basin in confined to the lower Kholo Subgroup and its lateral equivalents.
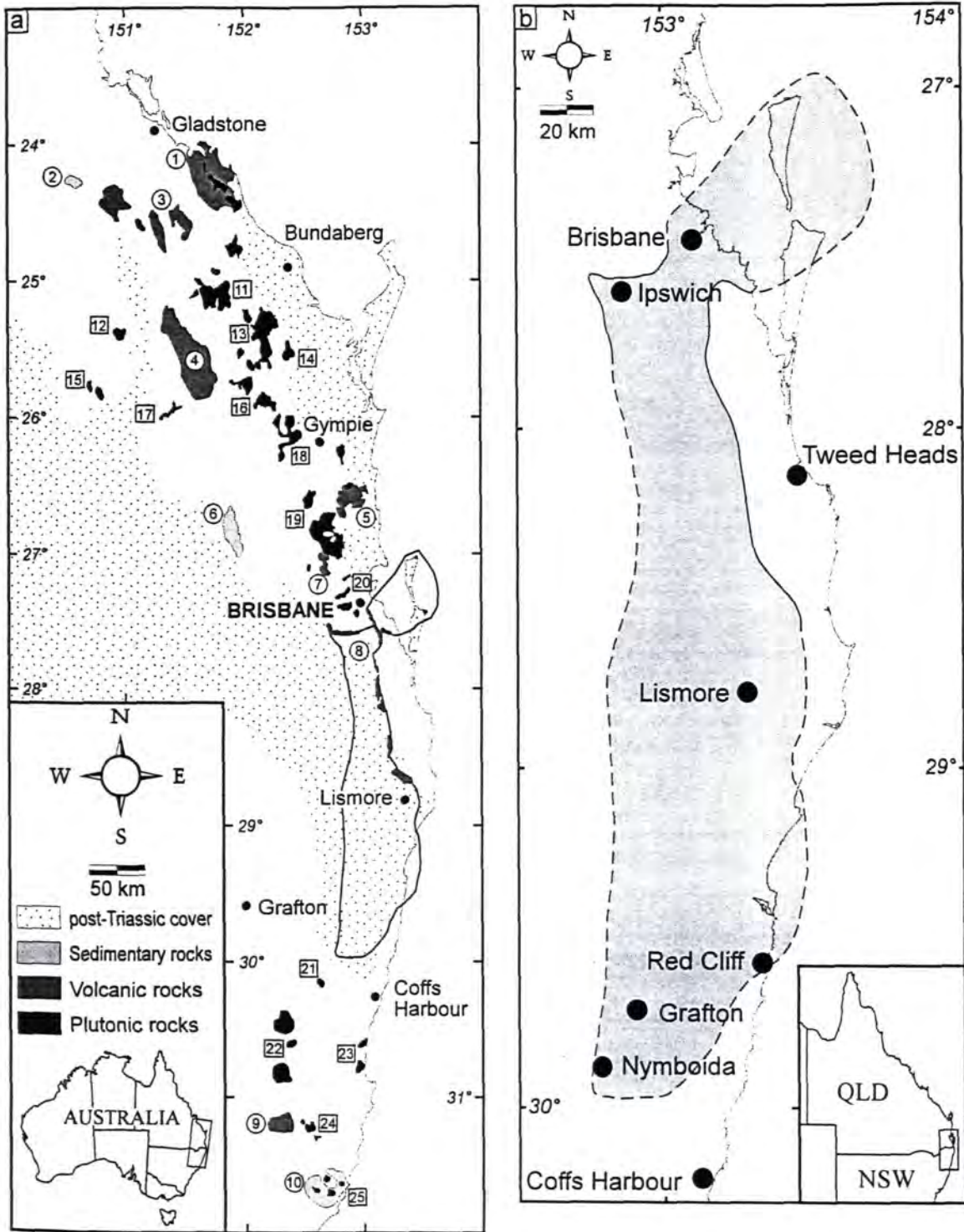
Figure 1.4 a) Distribution of Late Triassic plutonic (boxed numbers), volcanic (circled numbers), and sedimentary rocks (circled numbers), as detailed in Table 1.1, in central-eastern Australia, and the sub-surface extent of the Ipswich Basin (solid line). Data from Day *et al.* (1982), Veevers *et al.*, (1994), and Flood and Aitchison, (1993). b) Inferred sub-surface extent of the Ipswich Basin (after Falkner, 1982).

Table 1.1 Late Triassic plutonic, volcanic, and sedimentary rocks

MAP REF	UNIT	AGE (Ma), METHOD, and REFERENCE
		VOLCANIC AND SEDIMENTARY ROCKS
1	Agnes Waters Volcanics	Day *et al.*, 1982
2	Callide Basin	Floral, Day *et al.*, 1982
3	Muncon Volcanics	Floral, Day *et al.*, 1982
4	Aranbanga Volcanic Group	224.2±1 K-Ar Stephens, 1992; 221 K-Ar Ellis, 1968
5	North Arm Volcanics	217±2 Rb-Sr Ashley & Andrew, 1992
6	Tarong Basin	Floral, Day *et al.*, 1982
7	Mt. Byron Volcanics	228 K-Ar Cranfield *et al*, 1976
8	Ipswich Basin	229, 232 K-Ar Webb & McNaughton, 1978; Floral, Cranfield *et al.* 1989
9	Werrkimbe area volcanics	223.9, 225.4 Rb-Sr S.E. Shaw in Veevers *et al*, 1994, p. 156
10	Lorne Basin	Veevers *et al*, 1994, p. 40
		PLUTONIC ROCKS
11	Hogback Tonalite	228 ± 4 Rb-Sr Cranfield and Murray 1989
12	Boolgal Granite	218 K-Ar Whitaker *et al*, 1974
13	Broomfield Granite	226±16 Rb-Sr Ellis, 1968
	Degilbo Granodiorite	220 K-Ar Webb & McDougall, 1967 226 ±16 Rb-Sr Ellis, 1968
	Tawah Granodiorite	220 K-Ar , Webb & McDougall, 1967 226 ±16 Rb-Sr Ellis, 1968
14	Musket Flat Granodiorite	220, 222 K-Ar Webb & McDougall, 1967 225 Rb-Sr Ellis, 1968
15	Mt Saul Adamelite	219, 220 K-Ar Whitaker *et al*, 1974
16	Mungore Complex	221.8 K-Ar Stephens, 1992
17	Toondahra Granite	215 Whitaker *et al*, 1974
18	Station Creek Adamelite	231 Webb and McDougall, 1967
19	Neurum Tonalite	228 K-Ar Murphy *et al*, 1976
20	Dayboro Tonalite	238 K-Ar Cranfield *et al*, 1976
	Enoggera Granite	224 K-Ar Cranfield *et al*, 1976
	Samford Granodiorite	226/227 K-Ar Cranfield *et al*, 1976
	Mt. Samson Granodiorite	222 K-Ar Cranfield *et al*, 1976
21	Billip Creek Granodiorite	222 -228 Veevers *et al*, 1994, p 68
22	Round Mountain Leucoadamellite	226.4 Rb-Sr S.E. Shaw in Veevers *et al*, 1994, p. 156
	Carrai Adamellite	224.2, 224.4, 226.4 Rb-Sr *ibid*
	Botumburra Adamellite	226.5, 227.8 Rb-Sr *ibid*
23	Valla Adamellite	221.1, 224.7 Rb-Sr *ibid*
	Yarrahapinni Adamellite	222.6, 224.3 Rb-Sr *ibid*
24	Cascade Creek	222.9 Rb-Sr *ibid*
25	Brothers granitoids	205.9, 209.8 Rb-Sr *ibid*

Clarence-Moreton Basin								

Figure 1.5 Stratigraphic relations in the Carnian Ipswich Basin. The Ipswich area is on the left, and Stradbroke Island is on the right. Dark shading indicates mafic volcanic rocks, light shading felsic volcanic rocks.

The oldest known rocks of the basin are a succession of bi-modal volcanic rocks, which include calc-alkaline rhyolites dissimilar to the later rhyolites, penetrated by drill hole GSQ Ipswich 26 (subunits A to E) and APS 1 Matjara (A to D). Subunits F and G and the Moreton Island andesites are correlated with the outcropping Sugars Basalt, Weir Basalt, and Blackwall Breccia of the Ipswich region, as detailed in chapter 4. This early volcanism was probably associated with the initial rifting of the basin.

Coarse clastic sedimentary rocks followed this early volcanism, commencing in the westernmost sections, where the fanglomerates, and fluviatile sedimentary rocks of the Kholo Subgroup (Blackwall Breccia, Mount Crosby Formation, Colleges Conglomerate, and Cribb Conglomerate) were deposited signifying uplift and erosion. Elsewhere little deposition occurred. Extensive rhyolitic volcanism marks the base of the basin near Brisbane and south through to Mount Warning. The principal formations were the dominantly ignimbritic Brisbane Tuff near Brisbane, rhyo-dacitic air-fall tuffs and ignimbrites of the Mount Crosby Formation and Hector Tuff, rhyolitic lavas and pyroclastic rocks of the Chillingham Volcanics, and isolated occurrences of rhyolitic lavas on Moreton and Stradbroke Islands.

The succeeding Brassall Subgroup marks a change to quiescent fluviatile-

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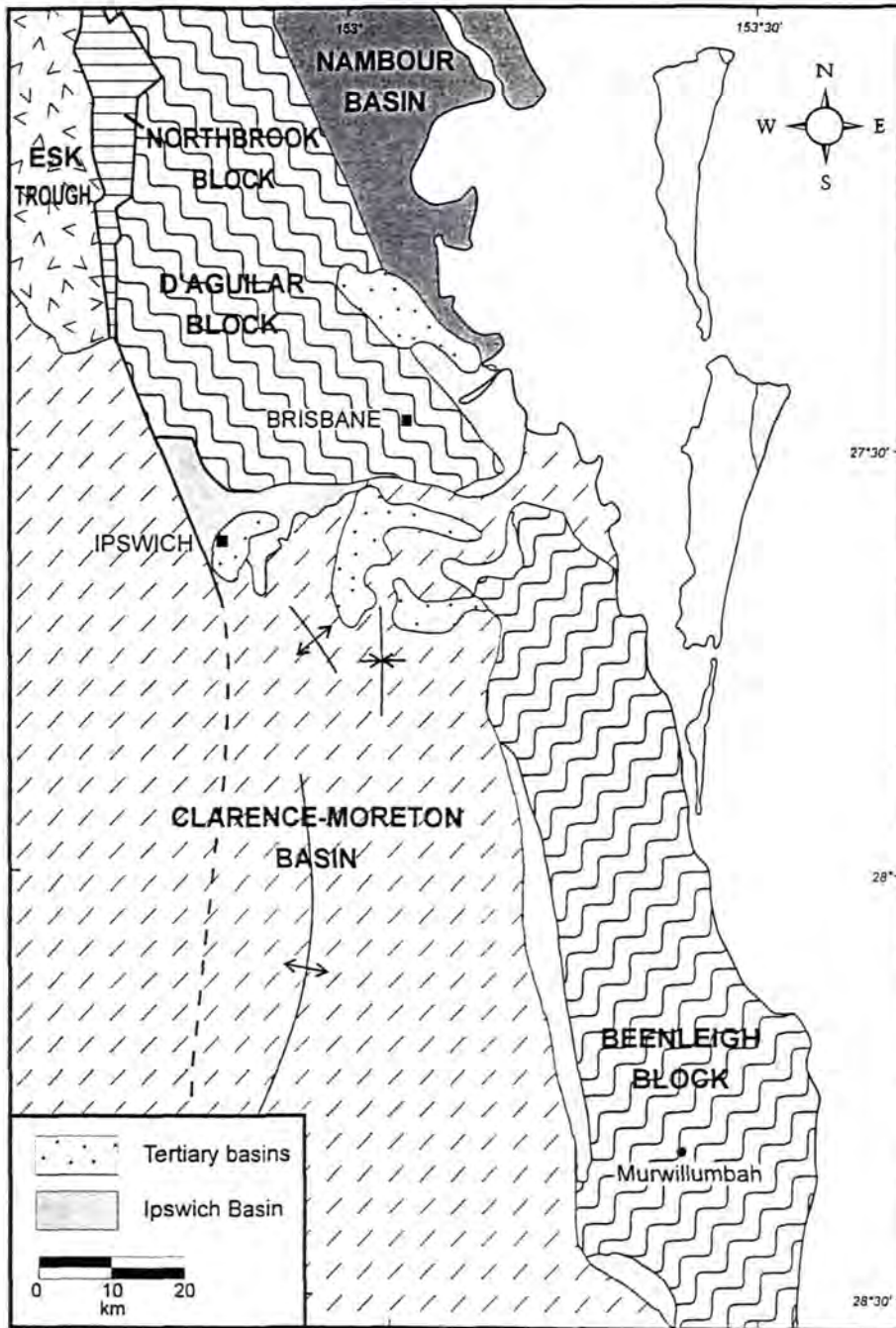**Figure 1.6** Major structural elements (after Whitaker & Green,1980)

lacustrine deposition of the coal measures. Terminal faulting and folding in the late Norian accompanied the formation of the Clarence-Moreton Basin (Fig. 1.6).

1.1.4 Clarence-Moreton Basin

The Clarence-Moreton Basin is an extensive intracratonic basin which succeeded the Ipswich Basin in the Norian to Rhaetian (Cranfield *et al.*, 1989) after a

minor episode of faulting and folding (Day *et al.*, 1982). The basin is dominated by sandstones and conglomerate and contains economic coal deposits. No volcanic rock occur in the Clarence-Moreton Basin. O'Brien (*et al.*, 1994) suggest a similar tectonic regime was responsible for the formation of the Clarence-Moreton Basin as was operating for the Ipswich Basin.

1.2 Nomenclature

1.2.1 Drill Hole Locations

The location of all drill holes discussed in chapters 2, 4, and 6 have been plotted on figure 1.7.
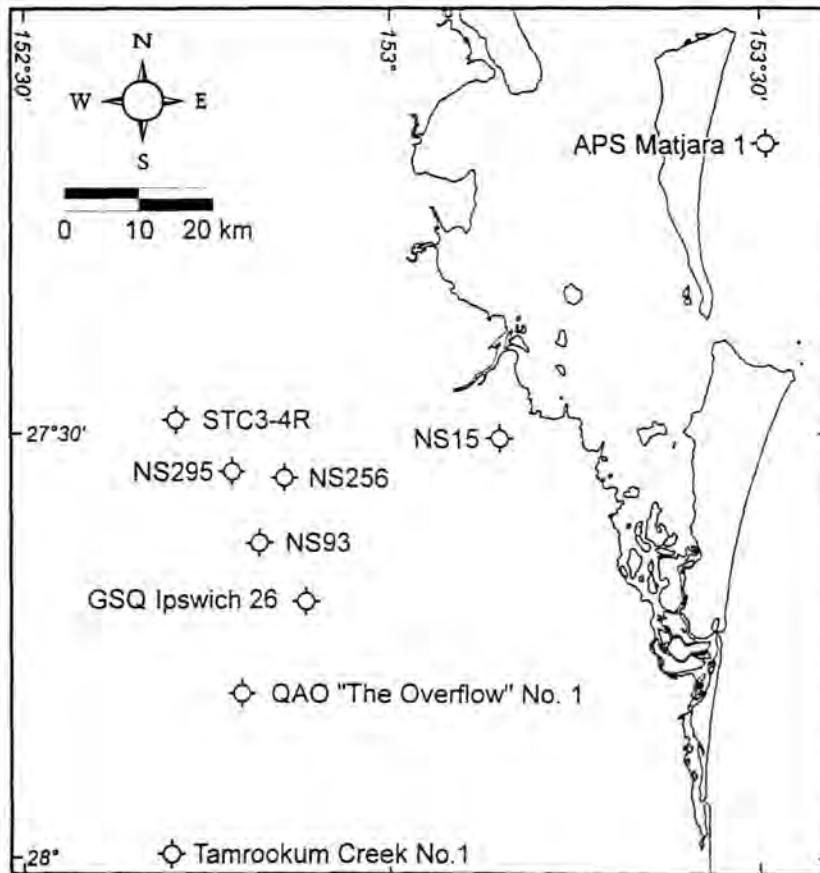

Figure 1.7 Location of drill holes discussed in the thesis.

1.2.2 Map Grid References

Map grid references in the text and on the diagrams in chapters 2, 3, and 4, are Australian Map Grid (AMG) references, part of the Universal Transverse Mercator

(UTM) grid, and all belong to Zone 56. Grid references in the text are quoted in the format of *(GR 4790E, 69654N)*. The first number (4 whole digits) is the easting component of the grid reference, and the second (5 whole digits) is the northing component. One grid reference unit is equal to one hundred metres.

1.2.3 Internal ignimbrite stratigraphy

The ignimbrite facies and internal stratigraphy are described by the standard nomenclature adopted by the volcanology community (Wilson, 1993; Cas & Wright, 1987; McPhie *et al.*, 1993). In this scheme, the ignimbrite is divided into three layers: Layer 1, Layer 2 and Layer 3 (Fig. 1.8). Layer 2 is the ignimbrite flow, Layer 1 (air-fall tuffs and ground surges) pre-dates the ignimbrite flow, and Layer 3 post-dates it. Layer 1 is not always present. Layer 3 includes co-ignimbrite air-fall tuffs formed from the elutriated fine material in the cloud above the flow, and late-stage ash-cloud surges (Cas and Wright, 1987). Due to its unconsolidated nature the preservation potential of layer 3 is low.
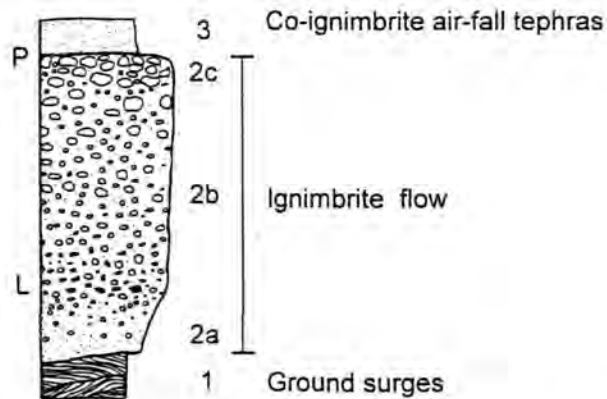
Figure 1.8 The *ideal* internal stratigraphy of a massive ignimbrite deposit similar to the Brisbane Tuff. "L" shows the approximate position of the dense lithic clast concentration zone (dense lithic clasts are drawn filled); "P" the approximate location of the pumice clast concentration zone (pumice clasts are open). After McPhie *et al.* (1993).

Layer 2, the ignimbrite flow proper, is commonly massive, with little or no internal variation except where increased fluidisation in the ignimbrite leads to density segregation or stratification in the flow producing internal layers called a, b, and c. Layer 2a is typically a reverse-graded fine-grained deposit which forms in response to

shearing at the interface between the main flow and the substrate (Mc Phie *et al.*, 1993). Layer 2b commonly constitutes most of the flow, and in ideal deposits will show normal grading of the dense lithic component, and reverse grading in the pumice component, leading to a concentration zone of dense lithic clasts near the base and larger pumice clasts at the top. Layer 2c is seldom preserved and/or formed extension of the upper portion of layer 2b, and is an "upper fines-segregated layer" (Cas and Wright, 1987); it may also contain larger buoyant pumice clasts.

In addition to subdividing an ignimbrite into three layers, Wilson (1980;1993) also classified ignimbrites according to the degree of segregation of clasts, such that Type 1 flows are ungraded deposits; Type 2 flows have a layer 2a base, and a layer 2b with normal grading of the dense lithic clasts and reverse grading of the pumice clasts; and Type 3 deposits have a layer 2a base, a well-segregated layer 2b with sharp boundaries between the concentrations zones, and gas segregation bodies and pipes (Cas and Wright, 1987). The types of flow range from the least fluidised (Type 1) to the most fluidised (Type 3).

I use the term *internal ignimbrite stratigraphy* when referring to the various layers within the one ignimbrite.

1.2.4 Lava Flows and Domes

Rhyolitic lavas, due to their viscosity and differing morphological forms, have been split into two categories, lava flows and lava domes. Lava domes are characterised by greater height/width ratios than flows, occur near the vent region, have inclined flow banding, and more convolutions. Lava flows have much lower width/height ratios, are thinner, are characterised by horizontal or sub-horizontal flow banding which parallels the original topography, and occur further from the vent. In theory, many lava flows have a lava dome originating at the vent, and a transitional area between the two (Fig. 1.9).
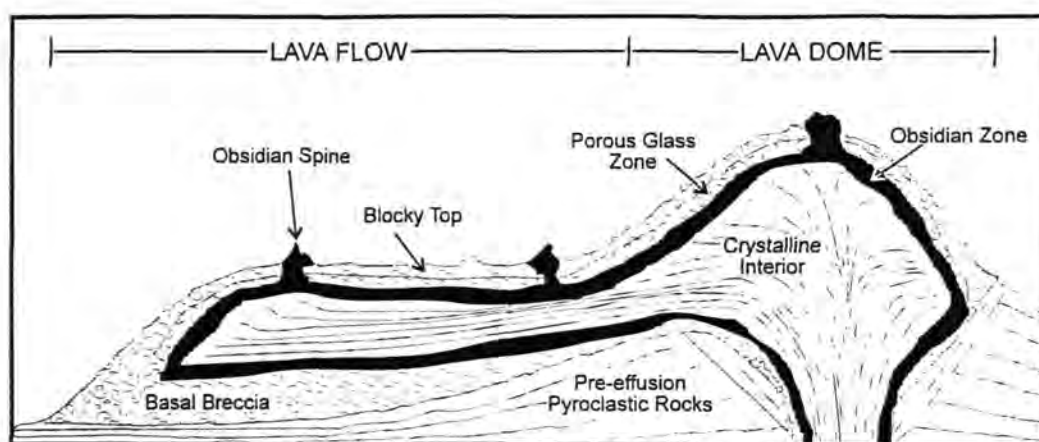
Figure 1.9 Structure of an idealised rhyolitic lava showing the relationship of flows and domes. After Hughes and Smith (1993).

1.2.5 Grain Sizes on Sedimentary Logs

Sedimentary logs use the following abbreviations on their grain scales (left to right, from fine to coarse): M = mud; S = silt; VF = very fine sand; F = fine sand; M = medium sand; C = coarse sand; VC= very coarse sand; G = gravel; P = pebble; and CB = cobble.

1.3 Thesis Format

Following this Chapter 1, introduction, Chapter 2 describes the geology of the constituent rhyolitic ignimbrites of the Brisbane Tuff, with emphasis on the facies relationships and internal stratigraphy of the ignimbrites, the environment of emplacement, possible vent regions, and the location and form of fossil fumaroles.

Chapter 3 describes the rhyolitic Chillingham Volcanics, with a facies analysis of pyroclastic rocks, and lava flows, the relationship between the lava flows and the pyroclastic rocks, and the eruptive history.

Chapter 4 describes the volcanic geology and stratigraphy of volcanic rocks of limited extent in the Ipswich Basin including the basaltic andesitic Sugars Basalt and Weir Basalt; the rhyo-dacitic Hector Tuff and Mount Crosby Formation tuff; rhyolitic lava flows on Stradbroke Island; sub-aqueous mafic lava flows and rhyolitic lavas on Moreton Island; rhyolitic and basaltic andesite lavas and pyroclastic rocks from GSQ26; and noteworthy occurrences of volcanic rocks (both mafic and felsic) at the base of NS93, APS 1 Matjara, and QA No1 "The Overflow".

Chapter 5 describes the trace element and whole rock geochemistry of the Weir Basalt, Sugars Basalt, Brisbane Tuff, Chillingham Volcanics, Mount Crosby Formation tuff, Hector Tuff, GSQ Ipswich 26 subunits E and F, and some plutonic rocks of the South D'Aguilar Block; the pyroxene chemistry of several of the mafic formations; and the isotope chemistry of selected rocks. Conclusions are then drawn as to the tectonic setting of the Ipswich Basin in the Late Triassic.

Chapter 6 comprises a synthesis and conclusions.

Appendix A lists my whole-rock and trace element chemical data, and Appendix B is the CIPW normative data derived from it. Appendix C is a table of previously published whole-rock data from volcanic rocks in the Ipswich Basin. Appendices D and E are my microprobe results from plagioclases and clinopyroxenes. Appendix F is the anisotropy of magnetic susceptibility (AMS) data from the Brisbane Tuff, and Appendix G is the rock-fabric flow-lineation data. Appendix H lists the program for "GCPLOT", used to produce the geochemical plots in the thesis. Appendix I is a table of specimens, their locations and corresponding Macquarie University catalogue numbers.

FACIES ANALYSIS AND FLOW DIRECTIONS OF THE LATE TRIASSIC BRISBANE TUFF: AN ANCIENT VALLEY-FILL RHYOLITIC IGNIMBRITE

The Brisbane Tuff consists of rhyolitic ignimbrite and minor air-fall tuff, conglomerate, breccia, and volcano-lithic arenite, and locally forms the base of the Late Triassic Ipswich Basin around Brisbane. It is overlain by fluviatile-lacustrine sedimentary rocks of the Ipswich Coal Measures. The ignimbrites, which were probably erupted from a single vent over a comparatively short period, were deposited in valleys, and formed a single cooling unit.

2.0 Introduction

The Brisbane Tuff is the basal unit of the Ipswich Basin in the Brisbane area. Petrological and outcrop descriptions of the Brisbane Tuff were contributed by Richards and Bryan (1927) and extended by Briggs (1928), who also provided an overview of the unit. Higginson (1946) described the Brisbane Tuff from a stratigraphic perspective, and redefined the unit to include the basal epiclastic rocks of the Ipswich Basin regardless of their ignimbrite content. Higginson's (1946) misidentification of several outcrops as tuff led to an overestimate of the Brisbane Tuff extent. Bryan and Jones (1960) included in the Brisbane Tuff rhyolitic tuffs outcropping at Numinbah Valley, which subsequent mapping has shown belong to the Chillingham Volcanics. Houston (1967b), during mapping for the City of Brisbane geology series, retained the expanded boundaries of Higginson (1946), and described several additional localities and drill logs from the stratigraphic drilling program of the Geological Survey of Queensland. Cranfield *et al.* (1976) undertook the most recent work on the Brisbane Tuff for the Brisbane 1:250,000 sheet map, and eliminated some non-tuffaceous rocks from the Brisbane Tuff and separated them from the Chillingham Volcanics to the south.

My re-examination of the Brisbane Tuff is made in light of the wider knowledge of silicic volcanism and internal ignimbrite stratigraphy as developed during the past two decades by workers such as Sparks and Walker (1977), Fink and Schmincke (1984), Cas and Wright (1987), McPhie *et al.* (1993), and Wilson (1993), and the development

of techniques for measuring flow lineations in ignimbrites (Elston and Smith, 1970; Ellwood, 1982). This chapter sets out to describe the internal facies relationships of the ignimbrites of the Brisbane Tuff, its fumaroles, mechanisms of eruption and emplacement, the palaeo-environment into which it was emplaced, and potential vent locations.

2.1 Geological Framework and Tectonic Setting

2.1.1 Age of the Brisbane Tuff

No published radiometric age data are available for the Brisbane Tuff, and the new data presented in chapter 5 indicates that the Rb/Sr system would not be appropriate for defining an age, therefore it is felt that the greatest potential for getting an accurate radiometric age for the Brisbane Tuff lies in a U/Pb zircon date. On the basis of plant fossils, de Jersey (1972) found that the Brisbane Tuff and the overlying Kholo Sub-Group of the Ipswich Coal Measures occupy the same biozone of Carnian (Late Triassic) age. The overlying Clarence-Moreton Basin is Norian-Rhaetian (Latest Triassic) and younger.

2.2 Distribution

The Brisbane Tuff crops out over a distance of 60 km between Narangaba in the north, to Redland Bay in the south (Fig. 2.1), with most outcrops within a 10 km radius of the city of Brisbane. In outcrop, the Brisbane Tuff ranges in thickness up to 40 m at the Kangaroo Point Cliffs (Plate 2.1) along the Brisbane River. Thicker sections, such as the 300 feet (96 m) reported by Briggs (1928), 700 feet (225 m) (Bryan and Jones, 1960), and 250 m (Cranfield et al., 1976), probably include rocks other than the Brisbane Tuff: a) younger non-tuffaceous beds, formerly known as the "Aspley Phase" of the Brisbane Tuff, and now considered to be part of the Ipswich Coal Measures; and b) conglomerates which are now believed to be Quaternary alluvium (Chris Stephens, *pers. comm.* 1992). Smith (1960) estimated the volume of the Brisbane Tuff as approximately 100 km^3, but this figure includes rocks now known to be the Chillingham Volcanics.
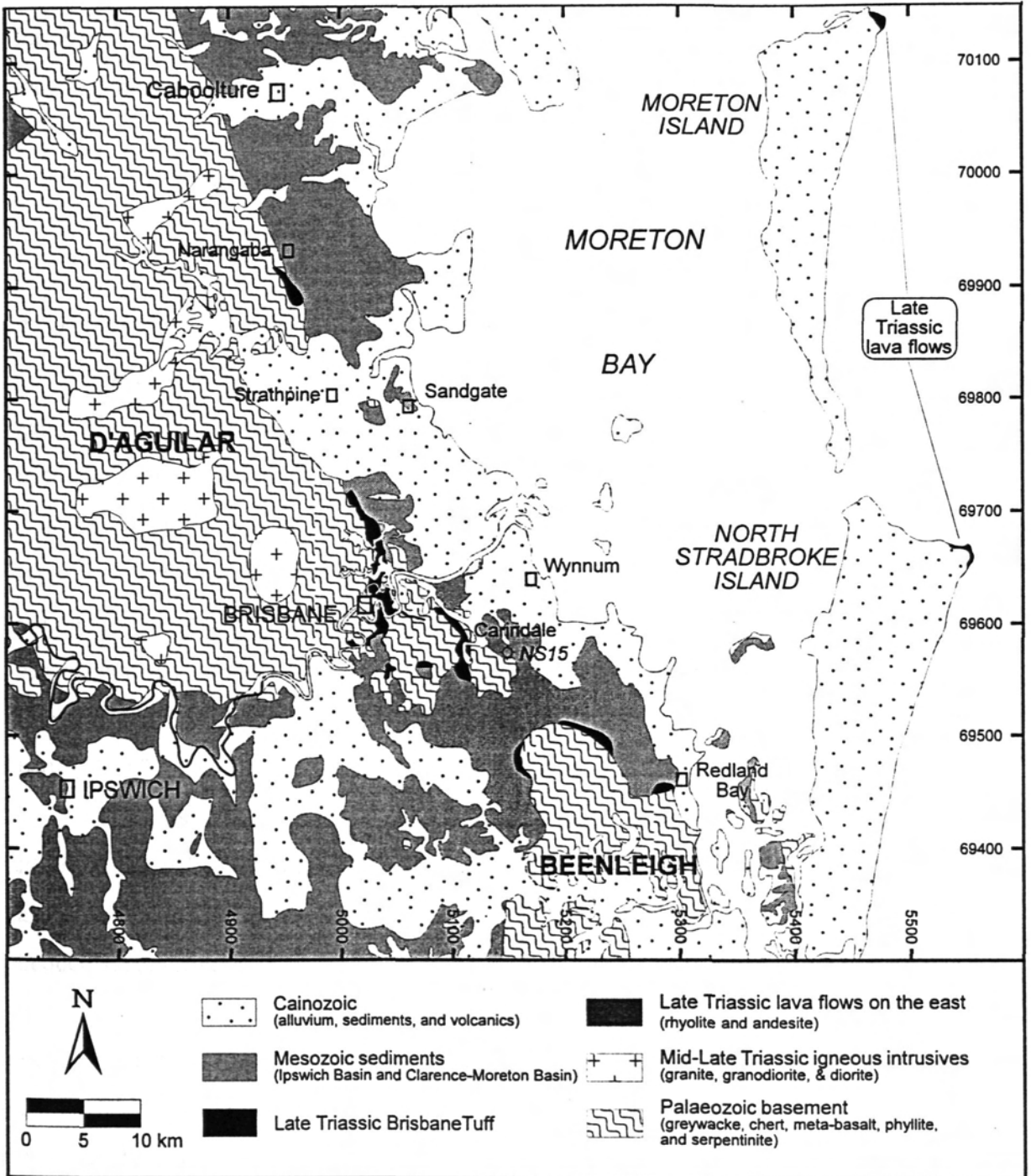
Figure 2.1 Distribution of the Brisbane Tuff and other Triassic igneous rocks of the Brisbane region. (Base taken from Moreton Geology 1:500,000 sheet, Whitaker & Green, 1980)

2.3 Facies Analysis

The base of the Brisbane Tuff overlying the Palaeozoic basement is commonly marked by a thin layer of breccia clasts composed of the local basement. Clasts are sub-rounded to angular, unsorted, and set in a muddy matrix. Most of these layers have been

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interpreted as Triassic regolith or scree on which the ignimbrite was deposited. Three facies of the Brisbane Tuff overlie the breccia:

        1) Ground-surge deposits;

        2) Air-fall tuff deposits; and

        3) Ignimbrites.

2.3.1 Brisbane Tuff: Layer 1 Deposits and Precursory Air-falls

Layer 1 deposits and precursory air-fall deposits at the base of the ignimbrite are generally less than 2 m thick. Ground surges are preserved at the contact with basement in the Kedron area (GR: 5022E, 69682N), Chermside (GR: 5019E, 69693N), Windsor (GR: 5030E, 69660N), and Spring Hill (GR: 5023E, 69628N). The surge layers are typically comparatively crystal-rich, and also contain abundant charcoal, but are deficient in lithic clasts. The ground-surge horizon is commonly thin, with individual surges typically thinner than 5 cm. Surges usually have poorly defined cross beds, except at a disused quarry at Windsor (GR: 5030E, 69660N), where prominent cross beds (Plate 2.2) indicate a local flow direction towards 150°.

The cross-bedded deposits are interbedded with massive silicified crystal-rich layers and stratified tuffaceous layers, interpreted as either non cross-bedded surges or air-fall tuffs. At Chermside, several thin layers in this interbedded zone contain cross-bedded surges (Fig. 2.2). At Spring Hill, numerous poorly defined surge layers are each no more than 5 cm thick. Reports of a well-stratified "wind-laid" tuff at the base of the Brisbane Tuff, containing fossil trees and charcoal by Bryan and Jones (1960) and Higginson (1946) probably refer to this ground-surge layer, the cross beds having been mistaken for aeolian ripples in a "wind blown tuff".

Air-fall tuff deposits (or possibly planar bedded surge deposits), commonly exhibiting mantle bedding, also underlie the main ignimbrite body. They are typically crystal-rich, and commonly silicified, and often well bedded (Fig. 2.2; Plate 2.3). Some of these air-fall tuffs contain conspicuous charcoal (Plate 2.4), and many are associated with ground-surge deposits. At Kitchener Road and in a quarry at Windsor, rare air-fall tuff beds which are highly indurated and appear superficially similar to welded ignimbrite occur below the main ignimbrite and may have been welded. These tuffs

exhibit mantle bedding and have chaotic non flow like textures dissimilar to ignimbrites in that they lack the obvious bedding-parallel eutaxitic texture of the ignimbrites, and phenocrysts show no apparent flow parallel orientation. The beds are too thin (< 25 cm) to allow for self-welding, and it is more likely that they were just originally vitric-rich air-fall tuffs which have become highly indurated.
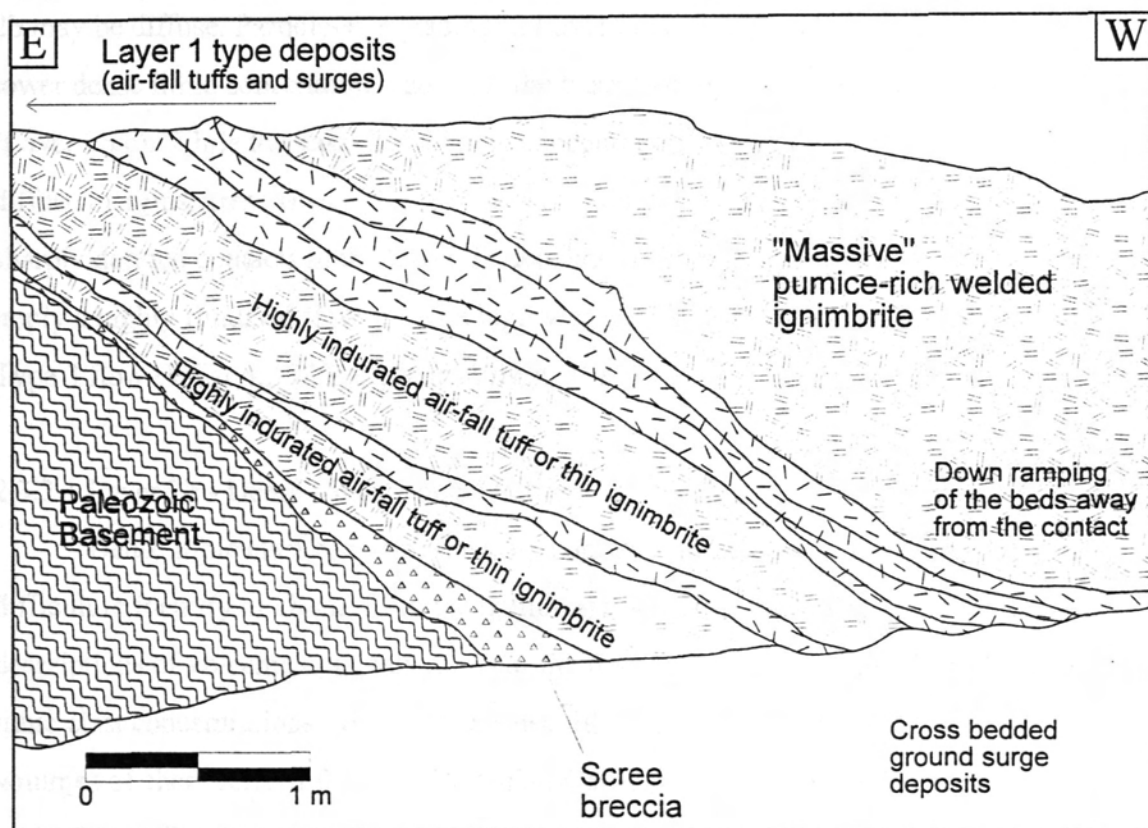

Figure 2.2 Sketch of the contact between the Brisbane Tuff and basement at Kitchener Road (*GR: 5022E, 69682N*). The stratified deposits below the main ignimbrite include cross and planar bedded ground surges, highly indurated air-fall tuffs or thin ignimbrites, and a scree deposit.

Richards and Bryan (1927) reported accretionary lapilli tuff in the lower portions of the Brisbane Tuff at several localities. Their accounts of the lapilli are not specific enough to conclude whether it is part of the ignimbrite body or part of the underlying layer 1 deposits, however, most of the reported localities of accretionary lapilli are in outlying areas dominated by air-fall and reworked tuffs. The lapilli formed when distal ash clouds encountered rain. In come cases these accretionary lapilli may have been further concentrated by alluvial/fluviatile processes, and preferentially preserved in the re-worked outlying sequences, as has been observed in modern examples (McPhie *et al.*,

1993).

2.3.2 Layer 2 Deposits

Layer 2 deposits are well developed in the ignimbrites of the Brisbane Tuff. Some outcrops have a recognisable Layer 2a, but the contact with the overlying Layer 2b may be diffuse. Particle-size grading in Layer 2b is common, though subtle, with lower dense lithic concentration zones at the base grading into pumice-rich layers (Layer 2b/c). While the basal dense lithic concentrated zones of Layer 2b usually have diffuse margins, areas where pumice clasts are concentrated (Layer 2b/c) often form sharply defined contacts in the Layer 2b deposits. The grading and the lithic-clast trains imply a highly fluidised flow, either a highly energised Type 2 or a poorly energised Type 3 flow (Wilson, 1993; Cas and Wright, 1987) .

2.3.2.1 Layer 2b - Dense Lithic Concentration

Dense lithic clast concentrations are common in the Brisbane Tuff but may be difficult to identify or absent from the ignimbrite. Richards and Bryan's (1927) descriptions of volcanic agglomerates near the base match those of the observed dense lithic clast concentrations. Most of the dense lithic clasts are schist, phyllite, and lesser volumes of chert derived from the Devonian-Carboniferous Neranleigh-Fernvale Beds or the Bunya Phyllite. Rare clasts of rhyolitic lava and ignimbrite, presumably co-genetic, have also been identified, although they are typically less than 1 cm in size. Briggs (1928) found clasts comparable to the Palaeozoic Rockseburg Greenstone, but gave no locality description. No plutonic igneous rocks are known as clasts.

Clasts in the layer 2b dense lithic rich concentration zone are typically < 10 cm across, with a few > 100 cm across (Plate 2.5). Chert clasts are typically the smallest (pebble sized) and well rounded; phyllite and schist clasts are angular and cobble sized. The largest clasts (>50 cm) are chert. Many of the clasts have yellow, pink, or less commonly red, white, or green, metasomatic aureoles approximately 0.5 to 2 cm wide surrounding them, suggesting hydrothermal and low-grade metamorphic alteration during emplacement. The basement rock onto which the tuff was erupted is largely composed of phyllite and schist with little or no chert, so the incorporation of the chert

into the ignimbrite flows may have occurred at or near the vent.

Lithic clasts derived from the Palaeozoic basement occur through the entire ignimbrite, but become sparse and smaller (on average < 1 cm) towards the top.

2.3.2.2 Layer 2b/c - Pumice Clast Concentration

Large pumice clasts are common except in the lowermost, dense lithic-clast rich layers, where they are comparatively sparse. The degree of flattening of the large pumice clasts, together with their abundance, varies widely. In the highly welded sections of the ignimbrite the recognition of smaller pumice clasts becomes possible only in thin sections where they are defined by areas of relic bubble-wall structures and domains of irregular grains.

Three different types of pumice clasts have been recognised:

1) non-porphyritic;

2) porphyritic in quartz and felspar; and

3) porphyritic in quartz and biotite.

In any one outcrop only one of the above types of pumice clast are apparently present, to the exclusion of all other types. Most common are the non-porphyritic pumice clast. The porphyritic quartz and biotite pumice clasts have only been recognised in the ignimbrites in the Carindale area. The three types of pumice clast could indicate:

1) that the magma vesiculated at different depth stages of the eruption thus tapping the same magma with varying degrees of crystallisation in the groundmass of the pumice;

2) magma bodies of slightly different composition (by zonation of a common magma) were responsible for the generation and eruption of each pumice type; or

3) different magma bodies associated with different eruptions produced each of the different pumice types.

Regardless of which mechanism operated, the production of three kinds of pumice clast infers multiple ignimbrite eruptions, or at least separate flows.

Red to purple alteration colours, thought to indicate vapour-phase haematitic alteration, are associated with pumice-rich areas. Alteration occurs commonly as distinct haloes around the pumice clasts or by haematitic alteration of the entire pumice-rich section. Briggs (1928, p. 153), describing inclusions in the ignimbrite, noted that "*In some cases there is no definite arrangement, while in others there is a distinct tendency towards parallelism. The latter is often exhibited by the soft powdery spots which occur in the pink variety*". Although Briggs did not recognise the inclusions as pumice clasts, she is clearly describing the pumice clasts with their frequent association with the haematitically altered rocks.

2.3.2.3 Dense Lithic Clast Trains

At several localities, larger (up to 5 cm) clasts of dense lithic material have been preferentially arranged in linear concentration zones in thin (< 25 cm) horizons. These horizons are several metres long and are discontinuous, possibly having a lens-like geometry. The clasts have their long axes aligned parallel with bedding. The lenses only show a slight concentration of the lithic clast component when compared with respect to the host rock, which is a layer 2b facies. Similar arrangements of lithic clasts have been noted in modern ignimbrites, some of which have been interpreted as being related to segregation pods.

Wilson (1993) interpreted segregation pipes and pods in ignimbrites as due to fluidization during flow, and views them as having formed when most of the fine constituents of the ignimbrite were elutriated off leaving only coarser material, and compares these zones with material accumulating in the layer 2a facies of the ignimbrite.

2.3.3 Possible Layer 3 Deposits

Overlying the ignimbrite is a rarely preserved section of tuff comparatively free of lithic fragments. This tuff lacks both large pumice and dense lithic clasts, and is commonly crudely stratified. It may represent a co-ignimbrite air-fall tuff formed by finer material elutriated from the main body of the ignimbrite as a fine cloud, fluviatile reworking of air-fall tuffs or ignimbrites, or the layer 1 deposits of an overlying flow.

Deposits of co-ignimbrite air-fall tuff are characteristically enriched in fines, and the host ignimbrite has a complementary degree of crystal enrichment (Wilson 1993; Sparks and Walker, 1977). The ignimbrites of the Brisbane Tuff show varying degrees of apparent crystal enrichment, which is consistent with the loss of fines by elutriation during eruption and emplacement. The degree of crystal enrichment is difficult to assess because of compaction and welding. The possibility exists that the crystal enrichment observed in the ignimbrite is only an artificial concentration caused by the compaction and welding of the fine vitric component. Wilson (1993) notes that co-ignimbrite fall deposits are typically enriched in fines, but also points out that these deposits would not be dissimilar to those produced by a conventional fall deposit fed by a buoyant plume, with a similar degree of enrichment in the distal parts of the flow.

Other interpretations of the possible layer 3 deposits are that they are air-fall tuffs from the same eruption, but unrelated to the ignimbrite itself, or air-fall tuffs from unrelated eruptions.

The lateral extent of these air-fall deposits may have been greater than that of the ignimbrite itself. Several occurrences of tuffaceous sandstone recorded by Higginson (1946) can be interpreted as either air-fall tuffs, or more commonly re-worked air-fall tuffs. Higginson, (1946) grouped this material with the Brisbane Tuff probably based on its stratigraphic position immediately above the Palaeozoic basement.

2.3.4 Distal Air-fall Facies

Many of the outlying occurrences of the Brisbane Tuff are composed of air-fall or re-worked material, with no ignimbritic material preserved, if ever deposited. Isolated outcrops at Pine Mountain, Tarragindi, and further south-east near Redland Bay, are dominated by re-worked tuffs, and air-fall tuffs. Richards and Bryan (1927) also report accretionary lapilli in some of these areas. Further afield, on Moreton Island, tuffaceous (non-ignimbrititc) rocks are interbedded with sedimentary rocks of the Ipswich Basin. These easterly deposits, probably at the same stratigraphic position as the Brisbane Tuff, may represent distal air-fall tuffs and re-worked detritus.

2.4 Welding

Most ignimbrite from the Brisbane Tuff is welded. Thin-section studies indicate that welding ranges from moderate to extreme. The less welded samples (Plate 2.13) contain numerous relic structures of complete bubble walls, pumice clasts, and individual shards. Compaction is minimal, with pumice clasts showing little or no obvious flattening. Secondary (vapour phase) crystallization of feldspar commonly overprints the original pumice porosity.

In the most intensely welded samples (Plate 2.16), many of these features have been totally obscured by the welding and compaction, with only the eutaxitic welding textures preserved. Perlitic cracks (Plate 2.15) in the groundmass of the most intensely welded samples indicate original compacted glassy character of the groundmass. Spherulitic devitrification products are common (Plate 2.14), and granophyric intergrowths also occur.

The degree of welding in ignimbrites is a function of both ignimbrite thickness, and distance from vent (Briggs, 1977). While it was not possible to construct a welding profile for the Brisbane Tuff because of outcrop limitations, several trends concerning the welding in the ignimbrite did emerge. In the Brisbane Tuff, the most intensely welded sections occur in the thickest part of the main body between Chermside and Kangaroo Point. The least welded samples occur in the northernmost outcrops, at Narangaba, where it is thin. The typically less extensive welded ignimbrites at Carindale is probably caused by the smaller thickness of the unit there.

2.5 Evidence for Multiple Ignimbrites

Many lines of evidence, both direct and indirect, point to the Brisbane Tuff being composed of more than one ignimbrite flow.

Interbedded fluviatile sedimentary rocks (Higginson 1946; Houston, 1967b; Cranfield *et al.*, 1976), layers of accretionary lapilli air-fall tuff (Richards and Bryan 1927), weathered layers (Houston, 1967b), and air-fall tuff in the ignimbrite provide the best direct evidence for multiple ignimbrites, but these outcrops, mainly exposed in now in-filled quarries or subsequently urbanised areas, are no longer available for inspection. Many authors refer to an upper and a lower tuff separated by conglomerate. Houston

(1967b) furthered this idea by correlating the Mount Crosby Formation and Hector Tuff of the Ipswich Group with the lower and upper tuffs of the Brisbane Tuff respectively. The presence of this conglomerate is not certain, as the few areas remaining which still have outcrops of this sequence separated by the interbedded conglomerate layer which I have been able to investigate have proved to be either a result of miss-identification of overlying sedimentary rocks, or a repetition of the succession. The only exception occurs in a quarry at Chermside (GR 5017.5E, 69698N) where a breccia/conglomerate layer with a tuffaceous matrix in an inaccessible wall of the quarry overlies a distinctive layer 2b/c pumice concentration zone. The breccia is overlain, in turn, by an ignimbrite. This breccia is probably a layer 2b lithic concentration zone of a second ignimbrite.

In the same quarry, occupying a higher bench, a large pumice clast-rich layer (interpreted as a layer 2b/c facies) is overlain at a diffuse contact by a more crystal-rich layer with comparatively fewer and smaller pumice clasts. If the overlying layer is a poorly defined layer 2a facies or the layer 2b of an ignimbrite lacking a well defined layer 2a, then it indicates the presence of two ignimbrite flows. Together with the other ignimbrite (separated by an inferred layer 2b lithic concentration zone), the quarry therefore contains at least three ignimbrite flows forming a single cooling unit.

Ignimbrites at Carindale contain distinctly different pumice clasts from those in the main body of the Brisbane Tuff. The unit is also apparently quite crystal-rich, indicating that the rocks here may have been formed by a different eruptive pulse.

Houston (1967b) provided the only detailed drill logs through the Brisbane Tuff. NS15 (Fig. 2.3) possibly has two ignimbrite bodies. The material from this drill hole is no longer available for inspection, but notes annotated in Houston's (1967b) drill log indicate a possible layer 2b dense lithic concentration zone at the base of the lower ignimbrite, together with possible layer 1 pre-ignimbrite air-falls and surges. Towards the top of the drill hole, a conglomerate separates the lower and upper ignimbrites. The drill log shows "tuffaceous conglomerate" at the base of the upper ignimbrite, which probably represents the basal layer 2b deposits of the second ignimbrite.

Composite stratigraphic logs from the Brisbane Tuff provide additional evidence of multiple ignimbrites. At Love Street Spring Hill (GR 5023E, 69628N) (Fig 2.4b) surge deposits of the basal Brisbane Tuff occur at the stratigraphic base of a large
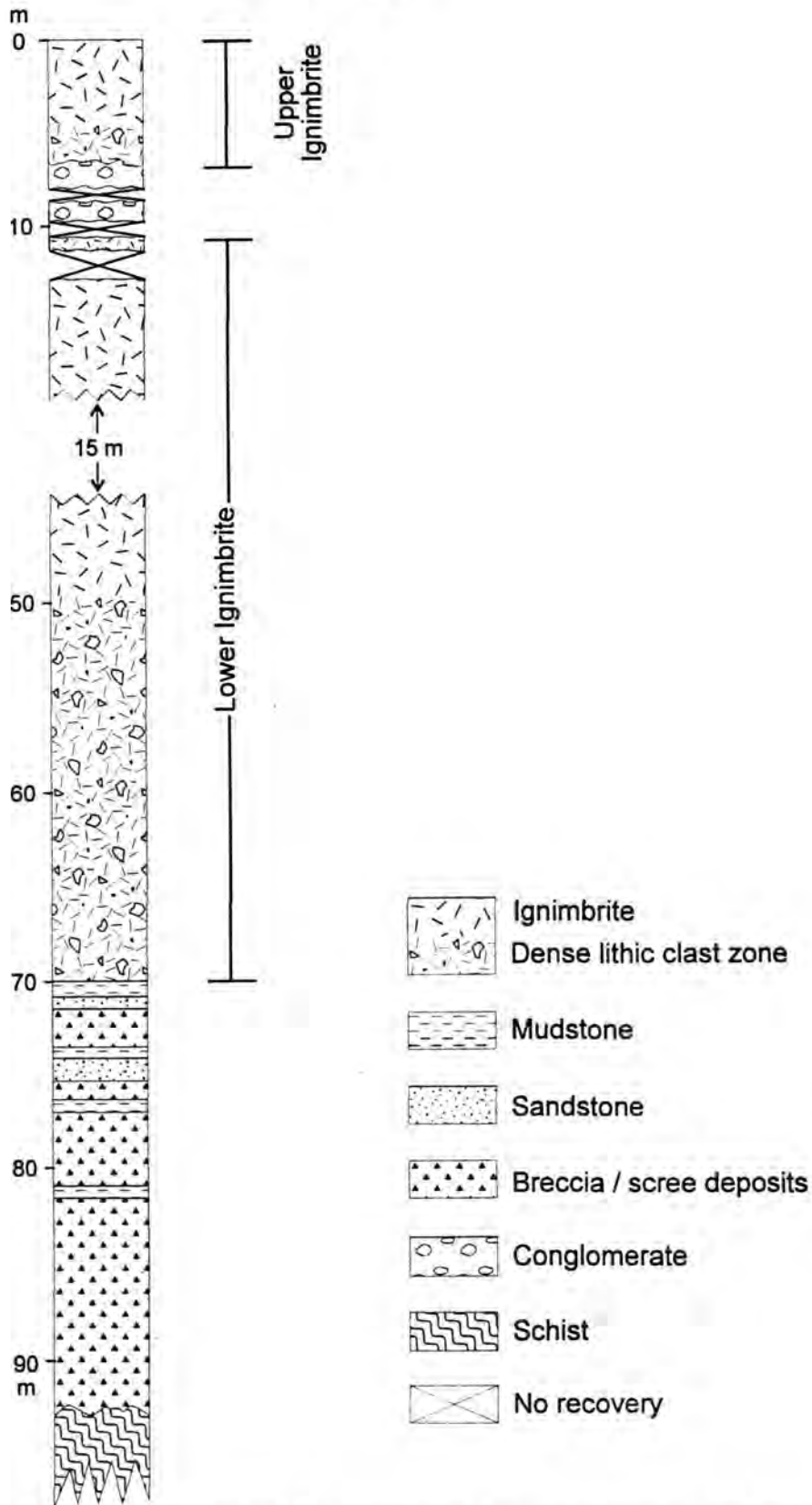
Figure 2.3 Stratigraphic column of the Brisbane Tuff in Geological Survey of Queensland drill hole NS15 (City of Brisbane Series), reinterpreted from Houston's (1967b) drill log and notes. I recognise two ignimbrites from Houston's (1967b) descriptions of conglomerate beds (= two distinct layer 2b dense lithic clast concentration zones), interpreted as marking the base of two ignimbrites. NS15 located on figure 2.1.

outcrop. The stratigraphic top of the outcrop is marked by a poorly defined layer 2c pumice concentration zone, possibly overlain by a layer 3/1a air-fall facies. Topographically and stratigraphically higher outcrops in an adjacent street 200m north show the preservation of layer 2a/b facies inferring the presence of an addition ignimbrite.

Inferred multiple ignimbrites occur at the Kangaroo Point cliffs in an abandoned quarry where the lower bench has layer 2b/c facies and the upper bench has layer 2a/b facies. The large fumarole at Kangaroo Point appears to have been covered by a later (and smaller) ignimbrite flow at its top.

Houston (1967b) reported the occurrence of "weathered horizons" in outcrops of the Brisbane Tuff, but did not record their localities. These "weathered horizons" signify a time break of some duration between eruptions, but no such weathered zones were recognised in the presently available exposures during this investigation. The outcrops studied indicate that the Brisbane Tuff occurs as a single cooling unit, so that the break between eruptions must have been short enough for the ignimbrite to have retained its heat. Charcoal that is conspicuous in the lower portions of the ignimbrite and surge layer indicates the mass destruction of vegetation during the early eruptions. The upper ignimbrites lack significant amounts of charcoal, suggesting that any re-vegetation between eruptions was weak, and that subsequent eruptions were not sourced from vents in different vegetated areas.

2.6 Evidence of Fumarolic Activity

Fumaroles are frequently associated with ignimbrites, and are commonly recognised in modern ignimbrites. In ignimbrites, fumaroles form in two principal ways. The first is when ignimbrite flowing over water vaporises it to drive steam though conduits in the ignimbrite. These fumaroles are often associated with phreatic eruption pits and mounds. The second and more common way is during the devitrification and welding of the ignimbrite, when hot gases and steam escape forming fumaroles. Often these fumaroles exploit rectilinear joints and crack in cooling columns within the ignimbrite for their escape, and hence are often controlled by the fracturing and cooling of the ignimbrite.

The fossil fumaroles range in size from minute pipes of less than 1cm in width to large fumaroles of several metres in width. While fossil fumaroles are rare, any area which has evidence of fumarolic activity usually has many fumaroles preserved. Fumaroles are usually restricted to the lower parts of the ignimbrite. While some of the fumaroles in the Brisbane Tuff are apparently rootless, for most it is just that the roots are not exposed.

2.6.1 Small Fumaroles

The smaller fossil fumaroles are preserved as

1) fissures infilled with phenocrysts or granular material (Plate 2.7);

2) fissures infilled with opaline material (Plate 2.8); and

3) small pods and pipes of granular material.

The fissure-infilled fumaroles are similar to the *"crystal and lithic enriched segregation pipe"* (Cas and Wright, 1987, p. 114). They are commonly between 0.5 cm and 3 cm in width, and most are sub-vertical. Less commonly the fumaroles are sub-horizontal, and rarely do they anastomose. Most examples of the phenocryst-enriched fissure fumaroles have the crystal or granular phase set in a red-brown iron-stained matrix which commonly has undergone secondary silicification. XRD analyses of some of these veins indicates they are composed of quartz, hematite and/or goethite, and in some samples sericite. Keith *et al* (1981) reported that the encrustation products filling the fumaroles associated with the 1980 eruptions of Mount St Helens were initially a green hydrous ferrous iron, which altered to a brown-red during oxidation. Keith *et al* (1981) found that this reddish material is composed of hematite in high temperature fumaroles, but amorphous iron hydroxide or goethite in a low temperature fumaroles.

The opaline fumaroles have the same shape and form as the phenocryst-enriched fumaroles, and contain sub-vertical veins of amorphous opaline material with the same dark-red iron-enriched matrix (Plate 2.8). The opaline veins may represent lower temperature activity, where hydrous silica was leached out of the ignimbrite, probably due to vapour phase alteration of the ignimbrite. Keith (1990, p.238) reported that in the Valley of Ten Thousand Smokes opaline material was commonly associated with fumaroles that were *"never very hot"*. He also noted that such opaline material also

sometimes formed when acid leaching was initiated from the interaction of ground waters and fumarolic gases. XRD analyses of opaline material from the Brisbane Tuff confirmed the amorphous nature of the infilling (suggesting it was opal) and differentiated minor components as being goethite, hematite, and chrysocolla.

Both types of "fissure" fumarole are typically surrounded by small diffuse alteration haloes. Two main types of alteration are observed in the surrounding ignimbrite, a silicic alteration, and a yellow coloured iron (XRD analysis indicating it is goethite and/or hematite) alteration. Sericitic alteration also occurs infrequently, overprinting the other styles. Keith *et al* (1981) described a yellow staining occurring with fumaroles from Mount St. Helens, and found the alteration products to be composed of ferric halide and sulphates (Cl^{-1}, Fe^{-3},F^{-1}, and SO_4^{-2}). They found that the sulphide, chlorine, and fluorine phases of this alteration product were rapidly (within a few years) leached out of the rocks once the fumaroles became extinct.

The smaller fumaroles probably represent areas where degassing occurred during the de-vitrification and vapour-phase alteration of the ignimbrite. The fissures are commonly along the margins of rectilinear or columnar joints. Later generations of jointing which cut across the fissures lack the opaline or goethite/hematite mineralisation of the fumarole fissures. Keith (1990) and Papike *et al.* (1991) have pointed out that in the Valley of Ten Thousand Smokes, the distribution of the fissure fumaroles was controlled by the degree of ignimbrite welding which affected the fracturing and permeability; and the original shape of the valley into which the ignimbrite was emplaced, which, also affected the fracturing.

The final type of small fumarole, which occurs as small pipes or pods of granular lithic-poor material, is wider than those of the vein/fissure type, and has a poorly defined foliation parallel to the diffuse emplacement margins. Although texturally distinguishable from the host ignimbrite, the alteration haloes associated with this type of fumarole show little or no staining. The fumaroles also do not have the iron mineralisation haloes, implying that the fumarolic gases were not related to the degassing and remobilisation of the vapour-phase of the ignimbrite (and hence iron re-mobilization through acid solution). Instead this type of fumarole possibly formed in areas where the ignimbrite flowed over a body of meteoric ground water (of neutral pH)

leading to vigorous or sustained water boiling, the escaping vapour then causing texture modification of the host, but doing minimal modification to its composition. Alternatively, this type of fumarole may be a type of contained phreatic eruption feature, with the original structure (and texture) of the host being modified by the escaping gases and fluids.

2.6.2 Large Fumaroles

A large fossil fumarole is preserved in the banks of the Brisbane River at the Kangaroo Point Cliffs (Plate 2.9). The fumarole, which is roughly triangular in shape in vertical cross-section, consists of a central zone of highly altered ignimbrite, which is surrounded by symmetrically arranged alteration haloes. The vent zone of the fumarole is dyke-like at its base with parallel sides and near vertical orientation. Over the top 3 m of the fumarole, the emplacement pattern becomes irregular, with the fumarole diverging from the vertical and wedging out, as do the alteration haloes.

The vent zone is medium grey, depleted in lithic grains, and has a granular appearance. XRD analysis of material from this central zone indicates it is composed of quartz, dickite, illite, and kaolinite. A zone 5 to 10 cm in width at the margins of the fumarolic vent is marked by a set of anastomosing foliations parallel to the contacts with the surrounding rocks (Plate 2.10). The host for the set of foliations is darker than that of most of the fumarolic vent, probably due to differing weathering affects along the foliation planes.

A halo approximately 3 m wide of iron-stained and silicified ignimbrite immediately surrounds the central vent zone, with a sharp contact with the vent. This material has the usual lithic and crystal content of the rest of the ignimbrite and is therefore considered a part of the host rock of the fumarole. Occurring at a gradational contact with the silicified zone is a zone of highly altered (Sericitic) ignimbrite which varies in width from 10 m at the base and lower 2/3 of the fumarole to 1 m at the top. XRD analyses of samples collected over this 10 m base show uniform assemblages of quartz, sericite/muscovite, and illite. Very little relic ignimbrite texture is preserved in this zone, but some lithic clast material is preserved essentially unaltered. This fumarole may represent an area where the ignimbrite was emplaced over a large or continuously

flowing body of water, resulting in a prolonged period of fumarolic activity from one vent. Several other smaller crystal-rich fumaroles also occur at the same locality as the larger fumarole.

2.7 Flow Lineation Data

Flow direction measurements taken in the Brisbane Tuff should in theory provide a good indication of the vent location, and such criteria have been used by many workers in modern environments to delineate known vents (Ui *et al.*, 1989; Suzuki & Ui, 1982; Elston and Smith, 1970). Theoretically the measured flow lineations should radiate outwards from the source, however, when flow is constrained by the topography (as opposed to blanket style outflow sheets), the flow lineations will serve only to delineate the path of the flow and not indicate the vent location directly (Ui *et al.*, 1989; Suzuki & Ui, 1982).

2.7.1 Methods

Samples of ignimbrite oriented in the field using a combination clinometer and sun compass were collected at well-spaced field locations. If weather conditions allowed, a sun angle was measured for each sample and the time of day recorded. A magnetic direction was also recorded.

Although multiple ignimbrite flows were sampled, no distinction was made between the results from individual flows as in most areas it was impossible to determine accurately which particular flow was being studied. In the one area where multiple flows were known to exist and from which more than one flow was studied, the flow direction data showed no variability outside expected error ranges occurred, suggesting that all the flows followed a common path, and indicating that not distinguishing between individual flows was not important.

2.7.1.1 Grain Orientation Method

The oriented blocks were cut by a diamond saw in several sub-vertical orientations so that the bedding (S0) plane could be defined on the basis of flattened pumice clasts and grain orientations. Once bedding was defined, the sample was

oriented in a diamond saw, and slabbed parallel to bedding to get blocks 1 to 3 cm thick. The sample was then re-oriented to its original orientation in a sand pit, and the orientation of the bedding plane determined.

A modification of the technique outlined by Elston and Smith (1970) for determining the flow direction in ash flow tuffs was used. The bedding-plane surfaces were examined under a binocular microscope which contained a graticule calibrated in angles. The surface of the slab was then systematically scanned using the x-y traverse of the stage. The long axis orientation of all crystals and shards that had longitudinal axes at least four times their width were measured and recorded. Phenocrysts or shards with directional features, such as "Y" shaped shards, blocking structures, spindle-shaped fragments, and penetration effects (Elston & Smith, 1970), were noted so that the vector direction could be determined. A minimum of one hundred measurements were made for each rock, commonly necessitating measurements being taken from many slabs from the same rocks. To minimise bias, the slabs were placed under the microscope initially without knowing their orientation, the orientation of the slab only being determined after the measurements were completed. A purpose-written computer program was then used to re-calculate the true directions of the elongate shards and phenocrysts based on their measured direction in the slab, the orientation of the rock slabs under the microscope, and original field position. The true orientation of the phenocrysts was plotted on a rose diagram, and uni-modal and bi-modal statistically best estimates were made of the mean vector. A qualitative assessment was made on the quality of the directional data, depending on the statistical confidence of the indicated flow vector (determined using the techniques of Buck, 1988), and data were ranked according into three groups: non-directional data; poorly indicated directional data; and confidently indicated directional data.

2.7.1.2 Anisotropy of Magnetic Susceptibility (AMS) Method

Sixteen oriented blocks from 12 separate localities were used in the AMS study. Each of the oriented blocks were drilled in the laboratory into several 2.5 cm x 2.2 cm cores for susceptibility measurements. Volume susceptibility (induced magnetism/applied field) and principal susceptibility were measured at the CSIRO Rock

Magnetism Laboratory, North Ryde, following the techniques described by Lackie (1989).

2.7.2 Grain Orientation Results

Flow lineation measurements from the Brisbane Tuff suggest that the main body of the ignimbrite flowed along a valley, a theory supported by the observed contact relationship with the basement rocks. Of the 21 locations in the main body of the Brisbane Tuff (Fig. 2.4a), 5 are statistically weak vectors and 10 are azimuthal. Generally there was little statistical agreement for which direction the flow occurred along the flow lineation in the main body, with the only consistent flow direction being an easterly flow direction indicated by the outlying rocks at Carindale. Of the three samples in the main body which indicate a confident vector, the sample near Windsor indicates flow to the east, the other two indicate flow to the north. The sample at Windsor probably indicates secondary flow along the steep-walled contact with basement. Two less confidant inferred directions were also measured. One of these indicates a flow direction from north to south directly contradicting the data obtained 3 km to the north. The second vector indicates a westerly flow direction.

Five samples measured in the outlying body of the Brisbane Tuff around Carindale indicate an easterly flow in a radial pattern. The Brisbane Tuff outcropping in this region differs in some respects from the main body of the unit. The ignimbrite unit(s) are unusually free of cooling columns and rectilinear joints, are less welded, thinner, and contain unique biotite bearing pumice clasts occurring only in the ignimbrite at Carindale. The deposits are preceded by air-fall deposits but lack recognisable surges and fumaroles. Although the contact with the basement was not directly observed, it is probably low angled, and almost certainly not a steep valley wall as in the main body. All the evidence would suggest that these outcrops represent an outflow sheet that may have emerged from the main valley.

2.7.2.1 Additional Evidence supporting the Valley Deposition of the main body

Supplementary evidence that the Brisbane Tuff was emplaced in a valley is:

1) the form of contacts between the ignimbrites and basement;

2) the orientation of cooling columns; and

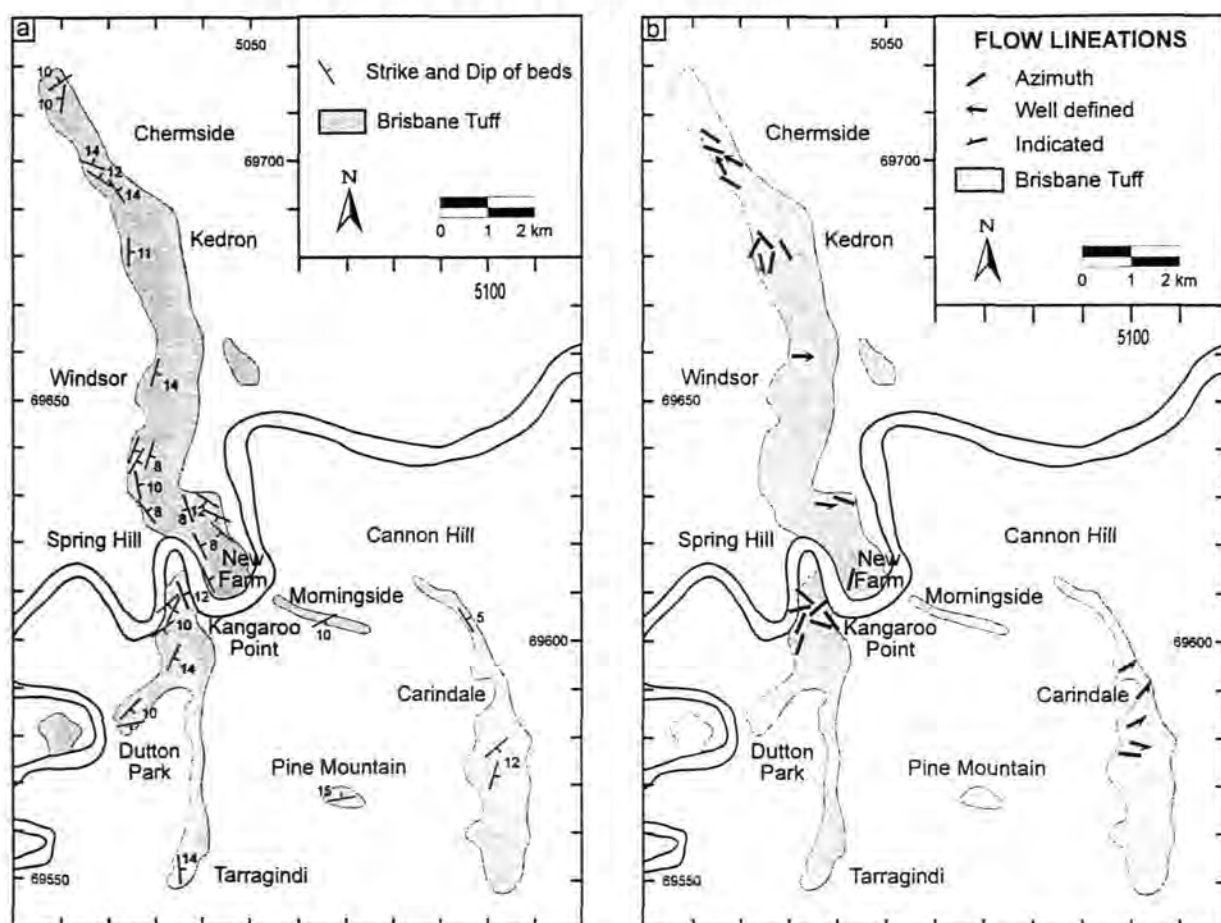3) the shape of the main flow of the ignimbrite.

Figure 2.4 a) Flow lineations in the Brisbane Tuff determined from rock fabric studies. b) Strike and dip direction of flattened pumice clasts (bedding) of the Brisbane Tuff.

Most contacts between the basement rocks and the Brisbane Tuff are steep (some almost sub-vertical) in contrast to the usual 8-14° dip of bedding within the ignimbrite. Many localities also have fossil scree slopes of brecciated basement under the ignimbrite consistent with the topography of valley walls (Fig. 2.2). Prominent cooling columns preserved near the contact with the basement at Windsor are near horizontal (structurally corrected), indicating that the cooling surface (a valley wall) was nearly vertical (plate 2.11 - plates are grouped at the end of each chapter).

The outcrop pattern of the Brisbane tuff is ribbon like, suggesting that the Brisbane tuff follows the path of an ancient valley. In addition to the flow lineations which parallel or sub-parallel the outcrop orientation (Fig 2.4a), as would be expected had the ignimbrite flowed through the valley, fumaroles near the base indicate reaction

with water, consistent with emplacement in a river valley.

2.7.3 Anisotropy of Magnetic Susceptibility (AMS)

The low bulk susceptibilities (most samples was less than 10 μG/Oe) of the rocks indicate that they contain little or no ferromagnetics. All samples of the Brisbane Tuff, except for an altered sample collected in an area of extensive fumarolic activity which had an anisotropie of 1.21, had anisotropies less than 1.06. The AMS fabrics were all prolate, and most AMS lineations approximated the flow axis indicated by the rock texture method. In the main body, the AMS data indicate a north-south flow axis, and in the Carindale body an east-west flow axis, both confirming the rock texture data. Data are given in Appendix F.

2.7.4 Palaeo-topographic Reconstruction

The reconstruction (Fig. 2.5) was generated using information about the contact relations with the underlying Palaeozoic basement with the Brisbane Tuff and other rocks, the flow lineation data, the local geology, including the location and structure of the Mesozoic basins and the foliations pattern in the Palaeozoic basement, drill core data, published sections, and the present topography. Details are given in Appendix J.

The main body of the Brisbane Tuff was deposited in a steep-walled valley with high hills to the west, and lower hills, probably only slightly higher than the ignimbrite (approximately 50-70 m), to the east. Higher hills have been postulated for the west based on the steeper nature of the contacts, the presence of present-day basement highs in the area, and lack of outflow sheet type facies and other (later) Ipswich Basin sedimentary rocks to the west. The valley wall contacts to the east (where exposed) are not as steep, some outflow sheet units occur in the south-east, and an extensive sheet of Ipswich Basin sedimentary rocks overlies the ignimbrites of the Brisbane Tuff, and extends over the top of "ignimbrite free" basement to the east of Chermside, implying that subsequent units filled and breached the narrow confining wall of the eastern side of the valley.

The valley into which the main body of the ignimbrite was emplaced was at its narrowest no more than 1 km wide (near New Farm), averaged between 3 and 5 km in
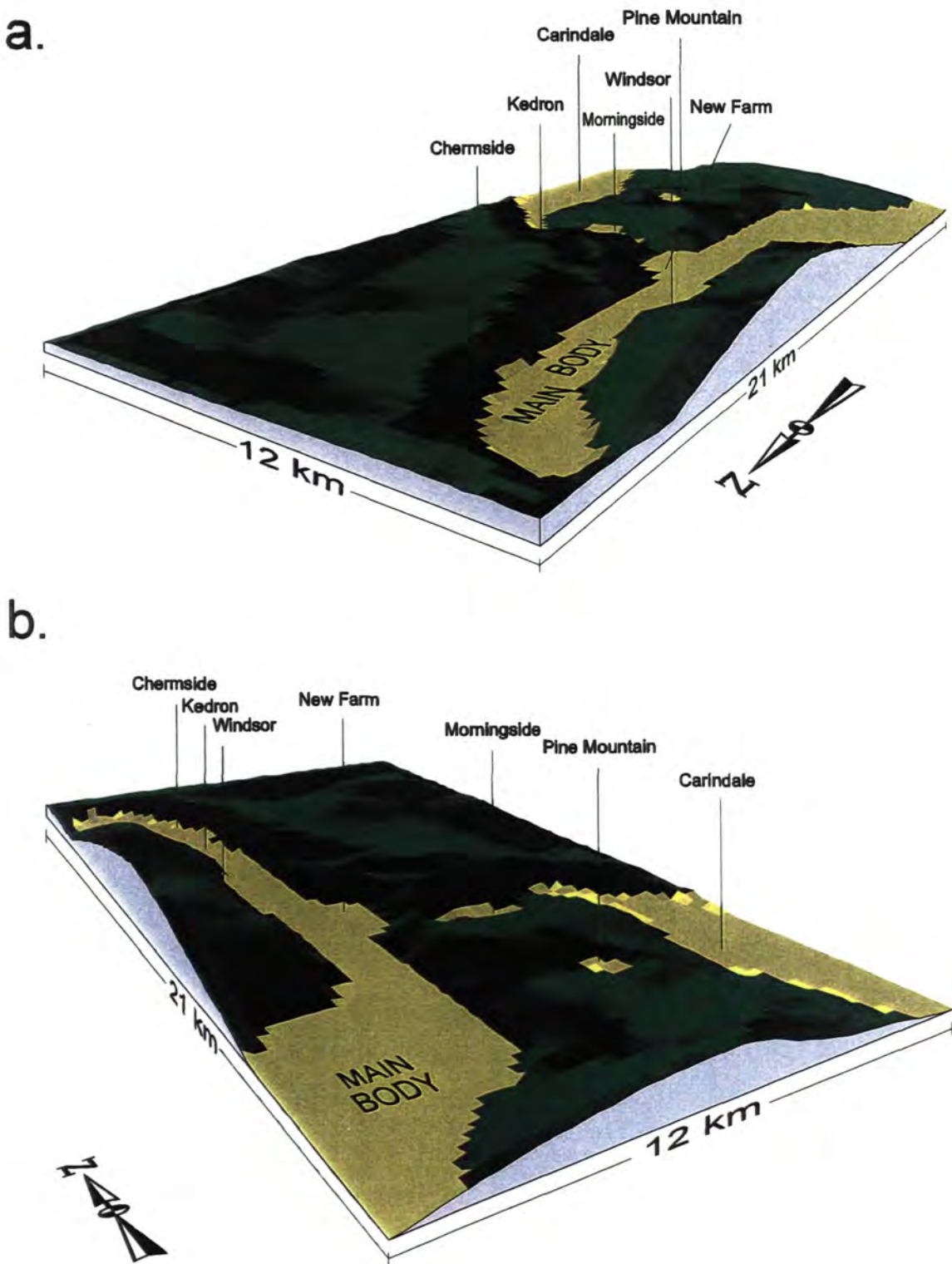
Figure 2.5 Schematic reconstruction of the Triassic topography over which the Brisbane Tuff flowed. (a) Looking southeastward along the valley across a prominent topographic feature which determined the site of the main body and the Carindale body. (b) Looking the other way (northwestward) along the valley from the inferred southern vent location.

its centre and to the north, and widened to a maximum preserved width of more than 8 km in the south. The southward widening of the valley is accompanied by a thinning of the ignimbrite before it terminates to the west. Figure 2.5a shows a prominent ridge, possibly fault related, running along the eastern contact of the main body in the north. The ridge, which was probably a more resistant block of Palaeozoic basement which formed a topographic high, as well as controlling the orientation of the northern part of the main valley, also influenced the depositional site at Carindale, by forming a barrier to the north of which no ignimbrites were deposited. The ridge was low enough to be breached by the Ipswich Basin sedimentary rocks overlying the ignimbrites at Carindale. The main part of the depositional site at Carindale opens into a broad fan which extended several kilometres to the south and about two kilometres to the east. Not visible on the reconstruction is the upland of the Beenleigh Block which blocked the easterly flow of ignimbrite. The flat lowlands into which the Carindale body was deposited probably extended part or all the way to Redland Bay (Fig. 2.1), perhaps because it was confined in the south by the highlands of the Beenleigh Block. The ignimbrite may have thinned out over this distance. A hilly region near present day Pine Mountain (Fig. 2.4) separated the valley of the main body of Brisbane Tuff from the Carindale area. Small depressions in these hills allowed the accumulation of air-fall deposits of limited extent.

2.7.5 Conclusions

The main body was deposited in a structurally controlled north-south trending valley, whose orientation and formation parallel the axis of the Ipswich Basin, suggesting it may have been related to deep basin-forming structures, while the ignimbrite at Carindale was deposited across a broad flat area, possibly as an outflow sheet.

2.8 Location of the Vent Area

Most informal suggestions for the vent area of the Brisbane Tuff are to the north or west of Brisbane.

Most commonly it is suggested that the vent was located north of the city of

Brisbane, the three locations proposed being Narangaba; out of the Ipswich Basin at Mount Byron; or the Tertiary Petrie Basin. The chief evidence for Narangaba being cited as a locality was probably the presence of coarse grained lithic breccia recorded in the literature, and assuming a north-south flow direction, that the northern-most units occur here. Contradicting this is the fact that the ignimbrites at this locality are comparatively thin, and the lithic breccia is at least in part apparently epiclastic in origin, and probably not a near-vent lag breccia. The Petrie Basin, north-east of Chermside, shows no evidence of containing volcanic rocks, nor any structures suggesting it might be an infilled caldera. The suggested source at Mount Byron was based on the presence of a reasonably well preserved caldera structure of Late Triassic age (Grenfell, 1975; A. Grenfell, *pers. comm.,* 1992*)*.

Proponents of a westerly source for the vent favour the unit being the volcanic equivalent of either the Enoggera Granite, or rhyolitic dykes intruding the D'Aguilar block at the University of Queensland Experimental Mine at Indooroopilly. The Enoggera Granite can be dismissed as its composition is sufficiently different from the Brisbane Tuff to invalidate it (see Chapter 5), and the dykes at Indooroopilly are possibly Mid Triassic in age.

2.8.1 Proximal Facies

The distribution of pyroclastic rocks with proximal and distal facies can help define the vent region. The thickness and grainsize of pre-ignimbrite air-fall tuff (as with other air-fall tuffs) varies inversely with distance from source (Fisher & Schmincke, 1984; Cas & Wright, 1987), so that thick coarse air-fall deposits are closer to the vent. Being falls, these deposits blanket the landscape and are not controlled in their thickness by the topographic features that restrict the distribution of the flow deposits.

The thickest deposits of pre-ignimbrite air-fall tuffs and surges (layer 1 facies) occur in the main body of the Brisbane Tuff in the Windsor to Chermside area (Fig. 2.4). Their clearly developed mantle-bedding indicates that they are not secondary re-worked deposits, and therefore their thickness indicates proximity. They are significantly thicker and more complex than the similar layer 1 deposits at Carindale,

which are taken to be farther from the vent. Ground surges are also a good indicator of proximal facies as they are more restricted in their distribution than either the ignimbrite or co/pre-ignimbrite fall units. Ground surge deposits have only been observed in the ignimbrites of the main body, mainly in the Windsor to Chermside area.

Lateral variations in an ignimbrite occur with distance from vent. The most prominent change is in the average diameter and maximum size of large lithic and pumice clasts which decreases with distance in ignimbrites as well as in air-fall tuffs (Cas and Wright, 1987). The largest dense lithic clasts (about 1 m across) occur at Chermside, Kedron, and Windsor. The largest pumice clasts(about 25 cm in length) occur at Kedron, and the Kedron-Windsor area also contains the greatest apparent volume of large pumice clasts. All these points confirm that the Chermside-Windsor area was proximal to vent. Welding also commonly varies with distance from source (Briggs, 1977), though it is also influenced by many other factors such as thickness of the deposit, which does not necessarily reflect distance (due to ponding of ignimbrites in depressions). Consistent with the other data, the most intense welding is found in the main body of the Brisbane Tuff in the Kangaroo Point to Chermside region.

The ignimbrites at Carindale differ in many respects from those of the main body. As noted previously, flow is to the east, differentiating them from the main body of the Brisbane Tuff, suggesting they accumulated in a different setting. Thin precursor air-fall tuffs (some of which looked re-worked) beneath the ignimbrite are not as extensive as in the main body, and obvious surge deposits are lacking. The ignimbrites are "finer grained" than those of the main body, lacking larger dense-lithic clasts. All of these observations suggest that the ignimbrites at Carindale represent a more distal ignimbrite facies of the Brisbane Tuff that accumulated in a broad flat area.

The most distal facies of the Brisbane Tuff are represented by the tuffaceous arenites and air-fall tuffs in outlying outcrops near Redland Bay. Outcrop in this region is unusually poor for ignimbrite, and the only material observed in these sections is re-worked. The presence of ignimbrites in this region could not be substantiated and it is assumed that none occur. This region is interpreted to represent distal air-falls and re-worked deposits. Small isolated outcrops on hilltops south of the main body (e.g. Pine Mountain) also lack ignimbrite, and are dominated by re-worked or air-fall

material, and a similar origin is suggested for these rocks.

On facies analysis alone, the vent region would be located close to the Chermside-Kedron area. These ignimbrites preserve comparatively good internal stratigraphy, however, Druitt and Sparks (1982) found that ignimbrites from the island of Santorini achieved sufficient fluidisation for separation into layers within a few kilometres from source, suggesting that the good internal stratigraphy shown by the Brisbane Tuff ignimbrites is consistent with proximal facies.

2.8.2 Ring Dykes, Domes, and Caldera Structures

Relic caldera structures in the Brisbane Tuff, such as circular depressions or basins corresponding to the vent caldera, or dykes and high level intrusions, though not presently observed, may have been obscured by later deposits, or even from backfill of the ignimbrite itself.

Ring-dyke complexes or rhyolitic lava domes also help delineate the vent area of rhyolitic ignimbrites when volcanoes are not obvious. The rhyolitic dykes intruding the D'Aguilar block at Indooroopilly, once thought to be associated with the Brisbane Tuff, are probably Mid Triassic, older than the ignimbrite. Rhyolitic domes in the Ipswich Basin, the closest of which are at Stradbroke Island (Cranfield et al., 1976, 1981), are probably the same approximate age as the Brisbane Tuff, and have a similar texture (as discussed in detail in chapter 4). Flow direction data for the Brisbane Tuff indicate flow towards (not away from) Stradbroke Island, and, additionally the Brisbane Tuff becomes more distal towards the east, suggesting a westerly source.

2.8.3 Conclusions

The two most probable vent locations are in the Chermside-Kedron area and southwest of Brisbane. Flow directions in the Brisbane Tuff near Chermside (Fig 2.4) have poorly developed flow direction indicators suggesting flow from south to north. Assuming the validity of the flow direction data, a vent region to the southwest would be consistent with the data, however, the proximal/distal facies relationships do not necessarily support this model.

The presence of proximal facies in the Windsor to Chermside area is the best

indicator for the vent location, although no obvious relic structures consistent with a source in this area have been preserved. The possibility that the ignimbrite backfilled its own caldera is one explanation which can explain this aspect. In this region the width of the palaeo-valley was between 3 and 5 km, sufficient to contain a small caldera structure. In the 1912 eruption of Novarupta, Alaska (Hildreth, 1983; Keith, 1991; Kienle, 1991), the caldera had a maximum diameter of approximately 2 km, however, the region was totally obscured by backfill of the ignimbrite. Only a shallow depression (which in the case of the Brisbane Tuff would be almost impossible to recognise) and a small resurgent dome mark the area presently. An added feature of this model is that it can account for the apparently anomalous flow directions indicating flow to the south and east.

The second possible vent region is in the southwest, from which ignimbrites flowed north along the main valley and east into the opening at Carindale (Fig. 2.5b). In common with the northern vent site, no preserved structures exist to directly support its existence, although many of the observed features do match the model. Deposits in this region are thinnest, which could be consistent with the elevated head of a valley system, with the thickest deposits accumulating in the more incised deeper parts of the valley at lower elevations. Few outcrops in this south-western vent region are preserved, and those that are show weakly developed internal ignimbrite stratigraphy (lacking dense lithic or pumice clast concentration zones), and little welding. Many of the deposits in this region (occupying hills) are air-fall deposits. The poorly stratified ignimbrites occurring in this region would be expected at distal areas once the energy (and hence fluidization) of the ignimbrite started declining (Cas and Wright, 1987; Druitt and Sparks, 1982). The ignimbrites in the Carindale area can also be explained by this model as the flow directions observed in this area are also consistent with a vent located in the southwest. The distribution of ignimbrites of the Novarupta eruption in the Valley of Ten Thousand Smokes is similar to the inferred model, in that a broad area of thinner deposits occurred at the head of the valley near vent, with the ignimbrite narrowing with the valley down slope (Hildreth, 1983; Hildreth and Fierstien, 1987; Keith, 1991). Ponding of the Novarupta ignimbrite in portions of the valley led to highly variable thicknesses along the length of the valley, with the thickest deposits being a few

kilometres from the actual vent. Against the location of the Brisbane Tuff vent being located in the southwest are the lack of any genuine vent facies, no obvious features to restrict the deposits accumulating much further southwest of the projected vent area, and the lack of any large dense lithic fraction in the deposits.

2.9 Secondary Flow Features

The flow studies, together with field observations, reveal evidence of many forms of secondary, non-rheomorphic, flowage in the ignimbrite. These types of flows occurred as grain flows prior to or during the welding of the ignimbrite. Flow lineations measured near the margins of the palaeo-valley indicate flow towards the centre of the valley away from the valley walls (Fig. 2.4a), as in the Ata pyroclastic flow in Japan (Suzuki and Ui, 1982).
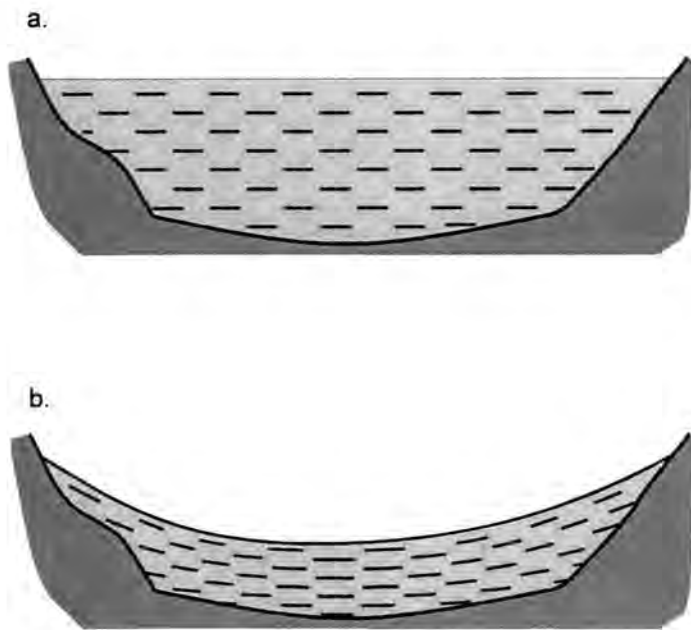
a.

b.

Figure 2.6 Schematic diagram illustrating the steepening of the ignimbrite flows accompanying differential compaction. a) Is the valley fill ignimbrite with 0% compaction. b) is the same ignimbrite with 50% compaction in the centre of the valley (where the ignimbrite is thickest). Slumping towards the valley centre has been caused by the differential compaction.

Differential compaction and gravity effects on the unstable tuffaceous material also formed secondary structural features in the Brisbane Tuff. The average dip direction of the bedding foliation in the ignimbrite, towards the centre of the valley (Fig. 2.4b), is believed to be due to differential compaction in the unit across the valley (Fig.

2.6). A greater degree of compaction in the thickest ignimbrite in the central part of the valley led to steep dips and then slumping near steep walls, and downwarping towards the centre of the valley. At Chermside, bedding-plane faults and shears in the ignimbrite and the underlying surge and fall deposits parallel the valley-wall contact, and indicate slumping and movement of the ignimbrite towards the valley centre (Fig. 2.2).

2.10 Discussion and Conclusions

Most of the Brisbane tuff is composed of ignimbrites, although small volumes of pre- and post- ignimbrite deposits, such as air-falls and ground surge deposits also occur in the unit.

The ignimbrites of the Brisbane Tuff are valley fill ignimbrites, with the main body deposited in a structurally confined north-south striking valley, while the ignimbrites at Carindale to the east were deposited in a broad flat area.

The entire Brisbane Tuff was probably erupted from a single vent, over several hours or days, and consisted of multiple individual flows which form a single cooling unit. It is likely that these flows were emplaced as multiple flows from what was probably a single eruptive event, as opposed to multiple separate eruptions (with large periods of quiescence between eruptions) from the one vent over an extended period of time.

Flow direction data for the Brisbane Tuff (principally grain orientation, but also AMS) indicate a north-south flow direction along the main valley, and a westerly source for the Carindale area, but fail to define the actual vent of the Brisbane Tuff.

Combining flow direction data and proximal facies, I conclude that the most likely location of the vent was in the Chermside-Kedron region. The vent was small, probably not more than 2-3 km wide, and was infilled by ignimbrite flows.

Fossil fumaroles ranging in size from 1 to 100 cm are common in the Brisbane Tuff. The smallest ones represent conduits and fissures through which gases escaped during welding and compaction, while the larger ones are areas where sustained and vigorous venting of gases occurred, probably due to the ignimbrite flowing over water.

Plate 2.1 The Brisbane Tuff at the Kangaroo Point Cliffs. The thickest exposure of the Brisbane Tuff (approximately 40 m) occurs in the cliffs. (GR: 5033E, 69606N)

Plate 2.2 Low angle cross bedded ground surge deposits in Layer 1 facies of the Brisbane Tuff at Kitchener Road, Chermside. (GR:5019E, 69693N)

Plate 2.3 Ground surge and air-fall deposits (Layer 1) above basement at Windsor. (GR: 5031E, 69660N)
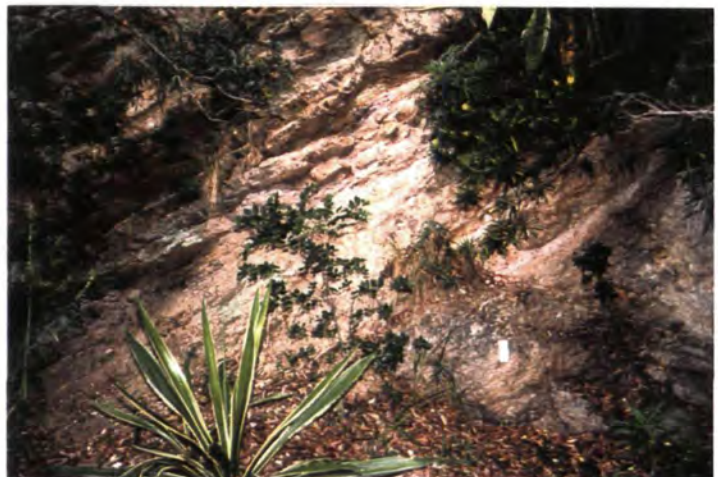
Plate 2.4 Charcoal (black specks) in layer 1 faces in a planar bedded ground surge or air-full tuff, at Chermside .(GR: 5017E, 69699N)

Plate 2.5 Large clasts of Palaeozoic basement rock at the base of layer 2 of the ignimbrite in the Brisbane Tuff at Windsor. (GR: 5031E, 69660N)

Plate 2.6 Flattened pumice clasts in an intensely welded ignimbrite. Also visible are several small (un-flattened) dense lithic clasts derived from the Palaeozoic basement. (Kitchener Road, Chermside.) (GR:5019E, 69693N)
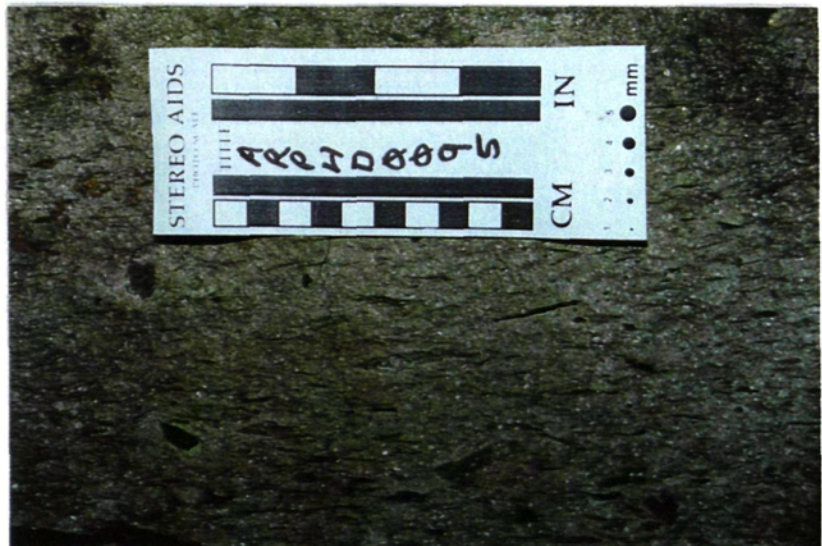
Plate 2.7 A fossil fumarole from Kangaroo Point, infilled with phenocrysts and granular material. The red matrix is composed largely of goethite. (GR: 5032N, 69605N)

Plate 2.8 An opal/goethite infilled fossil fumarole from New Farm. The original fumarole exploited a rectilinear joint in the ignimbrite.(GR: 5043.5, 69622.5N)

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Plate 2.9 A large fossil fumarole in the Kangaroo Point cliffs. The width of the central vent zone of the fumarole (dark grey area) is approximately 1 m, and the outcrop is approximately 40 m high. Visible is the central vent, the inner silicified alteration zone (shown by its lack of weathering), and the highly weathered outer alteration (sericite) zone. (GR: 5033E, 69607N)

Plate 2.10 Close-up of the central vent region of the large fossil fumarole from Kangaroo Point. The foliated margins of the fumarole are visible on the left contact with the wall rock. Width is approximately 1 m.(GR: 5033E, 69607N)

Plate 2.11 Horizontal cooling columns signifying a steep valley wall contact. Outcrop height is approximately 3.3 m.(GR: 5030.5E, 69659.5N)

Plate 2.12 Vertical cooling columns typical of the Brisbane Tuff, signifying emplacement over a flat floored valley. (GR: 5032N, 69605N)

Plate 2.13 Poorly welded ignimbrite of the Brisbane Tuff showing relic bubble-wall structures. Plane polarised light (PPL). Base of photo is 1.3 mm.

Plate 2.14 Moderately welded ignimbrite of the Brisbane Tuff showing relic bubble-wall and cuspate structures. Poorly defined spherulitic growth is apparent (A) as is partial (B) and complete (C) vapour-phase infilling of the voids in the bubble walls. PPL Base of photo is 1.3 mm.
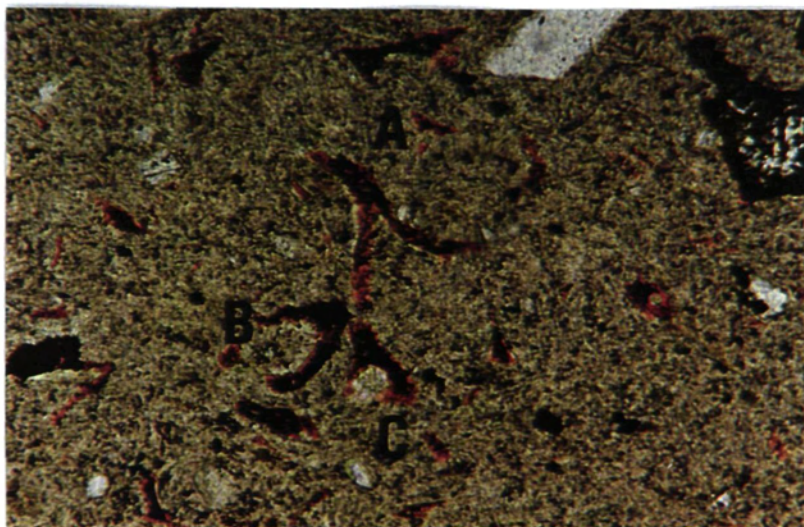

Plate 2.15 Perlitic cracking in a glassy part of a welded ignimbrite of the Brisbane Tuff. PPL. Base of photo is 4.5 mm.
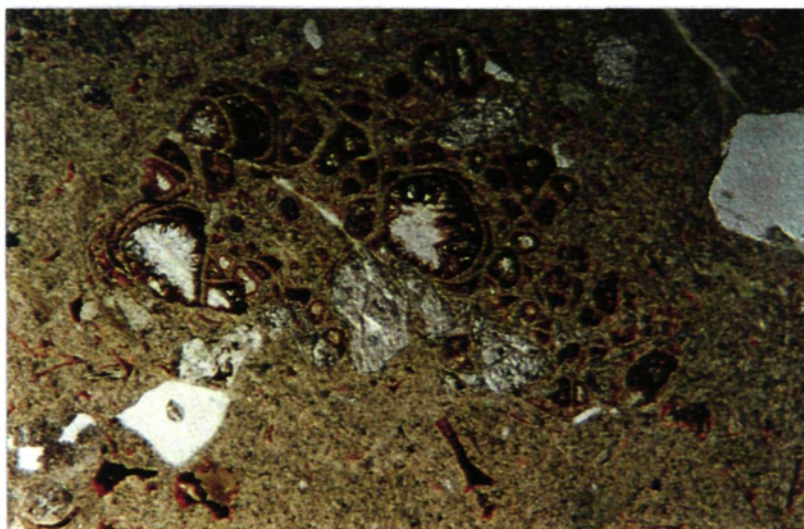

Plate 2.16 Photomicrograph of a highly welded ignimbrite of the Brisbane Tuff. Note the deformed pumice clasts (A) and how the eutaxitic texture flows around the quartz phenocrysts (B). PPL. Base of photo is 1.3 mm.