CHAPTER ONE

INTRODUCTION

1.1 PREAMBLE

The New England Batholith consists of a multitude of granitoid plutons within the southern part of the New England Fold Belt (Fig. 1-1). It outcrops over some 300 km along a meridional trend from Tamworth in southern New South Wales, northwards into southern Queensland. Excellent contact aureoles have developed within Palaeozoic sediments and volcanics around many of the plutons. Although an extensive amount of data has been accumulated on the granitoids and the Palaeozoic stratigraphy, until now little work has been done on the contact metamorphics within the New England region.

The contact aureoles of the New England Batholith provide an excellent range of rock types for study. These include pelitic, psammitic, calcareous and siliceous sediments, as well as acid, intermediate, basic and occasional ultrabasic igneous rocks. This thesis concentrates on the contact metamorphism of pelitic, psammitic (greywacke), and impure calcareous rocks, largely because of their well developed zonal variation with increasing grade. Metabasic rocks (including calc-silicate assemblages in the amygdales) have also been studied in detail, but limitations of space and time prohibit their inclusion as a major topic in this thesis. However, because of their relevance to the definition of metamorphic facies, a brief account of their contact metamorphism is given in the general synthesis of isograds at the end of this thesis. A study area was chosen within the batholith (Fig. 1-1C), and from reconnaissance within this area, the most rewarding localities were selected for detailed studies.

1.2 AIMS AND APPROACH

The general aims of this thesis are:

1) to delineate metamorphic zones;

2) to identify systematic variations in mineral chemistry with increasing grade across the aureoles;

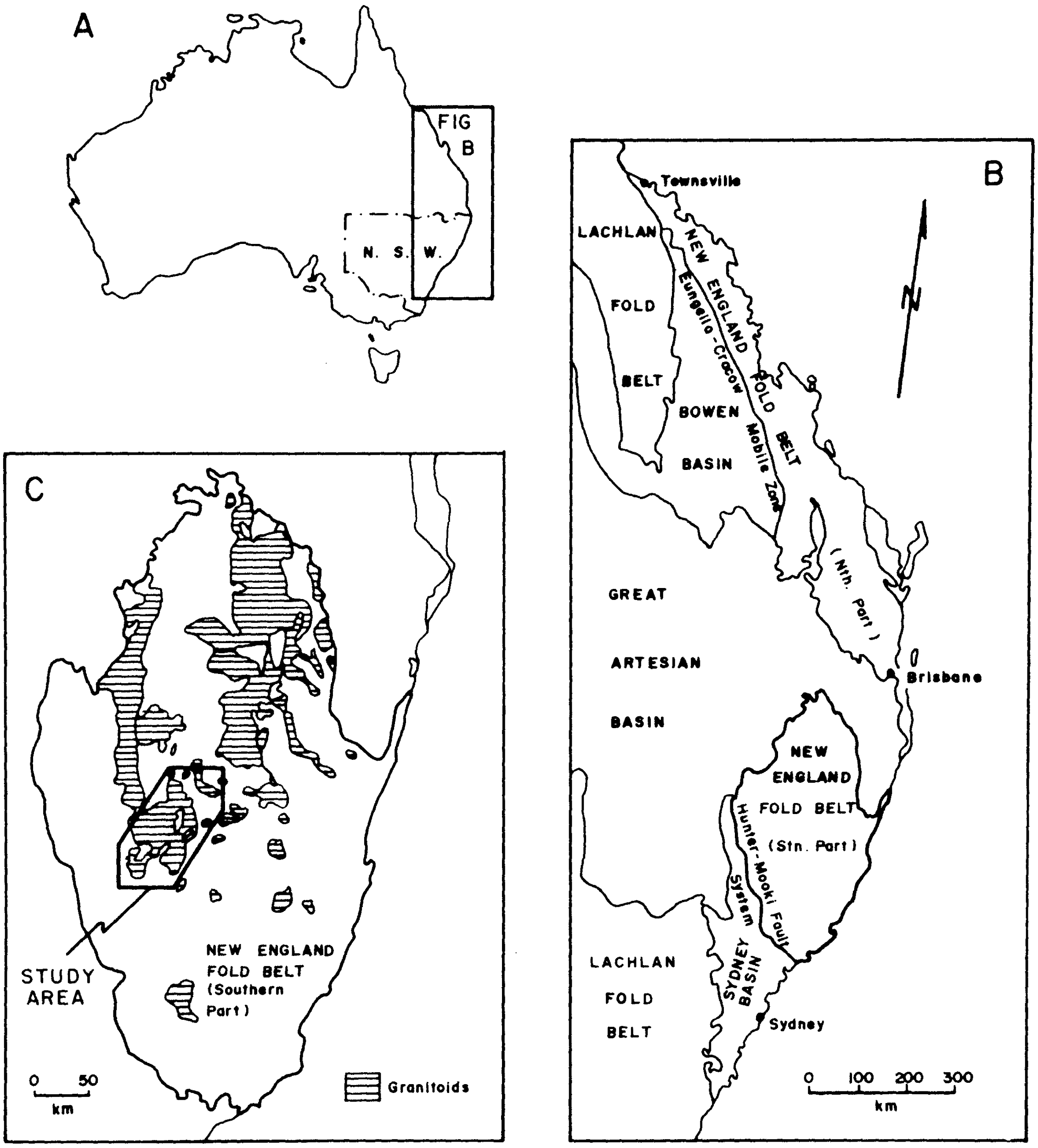


Figure 1-1: Location of the New England Fold Belt and study area. A: Location of inset B with respect to Australia. B: Outline of the New England Fold Belt. C: Location of the study area and distribution of the granitoids of the New England Batholith within the southern part of the New England Fold Belt.

3) to formulate (using probe data) balanced equations representing the reactions at the zone boundaries;

4) to examine phase relations associated with these reactions, for the purpose of establishing the types of reactions taking place (i.e. discontinuous, continuous, cation exchange);

5) to estimate metamorphic conditions across the aureoles examined;

6) to study small-scale diffusion in examples of reaction bands produced within the contact aureoles.

Examination of these aspects within the selected rock types has involved detailed description of over 1,000 thin sections, electron probe analysis of 150 polished thin sections yielding over 1,000 mineral analyses, and whole-rock chemical analyses of 40 samples.

Metamorphic zones are delineated within the various rock types. These zones represent a spatially progressive sequence of prograde assemblages assumed to have equilibrated with prevailing metamorphic conditions across the aureoles. Balanced equations based on probe data are proposed to represent the reactions relating supposedly chemically equivalent mineral assemblages on either side of zone boundaries. The actual reaction path in contact metamorphism is uncertain. It depends on the rates of reaction relative to the rate of heating, and therefore the inner-zone assemblages in contact aureoles are not necessarily derived via intervening formation of lower-grade assemblages and textures, but may instead develop more or less directly from the incipiently reconstituted country rocks (discussed by Spry, 1974, p.4; Turner, 1980, p.23). Because specific reactions can be assigned to the zone boundaries recognised here, the term 'isoreaction-grad' (after Winkler, 1976) could be applied to them. However, 'isoreaction-grad' is a cumbersome term and 'isograd' is used instead. Isograds, though, need not be isotherms, for the appearance of a new metamorphic assemblage is dependent on temperature, pressure and mineral composition.

Contact aureoles are ideal geological environments for the study of metamorphic reactions in relation to increasing temperature. Pressures are low and probably constant across the aureoles during metamorphism. The thermal history is simple (typically a single heating event), and the direction of progressive metamorphism (increasing temperature) is well defined, being directly correlated with distance from the igneous contact.

Particular attention is paid to investigating the variance of the metamorphic reactions believed to be responsible for changes in paragenesis. Discontinuous (univariant) reactions are recognised by the immediate loss of a phase in association with the incoming of a new phase, and these reactions define relatively sharp zone boundaries. Conversely, continuous (divariant, sliding) reactions involve the coexistence of reactants and products over a temperature interval. The divariance of reactions involving solid solution phases has been recognised for many years (e.g. Goldschmidt, 1911) and continuous reactions are now well recognised in the literature (e.g. Hensen, 1971; Vernon, 1976; Thompson, 1976a,b). Thompson (1976a,b) has developed a method of depicting progressive metamorphism as a sequence of continuous and discontinuous reactions on a T-X(Fe-Mg) diagram; continuous reactions are represented by divariant loops (as described by several previous authors, e.g. Ramberg, 1944; Hensen, 1971; Albee, 1972), which intersect to generate discontinuous reactions. Several authors (e.g. Yardley *et al.*, 1980; Labotka *et al.*, 1981) have recently used this approach to illustrate progressive contact metamorphism. This thesis investigates the applicability of Thompson's method to the reactions and phase relations delineated in this study (primarily with regard to the pelitic rocks). Reactions may also show divariant character because of buffering of the pore fluid during metamorphism (Greenwood, 1975). This is most applicable to calcareous rocks, whose pore fluid contains both H_2O and CO_2. Buffering of the pore fluid composition along univariant curves on $T\text{-}X_{CO_2}$ diagrams has been described by several authors (e.g. Ferry, 1975; Suzuki, 1977; Rice, 1977). However, Kerrick (1974) pointed out that examples of both buffering and non-buffering of the pore fluid have been described in regional and contact metamorphism, and that each geological system should be investigated independently. Possible buffering of the pore fluid during metamorphism has been investigated within the impure calcareous rocks of this study.

To estimate the conditions of metamorphism, reactions deemed to have occurred within the rocks are correlated with experimentally determined curves. However, the chemistry of the reacting phases must be taken into consideration. For the pelites, extrapolations appropriate to the rocks of this study are made from the work of Hoffer (1976,1978), who has experimentally determined curves using intermediate Mg/Mg+Fe ratios. For the impure calcareous rocks, reaction curves on $T\text{-}X_{CO_2}$ diagrams have been modified, using theoretical thermodynamic principles, to allow for compositional variations in the participating phases (c.f. Ghent and De Vries, 1972; Kerrick *et al.*, 1973; Slaughter *et al.*, 1976; Kerrick, 1977; Erdmer, 1981).

Numerous examples of chemical adjustment between incompatible rock types occur within the contact aureoles. These include calc-silicate reaction bands developed in association with Ca-rich veining in the greywackes, Ca-rich amygdales in the metabasalts, and between blocks of pelite and marble within impure calcirudites. These examples provide an excellent opportunity for examining small-scale diffusion of components during metamorphism. Reaction bands are best developed within the calcirudites, and these are studied in detail for two major purposes; firstly to calculate the chemical changes which have taken place across the reaction bands, and secondly to outline the manner in which the layering within the reaction bands has developed in terms of chemical potentials of the diffusing components. The calculations involved in the former approach are based primarily on the work of Thompson (1975a), while the latter follows the concepts expressed by Korzhinskii (1959, and many previous papers) and Thompson (1970). Several recent papers have investigated reaction bands using these concepts (e.g. Vidale and Hewitt, 1973; Joesten, 1974,1977; Brady, 1977).

The general characteristics of the contact aureoles and the pluton-to-aureole contacts are briefly described in this introduction (Section 1.6), with a view to categorising the style of contact metamorphism and relating it to the manner of pluton emplacement. The approach used is similar to that employed by other authors, in particular Pitcher and Read (1963) and Pitcher (1979).

1.3 GEOLOGICAL SETTING

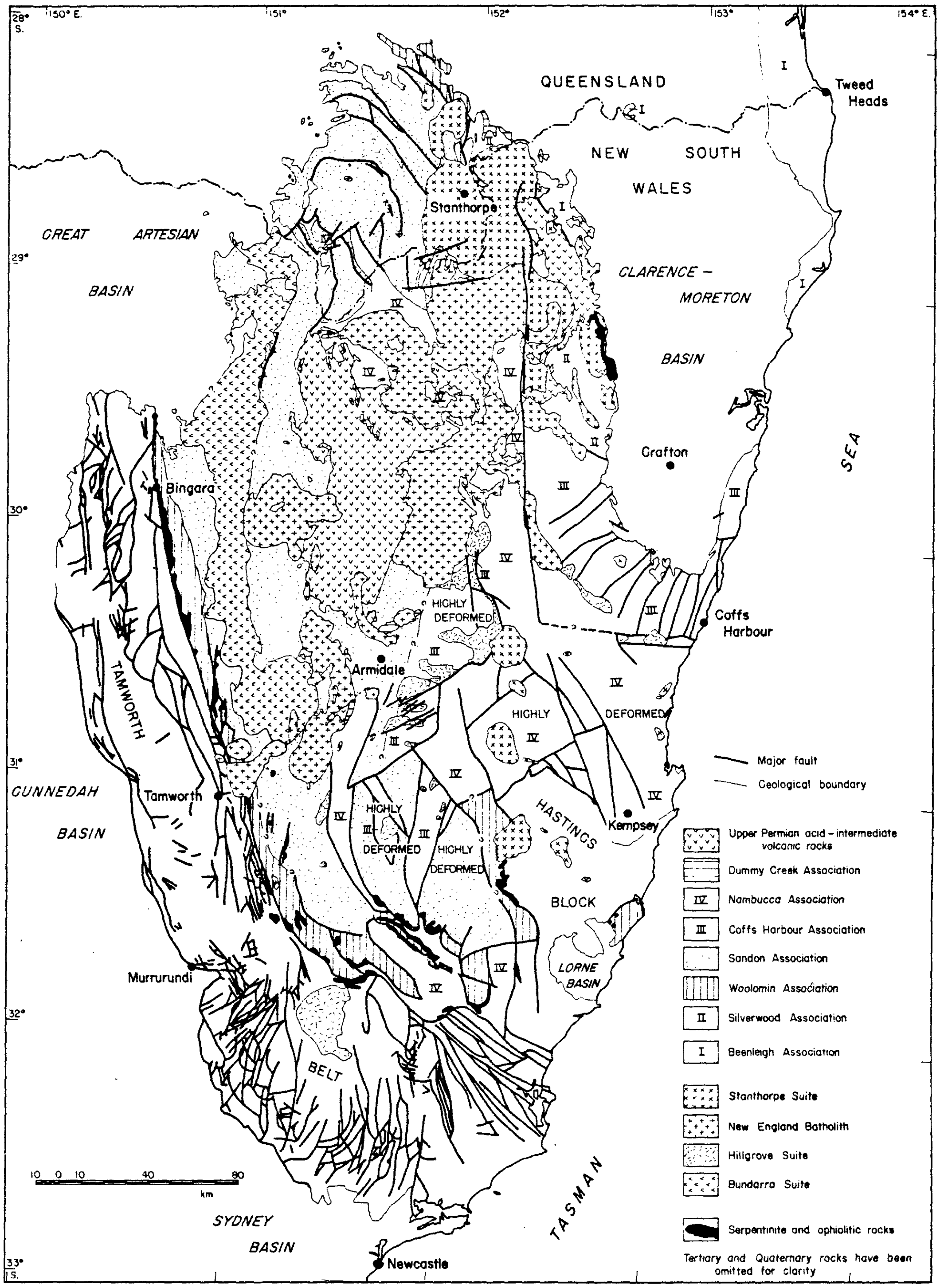
1.3.1 Introduction

The New England Fold Belt (synonymous with New England Geosyncline; Korsch, 1977) comprises the Palaeozoic sediments and associated igneous rocks that lie east of the Hunter-Mooki Thrust System in New South Wales and the Eugella-Cracow Mobile Belt in Queensland. The southern part of the Fold Belt is bounded by the Mesozoic cover of the Sydney Basin to the south and west, the Great Artesian Basin to the northwest, and the Clarence Moreton Basin to the northeast (Fig. 1-1B). The New England Batholith occupies a major portion of this Fold Belt (Fig. 1-1C), and Chappell (1978) has estimated a total pre-basalt outcrop area for the Batholith of approximately 20,000 km^2 (Cainozoic basalt covers much of the Fold Belt).

Much of the following account is based on geological descriptions by Leitch (1974) and Korsch (1977). The southern New England Fold Belt can be split into two major geological divisions, separated by the Peel Fault System (Fig. 1-2). The region to the southwest of the Peel Fault is referred to as the Tamworth Belt (Korsch, 1977), (synonymous with Zone A, Leitch, 1974). Sediments in the Tamworth Belt have been moderately deformed by continuous north-northwest-trending folds, and show effects of very low-grade burial metamorphism. Granitic intrusions within this Belt are rare. In contrast, the Tablelands Complex (Korsch, 1977), (synonymous with Zone B, Leitch, 1974), lying northeast of the Peel Fault, has apparently undergone intense deformation during several episodes of folding and block faulting, and lacks a well delineated regional trend. The sediments in the Tableland Complex are generally affected by only low to very low-grade regional metamorphism (excluding contact metamorphism). However, two areas, at Wongwibinda (Binns, 1966) and Tia (Gunthorpe, 1971), show higher-grade regional metamorphism, in association with regional-aureole granites (as defined by White *et al.*, 1974). Most of the granitoids of the New England Batholith are emplaced within the Tablelands Complex. A volcanic chain is believed to have existed, partly within and partly to the west of the Tamworth Belt, from Early Devonian to Early Permian (Leitch, 1974). This volcanic chain has important implications for the tectonic development of the New England region (Section 1.3.4).

1.3.2 <u>The Palaeozoic Sediments and Volcanics</u>

Sedimentation was markedly different within the two major geological divisions of the New England Fold Belt described above. The Tamworth Belt consists of a thick sequence of predominantly volcaniclastic sediments, ranging in age from Devonian to Permian. In the western part of the Tamworth Belt the sediments are typically terrestial and shallow marine, while the eastern part of the Belt (the Tamworth Group) consists of radiolarion argillites, greywackes, conglomerates, minor keratophyres and spilites, with coralline limestone lenses occurring throughout. Crook (1964) considered this latter sequence to be of deep-water origin, whereas Ellenor (1975) envisaged a relatively shallow-water environment. Sediments of the Tablelands Complex are believed to range in age from Ordovician to Early

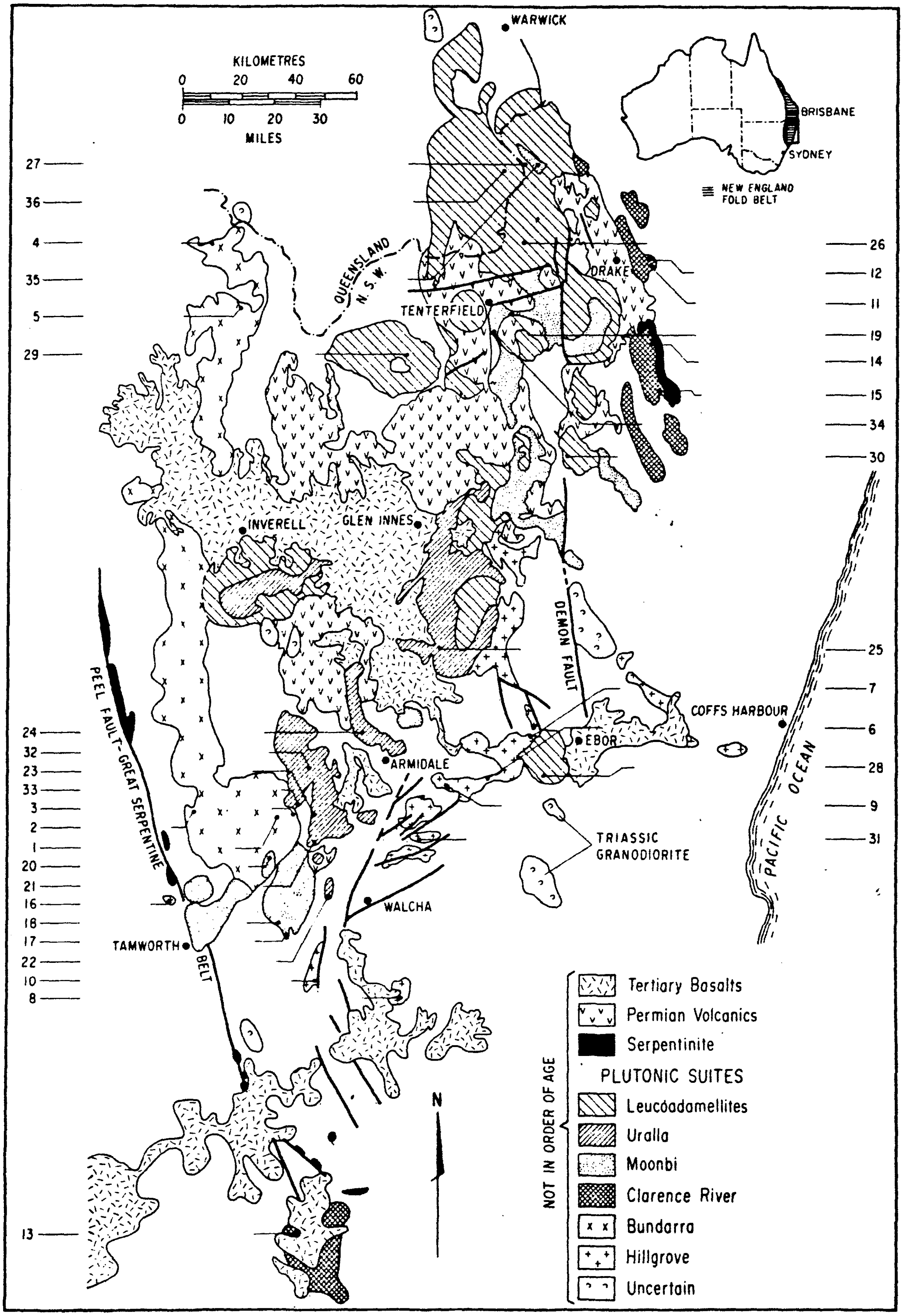

QUEENSLAND
NEW SOUTH WALES
Tweed Heads
Stanthorpe
GREAT ARTESIAN BASIN
CLARENCE - MORETON BASIN
Grafton
SEA
Bingara
HIGHLY DEFORMED
Coffs Harbour
Armidale
TAMWORTH
CUNNEDAH BASIN
Tamworth
HASTINGS BLOCK
Kempsey
LORNE BASIN
Murrurundi
BELT
SYDNEY BASIN
TASMAN
Newcastle
Major fault
Geological boundary
Upper Permian acid - intermediate volcanic rocks
Dummy Creek Association
Nambucca Association
Coffs Harbour Association
Sandon Association
Woolomin Association
Silverwood Association
Beenleigh Association
Stanthorpe Suite
New England Batholith
Hillgrove Suite
Bundarra Suite
Serpentinite and ophiolitic rocks
Tertiary and Quaternary rocks have been omitted for clarity
km

Permian, but at present they cannot be placed into any comprehensive clear stratigraphic sequence because of the combined effects of poor exposure, lithological monotony, severe deformation, and scarcity of fossils (Leitch, 1974). However, both Leitch (1974) and Korsch (1977) have recognised several major lithological associations. The scheme of Korsch (1977) agrees most closely with the observations of the present author. His divisions are shown in Fig. 1-2. In general, the sediments of the Tablelands Complex appear to be of deep-water marine origin, consisting of variable amounts of greywackes and argillites, with lesser cherts, jaspers, basaltic flows, conglomerates and occasional limestone lenses. Locally, flat-lying shallow-marine to terrestial deposits of mainly conglomerate (Dummy Creek Association; Korsch, 1977) unconformably overlie the above rocks. These conglomerates are in turn overlain by Upper Permian acid-intermediate volcanics (Korsch, 1977). Flood *et al.*, (1977,1980) have recognised several masses of porphyritic rhyodacite (Dundee Rhyodacite), closely associated with the Upper Permian volcanics, which they believe to be ignimbritic. They believe the ignimbrite to be co-magmatic with the New England Batholith (Korsch, 1977, included these rocks in the New England Batholith.). Flood and Shaw (1979) have also recognised three closely associated bodies of meta-dacitic ignimbrite southwest of Armidale. Lithologies to be studied within this thesis are further delineated in Section 1.4.

1.3.3 The New England Batholith

The term 'New England Batholith' refers to all the Upper Palaeozoic and Mesozoic granitoids in the southern part of the New England Fold Belt (Wilkinson *et al.*, 1969; Shaw and Flood, 1981). The Batholith is dominated by leucoadamellites, adamellites and granodiorites. More-basic intrusives and granites occur to a far lesser extent. The north-south elongation of the Batholith is more or less concordant with the structural grain of the New England region. However, several individual plutons are quite circular in plan and structurally discordant (e.g. Inlet Monzonite; Attunga Creek Adamellite).

Recent studies by Flood and Shaw (1975,1977), O'Neil *et al.*, (1977) and Shaw and Flood (1981) have led to the recognition of five plutonic suites and a group of leucoadamellites within the New England Batholith (outlined in Shaw and Flood, 1981), on the basis of mineralogical, chemical, isotopic and age characteristics. These groupings are shown in Fig. 1-3.



KILOMETRES
0 20 40 60
0 10 20 30
MILES
WARWICK
BRISBANE
SYDNEY
NEW ENGLAND FOLD BELT
QUEENSLAND
N.S.W.
DRAKE
TENTERFIELD
INVERELL
GLEN INNES
PEEL FAULT - GREAT SERPENTINE
DEMON FAULT
EBOR
COFFS HARBOUR
PACIFIC OCEAN
ARMIDALE
TRIASSIC GRANODIORITE
WALCHA
TAMWORTH
BELT
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15
34
30
25
7
6
28
9
31
NOT IN ORDER OF AGE
Tertiary Basalts
Permian Volcanics
Serpentinite
PLUTONIC SUITES
Leucoadamellites
Uralla
Moonbi
Clarence River
Bundarra
Hillgrove
Uncertain

The S- and I-type characteristics, as defined by Chappell and White (1974), of the plutonic suites and leucoadamellites have also been described by the above authors.

Two S-type plutonic suites are recognised in the New England Batholith: the Hillgrove Plutonic Suite (first recognised by Binns *et al.*, 1967) and the Bundarra Plutonic Suite (first recognised by Flood, 1971). They are characterised by a biotite-rich mineralogy (plus muscovite in the Bundarra Suite), and the presence of accessory phases of probable refractory residue from a presumed sedimentary source, represented by cordierite and occasional garnet in the Bundarra Plutonic Suite and pyrope-almandine garnet in the Hillgrove Plutonic Suite. The Hillgrove Suite plutons are commonly foliated. Granitoids of these two plutonic suites give Upper Carboniferous to Lower Permian ages (Flood and Shaw, 1977; Shaw and Flood, 1981).

In contrast the remainder of the Batholith (originally referred to as the New England Plutonic Suite by Flood, 1971) is dominated by hornblende-biotite-bearing granitoids, similar to the I-type granitoids of Chappell and White (1974). These plutons have high hornblende-to-biotite ratios, accessory sphene and magnetite, and varying amounts, though usually minor, of clinopyroxene. They commonly contain abundant mafic xenoliths which, along with much of the hornblende and pyroxene, may be residues of an igneous source, as described by Chappell (1978) in the Moonbi district. These plutons are typically non-foliated, though a distinct foliation may be developed at their margins (discussed in Section 1.6). The I-type granitoids, including the leucoadamellites, appear to be distinctly younger than those in the S-type plutonic suites, ranging in age from Upper Permian to Triassic (255 Ma → 225 Ma) (Shaw and Flood, 1981).

Shaw and Flood (1981) recognised three suites within the I-type granitoids: the Uralla and Moonbi Plutonic Suites of O'Neil *et al.*, (1977), and the Clarence River Plutonic Suite (Fig. 1-3). The latter is characterised by lower K_2O and lower $^{87}Sr/^{86}Sr$ initial ratios than the other I-type suites. The Moonbi and Clarence River Plutonic Suites show definite I-type character. The Uralla Plutonic Suite is distinguishable from them by lower hornblende-to-biotite ratios, higher $^{87}Sr/^{86}Sr$ initial ratios, and the presence of ilmenite (often with magnetite), and appears to show intermediate I-S-type characteristics (Shaw and Flood, 1981). The leucoadamellites have I-type affinities (O'Neil *et al.*, 1977), but show no mineralogical features diagnostic of any of the above suites. The leucoadamellites are the youngest of the I-type intrusives.

Other authors have suggested different subdivisions of the New England Batholith. Korsch (1977), using age and spatial distributions, divided the I-type granitoids into a younger eastern group, termed the Stanthorpe Suite, and an older western group, termed the New England Batholith (*sensu stricto*) (Fig. 1-2). Chappell (1978), in a study of the Batholith near Tamworth, delineated four igneous suites (Inlet, Bendemeer, Attunga and Looanga) within the I-types, and two suites (Banalasta and Tilamond) within the S-type Bundarra Plutonic Suite. Clearly, it is desirable that a consistent terminology be established, though this is not an objective of this project.

This thesis is primarily concerned with the I-type granitoids occurring in the area around Armidale and Tamworth, which are outlined in Section 1.4.

1.3.4 Regional Tectonic Development

There is significant divergence of opinion on the tectonic reconstruction of the southern part of the New England Fold Belt amongst workers in the region. No attempt is made here to reinterpret the tectonic history, but merely to summarize the major points which synthesize the various features of the geological setting. A brief summary of all ideas is impossible, and the following outline is based mainly on the plate tectonic reconstructions of Leitch (1974,1975) and Shaw and Flood (1981).

1) In the Ordovician to Silurian, cherts, jaspers, siliceous mudstones and basalts were deposited on an abyssal plain.

2) Subduction to the west is believed to have begun in the Devonian, and this initiated volcanism along a volcanic chain west of the Tamworth Belt. In a model analogous to present-day island-arc environments, the western part of the Tamworth Belt is equivalent to the fore-arc basin, and the Tamworth Group (the easternmost rocks of the Tamworth Belt) could represent the remnants of material deposited on the mid-slope high (Leitch, 1974). East of mid-slope high, the Woolomin Association of the Tablelands Complex (Korsch, 1977) is envisaged as oceanic crustal material accumulated against the inner trench wall.

3) Subduction continued throughout the Devonian and Carboniferous with the fore-arc basin becoming infilled with volcaniclastic material (rocks of the Tamworth Belt), and both oceanic crustal material and deep-marine trench fill was accumulated within the trench (the present sediments and basic volcanics of the Tablelands Complex).

4) In the Late Carboniferous to Early Permian the S-type plutons were intruded into the trench sediments (Shaw and Flood, 1981).

5) A major period of deformation is believed to have occurred between intrusion of the S-type plutons, and the younger I-types (Shaw and Flood, 1981). Leitch (1975) correlated this with the end of activity on the western volcanic chain, and the possible cessation of subduction. The deformation involved marked folding and faulting (including movement on the Peel Fault), but has produced only low- to very low-grade regional metamorphism.

6) Emplacement of the I-type unstressed plutons closely followed the end of deformation (Upper Permian to Triassic; Shaw and Flood, 1981). The I-type granitoids have mainly intruded the strongly deformed sediments of the Tablelands Complex. However, two plutons (the Moonbi Adamellite and the Inlet Monzonite) have intruded into the eastern edge of the Tamworth Belt (the Tamworth Group). Excellent contact aureoles have been produced around the I-type plutons (several of which have been investigated in the present study to examine the contact metamorphism of specific rock types).

   Upper Permian silicic volcanics are believed to have been co-magmatic with the I-type granitoids (Flood *et al.*, 1977,1980), and Korsch (1977) has suggested that rim synclines have been developed at the margins of some of these plutons (deriving his Dummy Creek Association).

7) The New England region has been generally stabilised since the Upper Permian (Shaw and Flood, 1981). Mesozoic cover, and Cainozoic basalts and sediment cappings have been laid down over parts of the New England Fold Belt.

1.4 CONTACT AUREOLES AND ROCK TYPES INVESTIGATED

1.4.1 Plutons

This study of contact metamorphism concentrates on the aureoles associated with the Upper Permian to Triassic (unstressed) I-type plutons within the New England Batholith, for these show the best development of contact aureoles. The study area is primarily confined to the region west of Armidale and southwards toward Tamworth (Fig. 1-4), which includes I-type plutons of both the Moonbi and Uralla Plutonic Suites (Section 1.3.3). Although all the contact aureoles within this area were investigated, detailed studies reported in this thesis involve only the following plutons: Mt Duval Adamellite, Uralla Granodiorite, Walcha Road Adamellite, Moonbi Adamellite, Inlet Monzonite.

1.4.2 Rock Types

It is appropriate here to outline the general characteristics and occurrences of the major lithologies selected for study. Detailed petrological descriptions are given in later chapters. Lithological associations mentioned below are those defined by Korsch (1977) (Fig. 1-2).

Pelitic Rocks

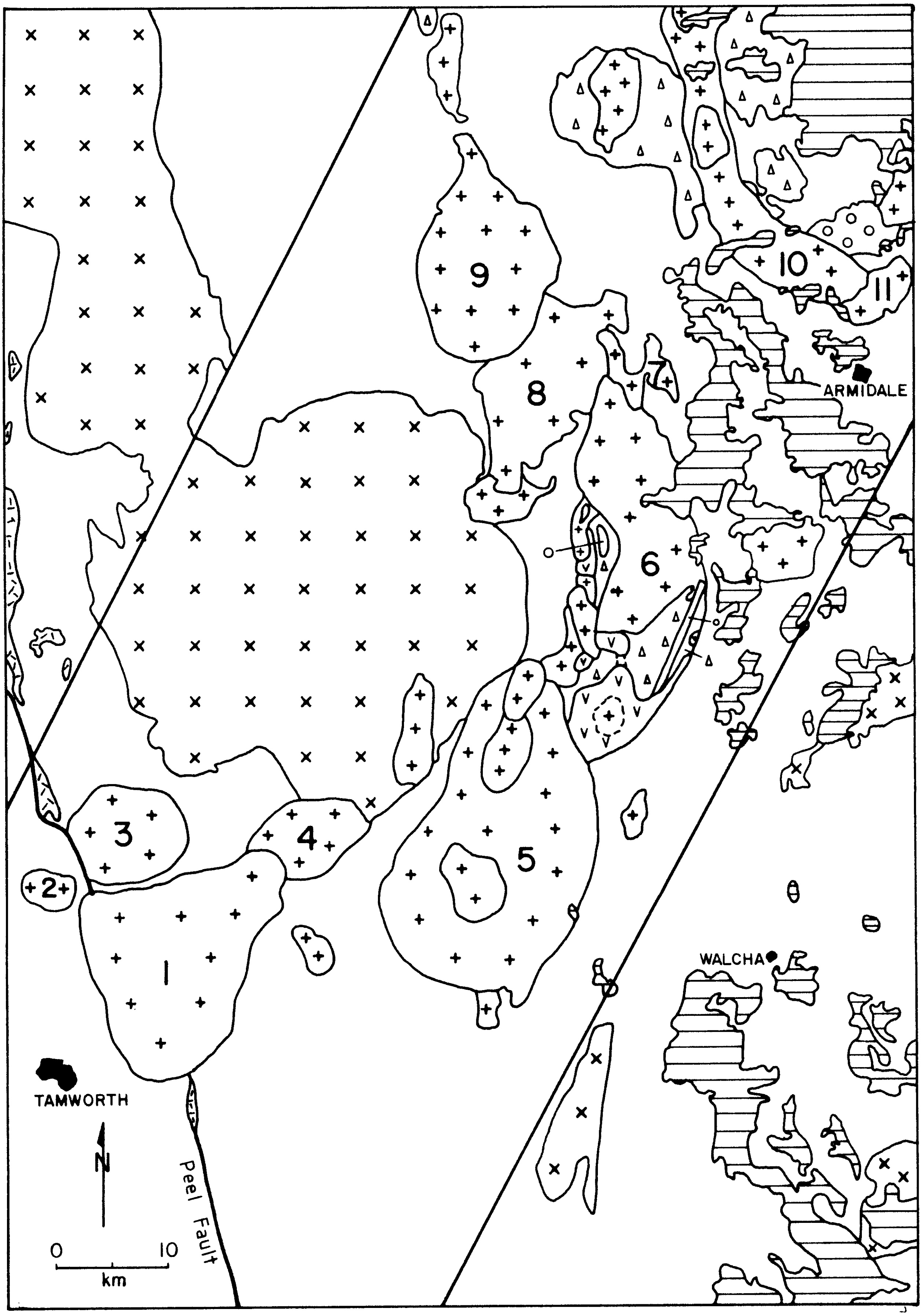
The term 'pelitic' refers strictly to fine-grained rocks (<1/16 mm). However, it is common practice in metamorphic petrology to use the term 'pelitic' to refer to rocks with an original high clay content (aluminous rocks) (e.g. Winkler, 1976; Turner, 1980) and this usage is followed here. Pelitic rocks are a relatively minor component of the country rocks within the study area, with the finer-grained sediments of the Woolomin Association and much of the Sandon Association being very siliceous. However, in the southern part of the Sandon Association, pelitic to semi-pelitic rocks are abundant, and well developed contact metamorphic effects are found within the aureole of the Walcha Road Adamellite.

Psammitic Rocks

The term 'psammitic rocks' refers here primarily to the greywackes, which are abundant throughout the Tablelands Complex. The greywackes investigated in this thesis are mainly those of the Sandon Association, in which they are interbedded with mudstones, minor cherts, jaspers and basic volcanics, and rare limestones. The greywackes have been studied in detail within the contact aureole of the Mt Duval Adamellite and at the northeast contact of the Uralla Granodiorite.

Impure Calcareous Rocks

Calcareous units of the study area are found mainly within the Tamworth Group, and investigation of these rocks is therefore centred on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ARMIDALE
WALCHA
TAMWORTH
N
Peel Fault
0
10
km

the aureoles of the Moonbi Adamellite and Inlet Monzonite. Several broad rock types are recognisable amongst the impure calcareous rocks. These are impure calcirudites, impure calcarenites, calcareous litharenites, impure biomicrites and stylolitic limestones. These rock types are fully described in Chapter Four. Three major localities are studied. Within the southern and western aureoles of the Moonbi Adamellite (termed the South Kootingal and Seven Mile Creek localities respectively), impure calcirudites are common within a sequence of arenites, siliceous mudstones, and volcanic breccias, while in the northern aureole of the Inlet Monzonite (termed the Horse Arm Creek Locality) calcareous units (including two major limestone horizons) form part of a well bedded sequence with siliceous mudstones, greywackes and conglomerates. Excellent examples of calc-silicate reaction bands occur within the calcirudites of the Horse Arm Creek locality, which are studied in detail in Chapter Five. Garnet skarns also occur at the contact of the Inlet Monzonite.

Basic Volcanics

Lenses of basic lava with tholeiitic affinities are minor components of the Woolomin and Sandon Associations. They occur within the aureoles of several of the major plutons and have been sampled in detail around the Mt Duval Adamellite, the Uralla Granodiorite, and the Moonbi Adamellite.

1.5 PREVIOUS INVESTIGATIONS

This thesis is the first major appraisal of contact metamorphism associated with the New England Batholith. Spry (1953,1955), Vernon (1961) and Binns (1965) are the only authors to have published papers primarily concerned with contact metamorphism in the New England region. Spry (1953) described the contact metamorphism of basic lavas and quartzofeldspathic sediments by the Puddledock Igneous Complex (16 km northeast of Armidale). Spry (1955) examined similar rock types in the southern and northern aureoles of the Mt Duval Adamellite. However, he found no relationship between the degree of metamorphism and distance from the contact in the sediments of either locality, and only a slight relationship in the basic lavas around the Mt Duval Adamellite. This is in marked contrast to the results of the present study. Vernon (1961) broadly delineated a sequence of mineralogical and textural changes related to grade within argillaceous sediments west of Uralla. Binns (1965) is the only author to have presented chemical data

Addendum to Section 1.5

Special reference is made to the Honours thesis of Teale (1974) submitted at the Macquarie University. Teale (1974) studied the contact metamorphics of pelitic rocks in the southeast aureole of the Walcha Road Adamellite, and represents the first detailed study of these rocks.

on minerals within the aureoles of the New England Batholith. He examined hornblendes from basic lavas located in the northern contact aureole of the Mt Duval Adamellite (described by Spry, 1955) and the eastern contact aureole of the Moonbi Adamellite, and noted distinct compositional trends in the hornblendes with increasing grade. (Unfortunately an error in scale, incorporated from a map by Spry (1955), belies comparisons made by Binns on the relative widths of these two aureoles; the scale bar shown in his Fig. 1 is approximately twice correct length.).

Numerous unpublished theses from the University of New England refer to contact metamorphsim around plutons of the New England Batholith. Many third-year and several B.Sc. Honours project reports include descriptions of contact aureoles, with those of Chappell (1959), Boesen (1960) and Flood (1964) being the most noteworthy. A Masters thesis by Ransley (1970), and Ph.D. theses by Neilson (1971) and Flood (1971) are studies of parts of the New England Batholith near Armidale, and all three devote a section to brief description of the associated contact metamorphism. Ph.D. theses by Leitch (1969) and Korsch (1975) both refer to contact aureoles associated with plutons in the more eastern part of the Batholith.

A few more recent papers have also mentioned contact-metamorphic effects in the New England region. These are by Korsch (1978), who recognised a regional-scale thermal metamorphism, Chappell (1978), and Flood and Shaw (1979).

1.6 GENERAL CHARACTERISTICS OF THE IGNEOUS CONTACTS AND METAMORPHIC AUREOLES

1.6.1 Pluton-to-Aureole Contacts

Contacts between the plutons and their country rocks are not well exposed generally. However, where outcrop is sufficiently good, sharp (some knife-edge) contacts can be observed. In a broad sense, pluton outlines are quite smooth, though in detail the contacts can be distinctly irregular. All contacts investigated in this study appear to be vertical or near-vertical, because their map traces are consistently unrelated to variations in topographic relief.

The plutons show no obvious chilled margins. With the exception of the Rocky River Leucoadamellite, inclusions of adjacent country rock within the granitoids are rare, even at the contacts. Aplitic and pegmatitic dykes are a common feature of the pluton margins, especially around the more-felsic bodies. Apart from the formation of garnet skarns in limestones at the northern contact of the Inlet Monzonite (Map, Appendix I), there is very little evidence of metasomatism at the pluton contacts. For example, chemical analyses of greywackes and basalts at various distances from the pluton contacts reveal no obvious systematic changes in the major or trace elements which might be attributed to metasomatism (see Chapter Three, Section 3.2, and Appendix II).

The granitoids typically show little textural variation between core and edge. However, in a few plutons a distinct foliation has developed at their margins parallel to their perimeters. This feature is best developed in the Walcha Road Adamellite, where a foliation extends at least 750m into the pluton. This foliation becomes stronger as the contact is approached, and is defined by intense flattening of mafic xenoliths and alignment of mafic minerals (hornblende and biotite) and K-feldspar phenocrysts. Weaker foliations have been recognised by Chappell (1978) in the margins of the Moonbi and Bendemeer Adamellites, and within the more-mafic margins of the Inlet Monzonite.

1.6.2 Aureole Widths

Aureole widths around several of the plutons in the study area are summarized in Table 1.1. The aureoles are substantially wider than previously suggested by workers in the New England region.

The outer limit of an aureole may be delineated in different rock types at slightly different distances from the contact. However, these differences are sufficiently small that comparisons may be made between the aureoles, even though their outer limits may have been defined using different rock types. There is a broad positive correlation between size of the pluton and width of the surrounding aureole. This has been recognised by several previous authors (e.g. Kerrick, 1970), and is consistent with the models of Jaeger (1957,1959) and Parmentier and Schedl (1981). Aureole widths around the smaller New England I-type plutons are typically about half the pluton's diameter. However, although the aureoles are wider around the larger plutons, the ratio of aureole width to pluton width appears to decrease with increasing size of the pluton (to about 1:4 for

TABLE 1.1. Relative widths of the contact aureoles around selected plutons in the southern part of the New England Batholith.

PLUTON	PLUTON WIDTH APPROXIMATE (km)	AUREOLE WIDTH (km)	ROCK TYPE*
Rocky River Leucoadamellite	1½	0.7	Greywacke
Tilbuster Granodiorite	3	1½ → 2	Greywacke, Basalt
Inlet Monzonite	3½	2	Calcareous litharenite
Mt Duval Adamellite	5½	2½	Greywacke
Uralla Granodiorite	8 → 9	>2½, <5#	Greywacke
Gwydir River Adamellite	10 → 11	>3, <5#	Greywacke
Moonbi Adamellite (southern part)	11 → 12	3½	Basalt
Walcha Road Adamellite	16 → 17	4	Pelite

* The outer limit of the aureole was defined using these rock types.

The aureole width could be delineated only to within these limits.

the Walcha Road Adamellite). No obvious relationship exists between composition of the magma and width of the contact aureole. However, compositional differences between the plutons considered may be insufficiently large to properly examine such a relationship.

1.6.3 General Structural Trends

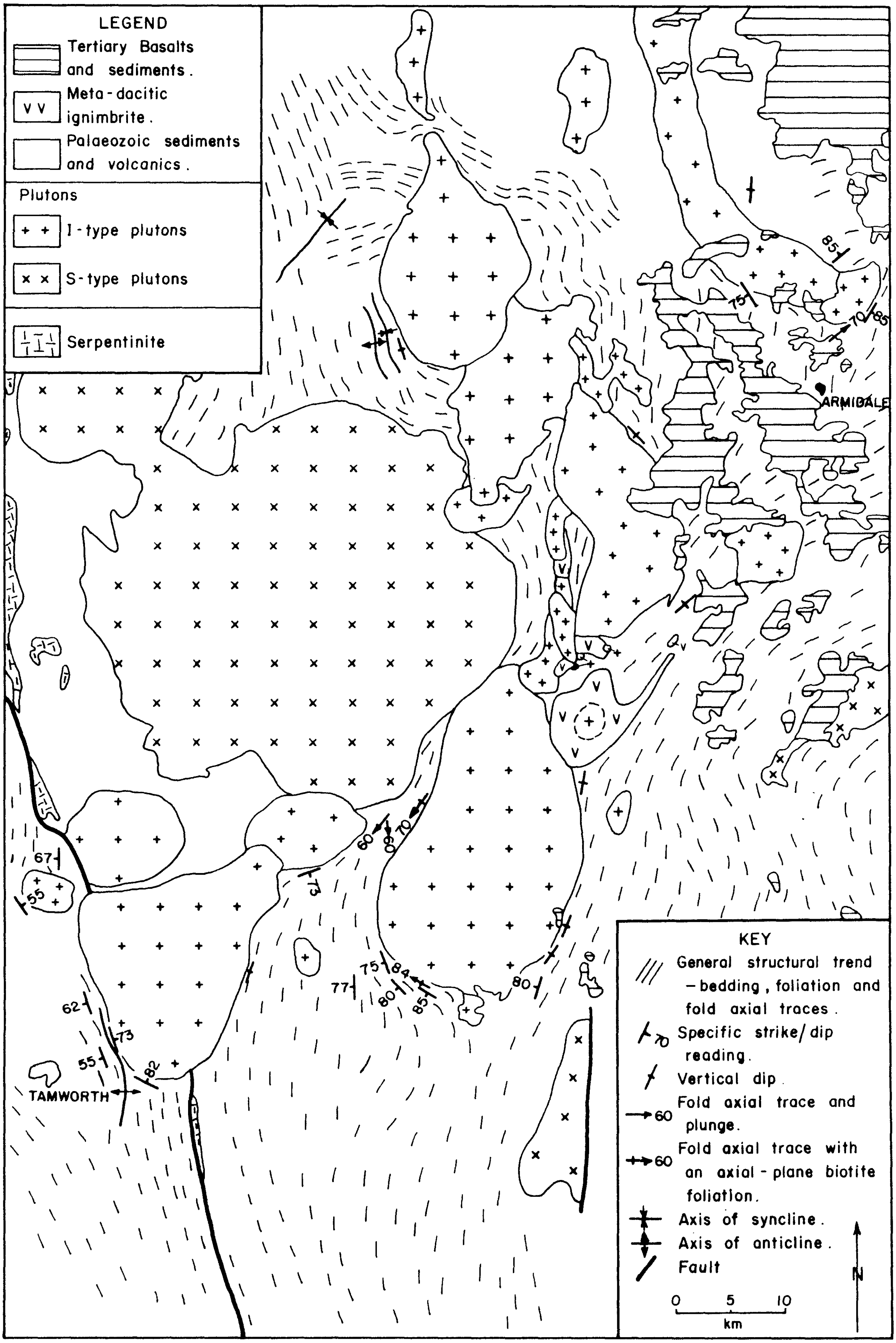
The general structural trends within the study region are shown in Fig. 1-5. Those of the Tablelands Complex (east of the Peel Fault) are based primarily on Binns *et al.* (1967) and Cuddy (1978). Those in the Tamworth Belt are mainly from the Manilla and Tamworth 1:250,000 geological maps, and recent theses of the University of New England. Structural data collected by the present author are also included.

The Palaeozoic sediments within the study area have a general N-S structural trend defined by bedding, fold axial traces and, in the Tablelands Complex, a regionally developed slaty cleavage. A marked foliation (typically defined by biotite) has been locally developed around a few plutons (described below).

From Fig. 1-5 it is apparent that the general structural trends in the country rocks wrap around the plutons, especially in the southern part of the area. As discussed by Fyson (1980, p.325), the tendency for structural trends to conformably curve around pluton outlines does not necessarily permit an unequivocal structural interpretation. This feature could result from outward stresses associated with emplacement of the plutons. Alternatively, it may result from regional deformation after emplacement of the granitoids. However, several authors have noted that there is no evidence of major deformation in the New England region after emplacement of the I-type plutons (e.g. Leitch, 1975; Chappell, 1978; Shaw and Flood, 1981). This is emphasised in the present study by the general lack of preferred orientation of phases developed during contact metamorphism, except in the inner aureoles of a few plutons. Consequently, the bending of structural trends around the plutons is believed to have been caused by pluton emplacement.

1.6.4 Mode of Pluton Emplacement

Pitcher and Read (1963) outlined four types of pluton emplacement which result in characteristic types of thermal aureoles: reactive


LEGEND
Tertiary Basalts and sediments.
Meta-dacitic ignimbrite.
Palaeozoic sediments and volcanics.
Plutons
I-type plutons
S-type plutons
Serpentinite
ARMIDALE
TAMWORTH
KEY
General structural trend - bedding, foliation and fold axial traces.
Specific strike/dip reading.
Vertical dip.
Fold axial trace and plunge.
Fold axial trace with an axial-plane biotite foliation.
Axis of syncline.
Axis of anticline.
Fault
0 5 10
km
N

emplacement, radial distension of the country rocks, lateral wedging and horizontal stretching, and permitted emplacement through cauldron subsidence. The mechanisms of radial distension and lateral wedging are forms of forceful emplacement, the latter being an extreme type of forceful emplacement and not applicable to the aureoles of this study. Reactive emplacement is characterised by contacts that are shallowly dipping, transitional with abundant rafts of country rock in the pluton margins, and show evidence of metasomatic activity. These features are not evident in the pluton contacts described above, and reactive emplacement apparently has not been an important mechanism. More-recent studies (e.g. White *et al.* 1974; Leitch, 1976; Pitcher and Bussell, 1977; Barriere, 1977; Pitcher, 1979) have concentrated on the remaining two possible mechanisms of Pitcher and Read (1963); 1) forceful emplacement associated with diapiric intrusion and 2) permitted emplacement by cauldron subsidence.

In this study, the I-type granitoids appear to have been forcefully emplaced, because deformational features believed to have resulted from the plutons' emplacement (described above) are found around most of the plutons. Similarly, there is no evidence within the plutons of rafted country rocks, expected to result from permitted emplacement associated with subsidence of a mechanically collapsed roof (e.g. White *et al.* 1974, p.169). Widths of the aureoles are also inconsistent with permitted emplacement. Pitcher and Read (1963) described very narrow aureoles (or none at all) around plutons apparently emplaced by cauldron subsidence, whereas aureoles around the larger plutons of this study are over several kilometres wide (Table 1.1). Wide aureoles are consistent with a forceful mode of emplacement (Pitcher and Read, 1963).

Two types of aureoles appear to occur around the forcefully emplaced plutons in New England. Aureoles around most of the plutons investigated appear to have been only mildly deformed and no foliation has been produced within the country rocks as a result of the intrusion. Deformation in these aureoles has mainly caused previous structures, including bedding, fold axial traces and the regionally developed slaty cleavage, to be aligned parallel to the contacts. Folds lacking an axial-plane foliation may also have formed (Cuddy, 1978). In contrast, the aureoles of a few plutons appear to have been intensely deformed during pluton emplacement, manifested by strong foliation in their inner part, and isoclinal folds, especially near the contacts, possessing an axial-plane foliation defined by the contact-metamorphic phases (typically biotite). The latter type of aureole is best shown around the Walcha Road Adamellite, but these features also occur around the Moonbi Adamellite and, to a lesser extent, the Inlet Monzonite.

The mild deformation associated with most of the plutons is unlikely to have provided sufficient room for emplacement of the plutons. To solve the room problem, it is possible that a crustal block above the magma was vertically displaced upwards during intrusion. This mechanism has been suggested by several authors, including Leitch (1975) in the New England region, White *et al.* (1974), and Barriere (1977). Alternatively the room problem could be partially solved by intrusion into a tensional regime (as suggested by Cuddy, 1978), and it is feasible that both possibilities were involved in the emplacement of these magmas. Contact metamorphism within the mildly deformed aureoles involves entirely static recrystallisation. This could be related to the mildness of deformation, but even where folds have been strongly reorientated, no alignment exists in the contact-metamorphic phases. Consequently, it appears that in these aureoles the peak of contact metamorphism may have been reached after deformation.

In contrast to the mildly deformed aureoles, deformation in the more-intensely deformed aureoles, appears to have accompanied the peak of contact metamorphism, developing the prominent foliation. Pitcher (1979) has described a model for development of this type of aureole, in which the initial emplacement of the magma (possibly in a manner similar to that described above) is further modified by radial distension (or ballooning), caused by the continuous infilling of the pluton core by fresh magma. A similar mode of emplacement is envisaged here for the plutons that have caused development of foliation in the country rocks. Pitcher (1979) also noted that emplacement of this type usually affects the carapace of the pluton itself, producing a schistosity common to both the envelope and pluton. This is consistent with the present study, where plutons associated with strongly deformed aureoles possess a foliation in their margins.

It is proposed that New England I-type plutons associated with both mildly deformed intensely deformed aureoles may have been initially emplaced in a similar manner, initially causing only mild deformation. Mostly deformation seems to have ceased early, followed by static contact metamorphism in a rigid envelope. However, in a few plutons (those associated with intensely deformed aureoles), deformation continued in the form of radial distension and affected the surrounding country rocks during contact metamorphism.