CHAPTER 4: STRUCTURAL GEOLOGY OF THE DYAMBERIN BLOCK

The structural work attempted in the Dyamberin Block has been of a reconnaisance nature because of its inaccessibility and extreme ruggedness. The picture presented below is of one widespread deformation throughout the Block producing a highly fissile slaty cleavage, and of a localised second deformational episode producing mesoscopic folds in the slaty cleavage. The stratigraphy, sedimentation and metamorphism of the Block are described in Appendix 1 (pp.7-9, 38-44 and 79-80 respectively).

Mesoscopic Structures

(a) D1 Structures

The planar surface imposed by D1 is a slaty cleavage which is penetrative in pelitic and diamictitic rock types on the scale of the outcrop. These rocks are very fissile, cleavage planes being spaced at 1-2 mm. In the coarser-grained lithologies the cleavage is usually not as well developed although in some conglomerate and greywacke horizons it is incipiently- to well-developed.

The L(So x S_1) lineation has two forms. Most common is a faint colour variation due to laminations in the bedding observed on the cleavage planes. Less common is the occurrence of extensively flattened pebbles in conglomerates. The long and intermediate axes of pebbles (X and Y respectively) define the principal plane XY of the deformation ellipsoid. At one locality in Marengo Creek (GR 5380 2688) this plane is oriented at 142/SW/75 at a slight angle to the cleavage plane at 140/NE/80. Nevertheless it is possible to imagine that the cleavage developed perpendicular to the direction of maximum finite shortening if one considers various situations of inhomogeneous strain affecting the pebbles and their matrix.

D1 mesoscopic folds are relatively rare and are observed mainly in the more competent sandstone layers which are up to 0.3 m thick. The folds have rounded hinge zones and cut by an axial plane slaty cleavage.

(b) D2 Structures

S_2, although rarely observed, does occur as widely spaced fractures cutting the slaty cleavage. The intersections define the $L(S_1 \times S_2)$ lineation the attitude of which was determined on the stereographic projection.

Mesoscopic D2 folds in the cleavage are also observed at isolated localities, and are open to gentle folds with rounded hinges and wavelengths commonly between 0.6 m and 1 m.

Macroscopic Structures

Because of the reconnaisance nature of the work in this block, no macroscopic folds have been identified by the writer, but Cumming (1971) located one and traced it over a distance of 500 m in a coarse sandstone near the Dyamberin copper mine (GR 5230 2650).

The Demon Fault is a really major structure which defines the eastern limit of the Dyamberin Block. It is by far the most prominent structure showing on ERTS-A images of the New England Tablelands. Dynamic metamorphic effects of movement on the Demon Fault are described in Appendix I (pp.85-86). Noticeable structural effects in the sediments of the Dyamberin Block are the development of kink bands in the slates, and, close to the fault, a pronounced swing in the strike of the cleavage from about 144° to 110°.

Both sinistral and dextral kink bands occur, some of them as adjacent conjugate pairs. The principal stress axes determined from one measurable pair are: σ_1 = 50 to 276, σ_2 = 25 to 152, σ_3 = 28 to 048, with σ_1 lying in the unrotated cleavage plane of attitude 160/W/50. Poles to dextral and sinistral kinks (FOLN 41 and FOLN 42 respectively) are shown on Figure 66 G, H.

Apart from those described above the structural effects of the Demon Fault on the Dyamberin Block sediments are surprisingly insignificant.

Macroscopic Geometry of the Dyamberin Block

Because of the limited amount of available data this tectonic Block is treated as a single domain but it is emphasised that the picture presented below is probably a simplification because the existence of major unrecognised macroscopic D1 folds is likely. Trends of the bedding and slaty cleavage form-surfaces are presented on Maps 4 and 5.

DYAMBERIN BLOCK

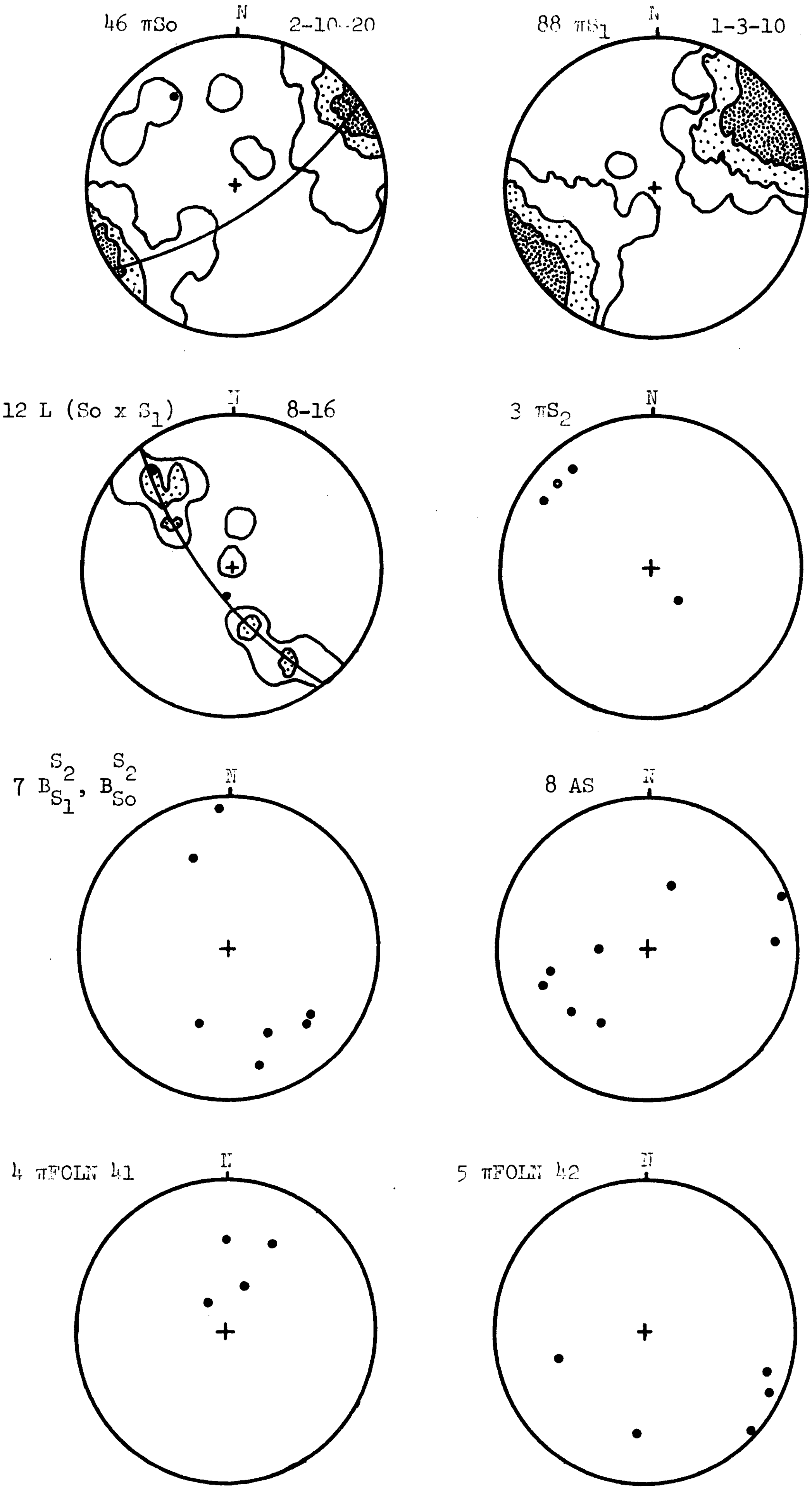


Fig. 66: Stereographic projections for the Dyamberin Block.
Figures in upper right hand corners are contour intervals.

Poles to bedding (Fig. 66A) fall on a partial great circle with orientation 056/SE/70, and β_{So} = 20 to 326. Poles to slaty cleavage (Fig. 66B) define a great circle at 051/SE/75 with β_{S_1} = 15 to 321, indicating that both bedding and slaty cleavage have been deformed by an episode of cylindrical folding. L(So x S_1) define a partial great circle girdle of attitude 140/SW/70 (Fig. 66C) suggesting that these lineations, which were probably co-planar after their formation during D1, were deformed by a slip mechanism during a second folding deformation.

S_2 surfaces are rare (Fig. 66D) but indicate planes striking northeast with variable dips. The net plots of fold axes and axial surfaces (Fig. 66E, F) might be interpreted as partial great circle girdles. However because different generations of structures have not been differentiated on the nets (FA = $B^{S_1}_{So}$ and $B^{S_2}_{S_1}$, AS = S_1 and S_2) it is not possible to determine the significance of these patterns.

Conclusions

The following conclusions can be drawn from a reconnaisance survey of the structures in the Dyamberin Block:

1. The Block has been affected by two episodes of mesoscopic deformation;
2. the first episode occurred over most of the Block or all of it, and produced mesoscopic folds, a penetrative slaty cleavage in fine-grained lithologies, and severe flattening of pebbles in conglomeratic horizons. Folding on a macroscopic scale is suspected;
3. the second deformational episode was very localised and produced mesoscopic open to gentle folds in the slaty cleavage;
4. movements on the Demon Fault, apart from the development of kink bands and slight changes in strike of S_1 in an extremely limited zone adjacent to the fault, have had almost no noticeable effect on the rocks of the Block;
5. the slaty cleavage, defined by a preferred orientation of white mica and chlorite, is axial plane to the D1 folds and hence there is a close temporal relationship between metamorphism and D1 deformation. Permian fossils have been found in the Dyamberin Beds (Appendix I, p.8). All deformation appears to have ceased before or during the emplacement of the Round Mountain Leucoadamellite at the close of the Permian period, and therefore the age of the deformation is Permian.

CHAPTER 5: COMPARISON OF STRUCTURES IN THE THREE TECTONIC BLOCKS

The three tectonic blocks in the Rockvale - Coffs Harbour region are similar in that all show the effects of at least two episodes of deformation that produced superposed mesoscopic and macroscopic folds. A very minor D3 deformation of the Wongwibinda Complex is considered to be a late waning stage of the major D2 deformation. It caused only minor flexuring of the S_2 schistosity.

Two major faults separate the tectonic blocks, the Demon Fault between the Coffs Harbour and Dyamberin Blocks, and the Wongwibinda Fault between the Dyamberin and Rockvale Blocks. It is not possible to trace any structures such as marker horizons, cleavage and macroscopic folds across the faults into an adjacent block. The D1 and D2 terminology has been applied separately to each block and it is not assumed that D1 in the Rockvale Block is the same episode as D1 in the Coffs Harbour Block. Until now, the deformations in each block have been treated as separate events and no attempt has been made to correlate them.

Burns (1972) invented an "algebra of geological events", and he has also written a conjugate computer programme, EVENT, (Appendix II) which is used here to check the sequence of s-surfaces and to check the estimate of the number of phases of deformation in each structural block. The computer results have been translated into chain diagrams (Fig. 67) for easier interpretation.

Examination of Figure 67 suggests that the Dyamberin Block has been affected by two deformations after the initial formation of primary foliations such as bedding, whereas the Rockvale and Coffs Harbour Blocks have both been affected by three deformations since deposition. The chain diagrams confirm the results of "normal" structural analysis of the Rockvale and Dyamberin Blocks, but contradict those of the Coffs Harbour Block. The chain diagram for the Coffs Harbour Block indicates that dextral (41) and sinistral (42) kink bands in quartz veins (35) cut across cleavage planes (31) and hence are a later development. It is considered that these quartz veins were emplaced in tension gashes opened during the formation of the kink bands, and consequently the quartz veins and kink bands are considered to be products of the same episode of deformation (D2).

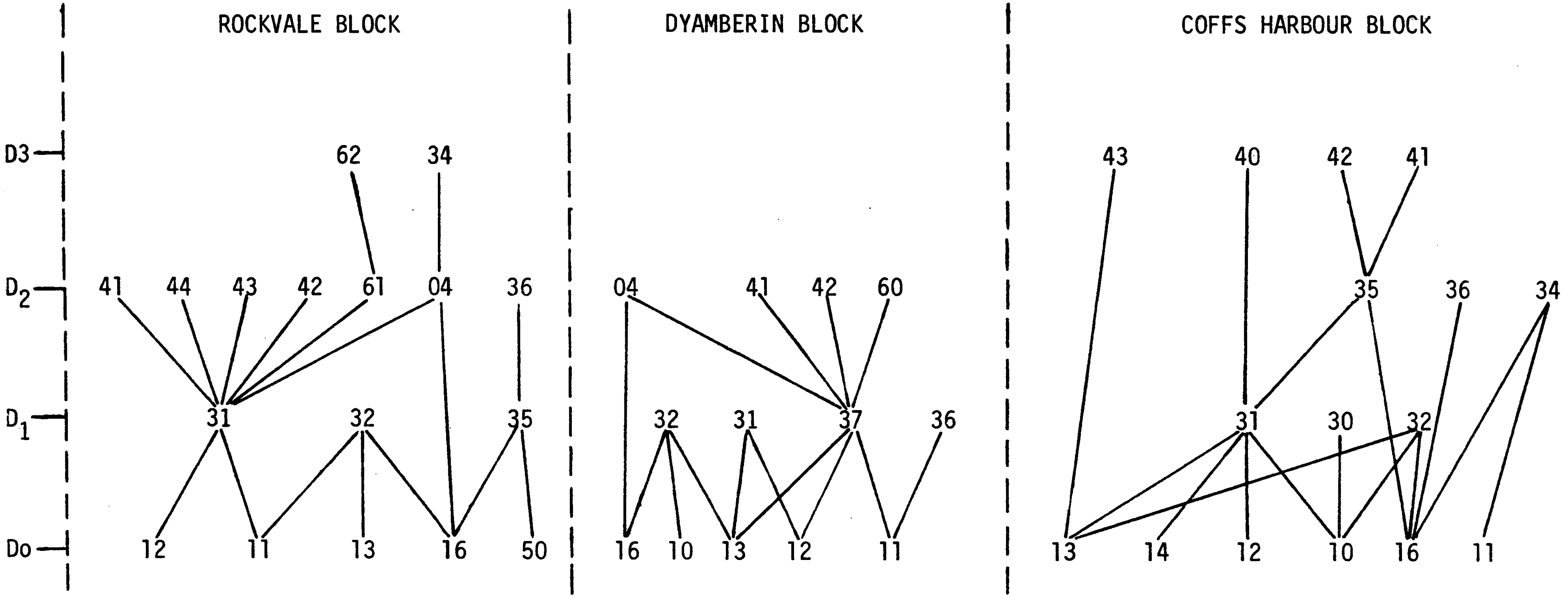


Fig. 67: Chain diagram derived from results of program EVENT showing sequence of S-surfaces for each structural block, and grouping of events into deformational episodes. (Key to numbers is given in Appendix II, Table 19).

It has been shown for all three blocks individually that the deformations occurred in the Permian. Moreover, it is likely that all the deformational episodes were associated with the Middle Permian orogeny that affected much of the New England region (Leitch 1974).

The similarity of the mesoscopic structures in the three blocks, and particularly of the slaty cleavages, makes it tempting and attractive to propose that these structures might have resulted from the same deformational episode (D1) over the whole of the Rockvale - Coffs Harbour region. As a further hypothesis D2 structures also could be a product of a second deformational episode affecting the whole region. If those hypotheses are pursued, the ages of the deformations could be determined more precisely with the aid of K-Ar ages of rocks from the Rockvale Block. D1 is considered to have commenced in early Permian time and was essentially completed prior to emplacement of the Tobermory Adamellite at 259 m.y. D2 is considered to have commenced then or later, perhaps at about 250 m.y. D2 finished before the emplacement of the Wards Mistake Adamellite at 244 m.y. It is possible that the two episodes of deformation were two phases of one protracted period of deformation which was operative during Early and Middle Permian time.

The only region adjacent to the Rockvale - Coffs Harbour region where detailed structural work has been done is the Nambucca Fold Belt in which Leitch (1972) has recognised five episodes of deformation, which he considered to be Middle Permian in age. He showed that the regional metamorphism of the Nambucca Fold Belt had a close temporal relationship with his D1 episode of deformation. By recent unpublished K-Ar dating of the low-grade rocks from this belt Leitch (pers. comm.) has shown that the average age of rocks of the prehnite-pumpellyite grade is 264 m.y. whereas it is 249 m.y. for rocks of the pumpellyite-actinolite and greenschist facies. These dates define the time range of metamorphism and therefore the approximate time range of D1 in the Nambucca Fold Belt, and they agree closely with the conclusions presented here for the Rockvale - Coffs Harbour region. Hence the D1 episode of deformation could be synchronous across the Nambucca Fold Belt and the Rockvale - Coffs Harbour region.

Just to the south of the writer's field area in the Wollomombi - Jeogla region Leitch (1972) recognised only two deformations D1 and D5, his D2, D3 and D4 being absent. The effects of these episodes are similar to those observed in the Girrakool Beds around Wollomombi and hence D2 described here is tentatively correlated with the D5 episode of Leitch (1972).

SECTION II : TECTONICS OF THE SOUTHERN PART OF THE NEW ENGLAND GEOSYNCLINE

INTRODUCTION

The tectonic setting for the southern part of the New England Geosyncline has not been explained satisfactorily, although several workers have speculated on this region while proposing models based on the theory of plate tectonics to interpret the geological evolution of various parts of Eastern Australia. To date the only detailed syntheses of the New England region have been those of Leitch (1975) and Runnegar (1974). The models proposed by these writers are considered to be invalid and will be discussed in Chapter 7.

Since the development of the theory of plate tectonics the concept of the geosyncline, as originally proposed by Kay (1951), has been undergoing extensive modification. Several authors have proposed that the term "geosyncline" should be discarded because the original concept has become outdated and that retention of the name would only lead to confusion (e.g. Coney 1970, Scheibner 1972). However Dewey and Bird (1970) and Dickinson (1971) have outlined schemes whereby the concept of the geosyncline can be accommodated within the framework of the plate tectonic theory. Continued use of the term is also advocated by Hsu (1972, 1973).

Several new names have been proposed for the New England region including New England Orogenic Belt (Griffiths 1971), New England Fold Belt (Scheibner and Glen 1972, Leitch 1974) and New England Mobile Belt (Packham 1973). The term New England Geosyncline, proposed by Voisey (1958), has beeen used by Marsden (1972) and Harrington (1974) and is retained in this thesis. The use of plate tectonic terms follows the definitions suggested by Dennis and Atwater (1974).

This section has been divided into two parts. Chapter 6 is a synthesis of the current geological knowledge to the end of 1974,of the southern part of the New England Geosyncline, and Chapter 7 develops a new alternative to previously proposed tectonic models.

Much use has been made of unpublished data contained in theses held at the University of New England and wherever possible the original source of the material is acknowledged. Whereas the synthesis has relied heavily upon both published and unpublished data, all the proposed stratigraphic associations have been examined by the writer in the field. Lack of data from certain areas have hindered the accurate determination of some boundaries, and these are likely to be modified by future work.

A copy of the published Geological Survey of New South Wales 1:500,000 Geological Map of New England which summarises published and unpublished data available up to January 1972, has been included as Map 8 for comparison with the maps outlining the distribution of the geological elements discussed in the synthesis (Maps 6 and 7).

CHAPTER 6 : SYNTHESIS OF GEOLOGICAL DATA FROM THE SOUTHERN PART OF THE NEW ENGLAND GEOSYNCLINE

The New England Geosyncline (*sensu stricto*), following the definition of Harrington (1974), consists of Palaeozoic sediments and associated igneous rocks lying to the east of the Hunter-Mooki Fault system in northern New South Wales, and to the east of the Bowen Basin in central and southern Queensland. The southern part of the geosyncline, for which this synthesis is compiled, is separated from the northern part by the Mesozoic Clarence - Moreton and Great Artesian Basins. A major review of this region by Voisey (1959) has been superseded recently by the work of Leitch (1974a). A summary of geological information available on the region up to 1967 is given in Packham (1969).

The southern part of the New England Geosyncline has been divided into two major subdivisions by Voisey (1959). These are separated by the Peel Fault system which is a well defined arcuate structure, commonly delineated by serpentinites, extending from Warialda in the north to at least Nundle in the south. To the southeast of Nundle the fault system becomes fragmented and has been termed the Manning Fault system by Voisey (1939b).

To the west and south of the Peel Fault system there occurs a sequence of mildly deformed and burially metamorphosed sediments termed the Tamworth Belt (after Harrington 1974). The Hastings Block, the northern part of which consists of the Parrabel Anticline (Voisey 1934) is correlated with the Tamworth Belt.

TAMWORTH BELT

Synonymy: Western Belt of Folds and Thrusts (Voisey 1959), Tamworth Trough (Crook 1961a), New England Foreland (White 1966), Tamworth Synclinorial Zone (Scheibner 1972), Zone A (Leitch 1972, 1974a), Tamworth Shelf (McKelvey 1974), Tamworth Fold Belt (Runnegar 1974). All of the above synonyms are considered to be unsuitable because all have structural or sedimentological connotations which are not strictly correct. The term Tamworth Belt is preferred because no genetic inferences are made.

The Tamworth Belt has been the subject of much intensive study, and compared with the region east of the Peel Fault, the geology is well understood. Detailed mapping has been attempted by Crook (1959, *et seq.*), White (1966) and McKelvey (1966) and the contributions by previous workers are adequately covered by the above authors. The University of New England has published a series of 1:100,000 geological maps on the belt (see list in McKelvey 1968). Recent summaries of the northern part of the belt have been provided by Packham (1969), Marsden (1972), Leitch (1974) and McKelvey (1974). The Carboniferous geology in the southern part of the belt has been recently described by Roberts and Oversby (1973). Jones *et al.* (1973) provide a chart correlating ten stratigraphic sections from the Carboniferous of the Tamworth Belt with other Carboniferous sections in Australia.

Recent work by Cross (1974) south of Nundle has shown the presence of an ophiolite suite consisting of basal serpentinite with gabbros, dolerites and spilites interbedded with Tamworth Group sediments. The sequence, from the base of the serpentinite, is over 2.5 km thick. A thin limestone unit containing Early-Mid Devonian corals occurs in a 100 m thick sequence of sandstone and mudstone found between the serpentinite and the first occurrence of albite dolerite. The contacts of the sediments with the serpentinite and dolerite appear to be faulted. The work of Cross indicates that the Tamworth Belt, at least in the Nundle area, is underlain by oceanic crust and this negates the suggestions of Rutland (1974) that the Tamworth Belt is underlain by Precambrian continental crust.

The Werrie Basin (Carey 1934, 1937) has been re-examined in the northern part by Moore (1974). The oldest unit is the Baldwin Formation which occurs along the western limb of the Werrie Syncline. The lowest beds in this unit consist of coarse volcanic breccias and flows considered by Moore to have been deposited on the flanks of the source volcanoes. This suggests that the western Baldwin Formation was the site of a volcanic island arc during Late Devonian time.

Metamorphism in the Tamworth Belt has been of zeolite and prehnite-pumpellyite facies developed largely due to depth of burial. Crook (1961d) has recorded a close association between depth of burial and development of metamorphic mineral facies in the northern part of the Belt. Preliminary work on the southern part of the belt by Offler (1973) suggests the metamorphism is regional rather than burial.

The Tamworth Belt is intruded by the Inlet Monzonite (average age 248 m.y. Cooper *et al.* 1963) north of Tamworth and by the Barrington Tops Granite (258 m.y. Cooper *et al.* 1963) in the Barrington Tops National Park area. The Inlet Monzonite is considered to be an early member of the New England Batholith (*sensu stricto*) whereas the Barrington Tops Granite (more correctly an adamellite or granodiorite, Mayer 1972) has preceded metamorphism (Offler 1973) and is here tentatively placed in the Hillgrove Plutonic Suite.

Deformation in the Tamworth Belt has not been as severe as deformation east of the Peel Fault System. The belt has been folded into a series of elongated, often doubly-plunging anticlines and synclines which are associated with numerous faults. Isoclinal folds have been observed adjacent to the Peel Fault and Cook (1973) has shown that interlimb angles for mesoscopic folds change from 5° adjacent to the Peel Fault System to 105° only 5 km to the west. Deformation in the belt has been summarised by Crook (1963) and Leitch (1974c).

HASTINGS BLOCK

Synonymy: Parrabel Anticline (Voisey 1934), Eastern Belt of Folds and Thrusts (Voisey 1959), Kempsey Block (Scheibner 1972), Hastings Block (Leitch 1972, 1974; Harrington 1974). Previous work on the Hastings Block has been carried out mainly by Voisey (1934, 1937, 1938, 1939 a, b). The northern part of the block consisting of the Parrabel Anticline has been examined recently in more detail by Lindsay (1964, 1969), Bourke (1971) and Northcott (1973).

Rocks from this block are similar to rocks from the southeast portion of the Tamworth Belt but because of conflicting palaeontological evidence (compare Campbell 1962 with Lindsay 1969) conclusive correlations with the Tamworth Belt have not been possible. Future work, concentrating in the southern part of the Hastings Block, might resolve the conflict.

Part of the Hastings Block is unconformably overlain by the Triassic Lorne Basin described by Voisey (1939c) and Pratt and Herbert (1973).

Deformation and metamorphism of the Hastings Block was only mild. Lindsay (1969) reported broad open noncyclindrical folds complicated by some cross folding from the lower Macleay region. Cleavage is not developed and Leitch (1972) recorded the presence of prehnite, and suggested that the rocks belong in the quartz-prehnite zone of the prehnite-pumpellyite facies, Igneous rocks within the Hastings Block at Gundle have been described by Matthias (1967) as intrusive adamellites, porphyries and aplites. A large body of biotite-hornblende porphyrite intruding the western margin of the block has been described by Matthias (*op. cit.*) and Bourke (1971).

CENTRAL COMPLEX

The term "Central Complex" as used here includes the "Central Complex" and "Upthrust blocks" of Voisey (1959).

Synonymy: Zone A (Leitch 1972, 1974) Tablelands Complex (Runnegar 1974), several blocks of Scheibner (1972) including Woolomin - Texas Block, Nambucca Block, and Demon Block. The Central Complex makes up the major portion of the southern part of the New England Geosyncline.

The writer concurs with much of the work of Leitch (1974) although several fundamental interpretations of his, particularly with regard to the distribution of his stratigraphic associations and recognition of metamorphic zones and tectonic blocks are questioned, and where considered necessary these have been extensively revised.

1. STRATIGRAPHIC ASSOCIATIONS

Up until very recently a comprehensive stratigraphic scheme had not been proposed for sedimentary rocks from the Central Complex. Voisey (1934) divided the coastal rocks into the Nambucca Series, Coffs Harbour Series and Devonian - Permian rocks of the Parrabel Anticline. Subsequently Voisey (1959, 1969) divided his Central Complex and Upthrust Blocks into the Woolomin Beds, Nambucca Beds and Coffs Harbour Beds.

Leitch (1974) recognised seven major lithological associations within the Palaeozoic sediments of the Central Complex. Similar subdivisions are recognised here but the areal distribution of the proposed subdivisions differs markedly from those proposed by Leitch (see Map 6).

The stratigraphic associations have been differentiated mainly on the basis of lithological types although some biostratigraphic control has been provided by known fossil localities. Conflicting palaeontological data from some associations have not been resolved and consequently precise ages cannot be assigned to much of the Central Complex.

(a) Woolomin Association

This association consists of chert, jasper, basic volcanics and rare sandstone, argillite and limestone lenses. Lusk (1963) divided the Palaeozoic sediments between the Bundarra Suite and the serpentinite near Bingara into two distinct units. The western unit (Forest Creek Beds) consists predominantly of chert, jasper and metabasic rocks with very rare clastic sediments, and contrasts with the eastern unit (Gundamulda Creek Beds) of greywackes, argillites and rarer cherts. Leitch (1974) includes both these units in his Lower Palaeozoic chert-jasper-siliceous argillite-basalt association. However only the western sequence (dominated by the cherts) is included in the Woolomin Association here. This association is mainly restricted to a narrow NNW trending belt adjacent to the Peel Fault (the Woolomin Beds, Chappell 1961). Other units in New England included in this association are the Myra Beds (Mayer 1972), Cascade Creek Beds (Heugh 1971), Leyburn Beds (Butler 1974) and the Redbank River Beds (Korsch 1971), an unnamed chert-jasper sequence around Port Macquarie (Goodwin 1962) and the part of the Oxley Block described by Bourke (1971) and Leitch (1972).

Cherts and jaspers are commonly radiolarian-bearing and are usually recrystallised. The rare sandstones are lithic greywackes (Fig. 68) and fall in the quartz-poor field of Crook (1974). Detrital plagioclases range from An_0 to An_{43} (53 determinations by Bofinger 1961) and K-feldspar is extremely rare. The main detrital constituents are basic-intermediate volcanic and sedimentary lithic fragments. The predominant grade of metamorphism recorded is prehnite-pumpellyite facies (Lusk 1963, Bofinger 1961) although Butler (1974) tentatively suggests the rocks northwest of Warwick have suffered greenschist facies grade of metamorphism. Chemical work on some basic volcanics in the Barraba district by G. Corbett (pers. comm.) suggests that the rocks have tholeiitic affinities. Fitzpatrick (in press) concluded that metabasites from the Woolomin Beds near Limbri may be potash-rich tholeiitic basalts.

Where reliable evidence can be obtained, most units of the Woolomin Association appear to be fault bounded. This association is separated from the Sandon Association at Barry by the Gogs Fault (Heugh 1971) and is fragmented in the Nowendoc - Gloucester region by the Manning Fault system. In southeast Queensland the association is separated from adjacent Palaeozoic rocks by thrust faults (Butler 1974). Lusk (1963) considers it to be conformable with the Gundamulda Creek Beds in the Bingara region, but Fitzpatrick (in press) reports a faulted contact further to the south.

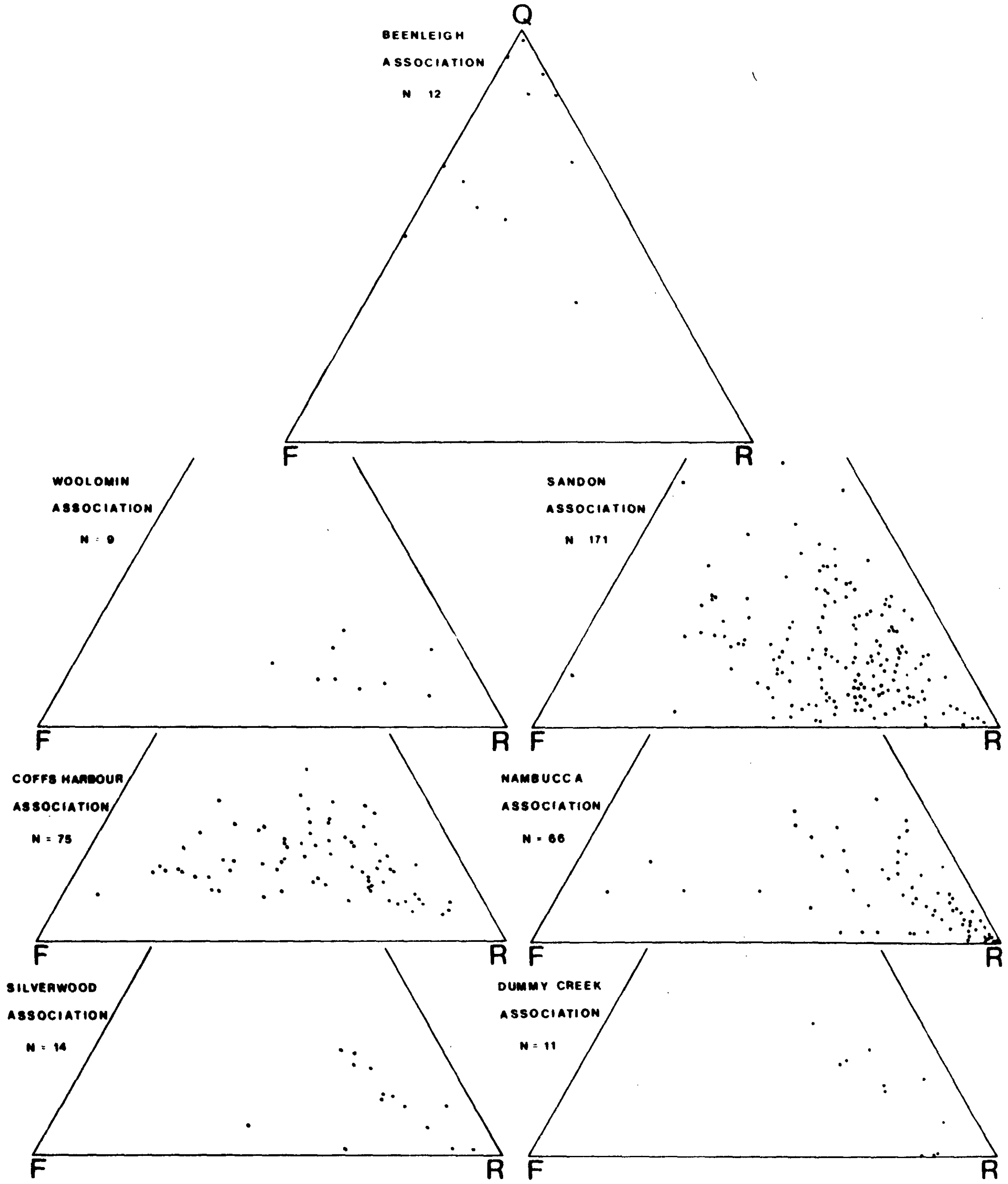


Fig. 68: Composite QFR diagrams for sand-sized sediments from the sedimentary associations recognised in the New England region.

The age of the Woolomin Association is not clear. Chappell (1961) recorded corals of Ordovician - Silurian age from limestone bodies in the Woolomin Beds northeast of Attunga. Hall (1970) re-examined these limestones and found some localities to be Late Ordovician (Eastonian) and others to be Silurian (Wenlockian - Ludlovian). Hall considered the Ordovician faunas occurred within a fault slice associated with the Peel Fault System and that the Silurian faunas were associated with the Woolomin Beds. Silurian limestones within the Woolomin Beds (or their equivalents) have been reported by Lusk (1963) from the Bingara district. K. Fitzpatrick (pers. comm.) has recollected from many of the localities of Chappell, Hall and Lusk and has also found several previously unrecorded occurrences of limestone. As well as the Ordovician and Silurian corals, Fitzpatrick found Early Devonian corals within the Woolomin Beds northeast of Attunga. In no case did he record a contact which he considered unequivocally conformable; on the contrary, where contacts were not obscured he found the limestones to be in fault contact with typical Woolomin Association rocks.

To date no worker has found fossils in the Woolomin Association which can be considered definitely conformable in the sequence, and because of the presence of fault contacts it is suggested the limestones have been emplaced as slivers along faults. Complex structural deformation, often producing isoclinal folds, has prevented the determination of the stratigraphic thickness of this association.

(b) Sandon Association

This association consists of greywackes and mudstones with minor cherts, jaspers, intermediate to basic volcanics and rare limestones and conglomerates. The rocks of the Sandon Association occupy a broad north-south trending belt up to 80 km wide extending from the Leyburn area in southeast Queensland to the Nowendoc area in northern N.S.W.; a distance of over 350 km. The association has been intruded by granitic rocks of the Bundarra Suite and New England Batholith (*sensu stricto*), and is unconformably overlain by late Permian acid volcanics.

Examples of this association are the Sandon Beds around Armidale (Leitch *et al.* 1969); Brandy Springs Beds at Barry (Heugh 1971); Gundamulda Creek Beds and sediments of the Bundarra - Kingstown area (Lusk 1963); Texas Beds in N.S.W. - Queensland border region (Olgers and Flood 1970). The Texas Beds comprise the Thanes Creek Slate, Beacon Mudstone and part of the "Permian" sequence described by Lucas (1960).

Also included in this association is the Ashford limestone (Raggatt 1941) and associated rocks.

The Sandon Association, as used here, consists of rocks of the Texas Block, portions of the Woolomin type blocks and portions of the Upper Palaeozoic blocks of Leitch (1972) and comprises parts of associations (i) and (iv) of Leitch (1974).

Petrographically the sandstones are quartz-poor to quartz-intermediate lithic greywackes (Fig. 68), and have been derived predominantly from volcanic sources. In the Texas region Butler (1974) considered that the greywackes were derived predominantly from a rhyolitic and dacitic volcanic provenance, supporting the earlier work of Lucas (1960). Lusk (1963) considered the greywackes in the Bundarra region to have been derived from a predominantly intermediate volcanic source. All workers consider the clastic sediments are turbidites. Contourites have been recognised in the Texas region by Butler (1974) and in the Armidale region. Reinterpretation of traction current deposits described by Smith (1973) suggests a deep water origin for sediments from this association.

Butler (1974) found that limestone deposits in the Texas region occurred as tectonically stretched horizons and as boulder sized blocks in disorganised conglomerates. He considered these limestones to be slide deposits forming allochthonous blocks within the turbidite sequence.

The age of the Sandon Association is not clear. Allochthonous limestones found in the Texas region are Carboniferous (Visean, Strusz *in* Olgers and Flood 1970a). A Late Visean age has also been determined for the Ashford limestone (Northcott 1972). The recognition of forereef to backreef facies by Northcott indicates this limestone is *in situ*. Crook (1958) found a plant fossil in the Sandon Beds just west of Armidale and considered it to be Early Carboniferous in age. More plant fossils from the same locality (Smith 1973) were considered by Dr. R.E. Gould (pers. comm.) to have Late Devonian affinities and to have been deposited in a near shore environment. He considered the plant roots may be possibly as young as Early Carboniferous. It is possible these roots were transported away from the near shore environment in which they grew, and were deposited in deep water. The close association with contourites and turbidites provides support for transportation to a deep water environment. Butler (1974) reports the presence of twigs and logs in turbidites from the Texas Beds.

The only other fossil locality found to date in the Sandon Association is a Silurian limestone reported by Lusk (1963) from the Gundamulda Creek Beds close to Woolomin Association rocks. As no contacts with the typical rocks of the association were observed it is possible that this is a slide deposit or a fault sliver. Lusk described the locality as clastic fragments of limestone in a carbonate matrix and grading into argillites containing limestone detritus. Apart from this Silurian limestone all fossils found from the Sandon Association are Upper Devonian to Lower Carboniferous. Because these localities are considered to be slide deposits the sediments may possibly be younger than the Visean age obtained from these limestones.

Part of Tia Complex (Oxley Metamorphics, Wybeena Metamorphics, Woombi Greenstones, Lochaber Greywackes of Gunthorpe 1970) consist of greenschist and amphibolite facies metamorphic rocks and are metamorphosed equivalents of this association. Chemical analyses by Gunthorpe of several basic lavas suggest they had tholeiitic affinities.

The thickness of this association is unknown but is considered to be several thousand metres (e.g. Texas Beds, Olgers and Flood 1970a). In places complex deformation of the sediments has occurred (e.g. Smith 1973; Butler 1974).

In most cases rocks of the Sandon Association are in fault contact with adjacent Palaeozoic sediments. Nevertheless Lusk (1963) considered these rocks were possibly conformable with rocks of the Woolomin Association.

(c) Coffs Harbour Association

This association consists of monotonous thick sequences of greywacke, siltstone and argillite. Conglomerates, volcanic rocks, chert and jasper are extremely rare and limestones have not been recorded. The association is typically developed in the Coffs Harbour Block (this thesis) which has been subdivided into three distinct stratigraphic units (Leitch *et al.* 1969). Detailed petrography of a small region around Woolgoolga (Korsch 1971) has now been extended to cover most of the block (Appendix I, Chapter 2).

The rocks were predominantly deposited by turbidity currents and have an acid to intermediate volcanic provenance. The Coramba Beds have been subdivided into four lithostratigraphic units on the basis of detrital composition of the greywackes. All greywackes are quartz-poor types and were subdivided on the feldspar to lithic fragments ratio and the presence or absence of detrital hornblende (see Appendix I, pp. 26-27). Feldspathic greywackes are more common than in other associations (Fig. 68).

Leitch (1974) considered that this association (his type v) only occurred in the southern part of the Coffs Harbour Block. However the sediments around Rockvale are very similar to those from the Coffs Harbour region (see Appendix I, pp. 44-48) and it has been possible to distinguish the Coramba Beds greywacke petrographic varieties around Rockvale although the areal extent of each unit has not been defined. To the south of Armidale rocks of the Coffs Harbour Association occur as fragmented blocks near Winterbourne (Haydon 1974) and constitute the Brackendale Metamorphics and Agnes Greywacke (Gunthorpe 1970).

It is interesting to note that the majority of intrusions forming the Hillgrove Plutonic Suite occur within this association and that the two amphibolite facies regional metamorphic localities in New England (the Wongwibinda Complex and Brackendale Metamorphics) represent metamorphosed equivalents of this association. Areas where thermal biotite is developed on a regional scale, apart from one area southwest of Stanthorpe, also occur in rocks of this association.

It is suggested that the volcanic rocks from which the sediments of this association were derived had calc-alkaline affinities (see Appendix I, pp. 31-32). Chemical analyses of greywackes from this association by Hensel (1973) and Haydon (1974) also suggest derivation from dellenites with calc-alkaline affinities.

The absence of limestones and paucity of conglomerates, which are the two main fossil bearing lithologies of other associations, coupled with the abundance of greywackes deposited by turbidity currents suggest that fossils might be rare. To date only one locality has been found (Gunthorpe 1963) and the broken shell fragments have been identified by Runnegar (1970) as *Atomodesma* sp. indicating a Permian age. Korsch (1971), on lithological grounds, considered the sediments in the Coffs Harbour region to be Late Palaeozoic, possibly Carboniferous, in age. Radiometric age determinations are at present being undertaken on detrital hornblendes from a greywacke of the Coramba Beds. Until this dating has been completed it is tentatively suggested that the Coffs Harbour Association is Late Palaeozoic in age.

Contacts with adjacent associations appear to be faulted. In some areas work is not sufficiently detailed to accurately locate the boundary while in other areas it is obscured by alluvium.

(d) Nambucca Association

The Nambucca Association is characterised by diamictite units which are often up to 50 m thick (Mayer 1972). Other rock types present are orthoconglomerates, greywackes, siltstones, mudstones and rarer acid to basic volcanic horizons and limestone members.

Rocks of this association are typically developed in the Nambucca Slate Belt where Leitch (1972) has recognised several lithostratigraphic units. However severe deformation has prohibited an estimate of the thickness of this sequence.

Mayer (1972) has reported thick sequences containing abundant diamictites in the Nowendoc - Gloucester area, and has been able to subdivide the unit (the Manning Group) into several formations, all of which appear to be conformable. In the border rivers area a thick sequence of diamictite, conglomerate, greywacke and argillite has been reported by Lucas (1960) and remapped by Vickery (1972). Oxley (1972) records rocks typical of this association in the Silver Spur Beds northeast of Texas and several small localities in southern Queensland have been described by Olgers and Flood (1970a). Isolated occurrences of this association have been recorded in the Walcha district (Flood 1964) and east of the Tia Complex (Gunthorpe 1970). The Dyamberin Block (this thesis) also belongs in this association.

The greywackes have been deposited predominantly by turbidity currents, the bulk of material being derived from a volcanic source area which was mainly acidic-intermediate in composition. These greywackes are mainly quartz-poor lithic types (Fig. 68). Gravity sliding of coarse material is considered to have been an important mechanism in the formation of the diamictites (Mayer 1972). While acid volcanics are an important source of material a significant contribution from acid plutonics and chert has been observed in some areas. Mayer (*op. cit.*) reports that chert clasts are abundant in the lowest portions of the Manning Group but become less important with an increase in acid volcanic material upwards in the sequence.

Several fossil localities have been recorded in rocks of this association, mainly from the diamictite horizons. Many localities are listed by Runnegar (1970) and new localities discovered since are recorded in unpublished theses held at the University of New England. The majority of localities suggest an Early Permian age (Allandale or Fauna II of Runnegar

1967). G.R. McClung (pers. comm.) regards the Allandale fauna as being possibly latest Carboniferous in age, and suggests that Fauna II is Early Permian.

From fossil evidence it is concluded that the Nambucca Association was deposited in Late Carboniferous to Early Permian time. In places the association is unconformably overlain by Mid-Late Permian acid volcanics. In every case where the situation could be determined, this association was observed to be in fault contact with rocks of other Palaeozoic associations described above.

(e) Silverwood Association

Rocks of this association consist of abundant andesitic lavas, tuffs and agglomerates along with sandstones, mudstones, chert and rare limestones. Leitch (1974) considered this association (his type iii) occurred only south of Warwick (the Silverwood Group of Richards and Bryan, 1924). Olgers and Flood (1970) divided this group into three formations and recorded a sequence 4400 m thick. P.C. Dennis (1974) revised the formations of Olgers and Flood but recorded a similar total thickness to that of the earlier workers.

Rocks in the Fine Flower region south of Baryulgil consist of andesitic tuffs, flows and agglomerates which appear to fine towards the west, where greywackes and mudstones become more abundant. These rocks have only had cursory examination (e.g. Gutsche 1961, Morrow 1967, McQueen 1971) and the relationship between the andesitic volcanics and the clastic sediments is not known. South of Fine Flower limestones associated with clastic rocks have been reported from around Jackadgery (Whiting 1950). Leitch (1974) erected a separate association for these rocks but he neglected the presence of the andesitic volcanic sequence. These rocks are here tentatively included in the Silverwood Association and hence association (ii) outlined by Leitch is considered superfluous.

The greywackes from the Silverwood Group are quartz-poor lithic varieties (Fig. 68) derived mainly from a volcanic source area. P.C. Dennis (1974) considers the volcanism was contemporaneous with rapid deposition, and his chemical data suggests volcanic rocks of this association have tholeiitic affinities.

Several fossil localities have been found in the Silverwood Association, particularly in the Warwick region. Poorly preserved corals from Jackadgery were considered to be Silurian by Fletcher (*in* Whiting 1950) but may possibly be Devonian (B.N. Runnegar, pers. comm.). Abundant faunas, mainly corals and conodonts, in the Rosenthal Formation of P.C. Dennis (1974) indicate an Early Devonian (Siegenian-Early Emsian) age (Hill 1940; Strusz 1967; Telford 1972). P.C. Dennis records all limestone localities as angular blocks within sediments of various types and considers that these limestone breccias formed by a mass movement mechanism.

Allochthonous limestones from the Mendip Formation of P.C. Dennis (1974) have yielded fossils of conflicting ages. J. Jell suggested an Early Devonian age for a coral which he identified as *Favosites bryani*. Conodonts were tentatively assigned an Ordovician or Silurian age by T. Jenkins and from the same limestone clast D.M. Dennis and R. Wass assigned a Carboniferous age to bryozoans. The conflicting palaeontological data make it difficult to determine the age of this association. If the Carboniferous age for the bryozoans is correct then the Mendip Formation must be at least as young as Carboniferous. This formation differs from the underlying predominantly volcanic formations in the absence of volcanic material and the presence of diamictites and boulder conglomerates containing granitic clasts. In other areas conglomerates contain granitic clasts which are Carboniferous in age (e.g. Paddys Flat, McCarthy *et al.* 1974; Neranleigh - Fernvale Beds, Green 1973).

The Silverwood Group is separated from the Texas Beds by a thrust fault and is either faulted against or unconformably overlain by the Permian Wildash Group. Relationships of the association in the Jackadgery region with surrounding associations are unknown.

(f) Dummy Creek Association

The Dummy Creek Association consists of shallow marine to terrestrial deposits of mainly conglomerates, with minor sandstones and mudstones and are usually intimately associated with acid volcanics which are tuffs, agglomerates and flows. This association is constructed here as Leitch made no provision in his associations for these rocks, appearing to include them with the Permian acid volcanics.

This association has been reported from several isolated localities around Armidale : Dummy Creek Conglomerate at Tilbuster (McKelvey and Gutsche 1969, Lewis 1973); east of Uralla (Heugh 1970); Wilsons Creek, west of Uralla (Want 1972) and near Yarrowyck (Bourke 1970). Similar rocks have been reported southeast of Tamworth at Mulla Creek (Short 1971) and R.G. Cuddy (pers. comm.) has found rocks of this type south of Tingha. In the border rivers region rocks of this association occur near Ashford (David 1885; Neuss 1966) and at Gibraltar Range (Lucas 1960; Vickery 1972). The Wildash Group south of Warwick is also included in this association and has been examined by several workers including Richards and Bryan (1924), Armstrong (1966), Olgers and Flood (1970) and D.M. Dennis (1974).

Apart from the Ashford Coal Measures all localities are closely associated with acid volcanic rocks which, in the Wildash Group, have calc-alkaline affinities (P.C. Dennis 1974) and all localities occur close to granitic plutons. Most localities contain conglomerates which have clasts derived from the underlying basement, as well as a volcanic and plutonic component. For example the Dummy Creek Conglomerate at Tilbuster contains clasts of chert, jasper and greywackes derived from the Sandon Beds on which the Dummy Creek Conglomerate rests unconformably. The conglomerate associated with the Ashford Coal Measures mainly comprises boulders of sandstone derived from the underlying Beacon Mudstone (Neuss 1966). In the Wildash Group clasts of volcanics, chert and limestone have all been recorded by D.M. Dennis (1974). She recorded Devonian fossils from the limestone clasts and abundant Permian faunas within the sequence. Thus a considerable amount of clasts in the Wildash Group conglomerates have been derived from the older underlying Silverwood Group. The petrography of the sandstones indicates they are quartz-poor lithic types (Fig. 68) and have been derived fromthe same source area as the associated conglomerates.

Fossils are common in rocks of this association. Permian *Glossopteris* - *Gangamopteris* floras have been recorded from Tilbuster (McKelvey and Gutsche 1969), east of Uralla (Heugh 1970), south of the Tingha Adamellite (R.G. Cuddy pers. comm.), the Ashford Coal Measures (Pittman 1896), Gibraltar Range area (Vickery 1972) and in parts of the Wildash Group (D.M. Dennis 1974), and thus support the terrestrial nature of at least part of this association. Inadequate preservation of fossils and absence of indicative species do not allow the precise defining of the time of deposition within the Permian. Nevertheless at Gibraltar Range the *Glossopteris* bearing Mossman Formation unconformably overlies the Silent Grove and Bodonga Beds which contain Early Permian (probably Fauna II) fossils (Vickery 1972). This suggests the Mossman Formation is possibly of Late Permian age.

Several Permian marine faunas have been described from the Wildash Group (e.g. Maxwell 1954; Campbell 1961; Armstrong 1966; Dickins *in* Olgers and Flood 1970a). The most recent work by D.M. Dennis (1974) indicates most of the fossils are Fauna IV in age. Only the Rokeby and Wallaby Beds have been assigned a Fauna II age. *Glossopteris* was found in the Wallaby Beds and Eight Mile Creek Beds (which is Fauna IV in age) and hence its occurrence at other localities cannot be assigned a definite age.

Most localities of this association are undeformed to slightly deformed and rest unconformably on more highly deformed basement. The major period of deformation in New England is considered to have occurred in the Middle Permian (Leitch 1969) and hence rocks of the Dummy Creek Association are probably Late Permian in age.

A problematical area is the Glenmore region where the only known fossils are Permian Fauna IV (McCarthy 1971, Boxall 1972). Olgers and Flood (1970b) claim a Carboniferous - Permian unconformity exists but this view is opposed by Warner (1970), McCarthy (*op. cit.*) and Boxall (*op. cit.*).

The Glenmore Beds (Lucas 1960, redefined by Boxall 1972) consists of an intensely folded sequence of lithic sandstones and siliceous mudstones with associated conglomerates, diamictites and rare cherts. The uppermost unit of the Glenmore Beds is a conglomeratic sequence named the Long Gully Conglomerate member by Boxall (*op. cit.*). The relationship of this conglomerate to the Glenmore Beds is regarded by Boxall to be either gradational or one of scour and fill and hence conformable. Boxall also considered the Glenmore Beds were conformably overlain by the Little Oakey Creek Volcanics which consist of acid to intermediate tuffs, lava flows, ignimbrites and associated sediments.

However, the deformation styles of the Glenmore Beds and Little Oakey Creek Volcanics are markedly different. Tight to isoclinal folds occur in the Glenmore Beds and contrast with very gentle deformational effects observed in the volcanics. It is difficult to concur with Boxall who considered that both units had suffered the same single period of deformation and that the volcanics were more competent and hence deformed less than the sediments. Therefore it is considered here that the Glenmore Beds (*sensu stricto*), but not the Long Gully Member, represent rocks of the Nambucca Association. The intimate relationship of the Long Gully Conglomerate member with the Little Oakey Creek Volcanics is reminiscent of the Dummy Creek Conglomerate - Annalee Pyroclastics relationship described by McKelvey and Gutsche (1969), and hence the Long Gully Conglomerate member is tentatively placed in the Dummy Creek Association.

An extremely close spatial relationship exists between the Dummy Creek Association and acid plutonic rocks which are often of batholithic proportions. The conglomerates occur near the margins of the plutons and the rocks of this association are here considered to be deposits infilling a *rim syncline*. Ramberg (1967, Fig. 35 and pp. 101-105) has described in detail the method of formation of rim (marginal) synclines which are a result of the intrusion into the country rocks of material such as salt or magma. Ramberg found in models and in nature that the depression forming the rim syncline is always located a short distance away from the root of the developing diapiric dome. Debris deposited in the rim synclines in the New England region has been eroded from the material being uplifted as a result of the intruding diapirs. Further upward intrusion has brought the diapir sufficiently close to or even in contact with the sediments in the syncline to produce the contact metamorphic effects frequently observed in rocks of this association.

(g) Beenleigh Association

Rocks of this association consist of mainly greywackes, argillites, cherts and rarer basic lavas and conglomerates and typically occur in the Southport Block of Hill (1957) which she later renamed the Beenleigh Block (Hill 1960). Detailed structural mapping of part of this block is at present being carried out by E. Lohe from the University of Queensland. Rocks examined by the writer east of the Clarence - Moreton Basin at Hastings Point and Byron Bay consist of interbedded greywacke, argillites and siliceous mudstones.

Petrographically the greywackes are considerably more quartz-rich than greywackes from west of the Clarence - Moreton Basin and are very similar to the quartz-rich to quartz-intermediate greywackes reported from several localities (e.g. Brisbane area, Tucker 1967; Slacks Creek, Gould 1967; Byron Bay, Cusack 1970; Tallebudgera Creek, E. Lohe pers. comm.). QFR diagrams for this association and those located west of the Clarence - Moreton Basin adequately illustrate this point (Fig. 68).

Fossils from the Beenleigh Association are rare but Carboniferous invertebrates have been reported from the Neranleigh - Fernvale Beds north-west of Brisbane by Fleming *et al.* (1974). Green (1973) records a radiometric age of 335 m.y. from a granitic clast in a conglomerate horizon of the Neranleigh - Fernvale Beds in Tallebudgera Creek.

The Mt. Barney Beds (Maxwell 1960) comprise a 2000 m thick marine Carboniferous sequence intimately associated with the Mt. Barney Central Complex in southeast Queensland. The Carboniferous rocks are exposed as the result of doming-up of the country rocks and up-faulting of a volcanic plug (Stephenson 1959) and appear to be the basement for the Clarence - Moreton Basin in that region. The Mt. Barney Beds consist of limestone, subgreywacke, feldspathic sandstone, siltstones and a conglomerate horizon (Maxwell *op. cit.*) and are included in the Beenleigh Association.

West of the Clarence - Moreton Basin at Paddys Flat McCarthy (1972) recorded a sequence of shelf-type sediments consisting of paraconglomerates, sandstones and calcareous mudstones (the Emu Creek Beds, after Voisey 1936). Acid plutonic clasts predominate in the paraconglomerate but boulders of acid volcanics and sediment occur also. Biotite from a clast of granitic rock has been dated by D.C. Green (*in* McCarthy *et al.* 1974) as 331 m.y. which is almost identical with the 335 m.y. age reported for a clast from the Neranleigh - Fernvale Beds by Green (1973). McCarthy (1972) recorded Late Carboniferous faunas both above and below the conglomerate (termed the Currawinya Conglomerate by McCarthy *et al.* 1974). The absence of four fossil zones at Paddys Flat between the Carboniferous and Permian Fauna II localities possibly suggests that sedimentation was not continuous during the period spanned by the two assemblages, even though the sequence appears to be conformable (McCarthy *et al.* 1974).

Petrographically the sandstones are quartzose and feldspathic types and are more akin to the Beenleigh Association than the associations proposed here for west of the Clarence - Moreton Basin. Palaeontological and radiometric age evidence suggest an age similar to that of the Beenleigh Association and hence the Paddys Flat sequence is placed in this association.

Relationships of this association with other Palaeozoic associations are unknown. The sequence at Paddys Flat is faulted against, or unconformably overlain by the Drake Volcanics to the west and is unconformably overlain by the Mesozoic sediments to the east.

2. METAMORPHISM

Palaeozoic rocks east of the Peel Fault, apart from those of the Dummy Creek Association, have suffered at least prehnite-pumpellyite grade of regional metamorphism. McKee and Leitch (1971) and Leitch (1974 a, b) have outlined a zonal scheme which they consider to be applicable over most of New England. The zones listed by Leitch (1974b) suggest an intermediate pressure facies series of Miyashiro (1973) because of the presence of the pumpellyite-actinolite facies. Work in the Coffs Harbour Block (see

Appendix I, pp. 51-79) indicates that a low pressure facies series type of metamorphism has affected large areas and the zonal scheme of Leitch might not be as widely applicable as first thought. Metamorphism from high pressure types to very low pressure regional types have been recorded from the New England region (see Map 7).

Rocks indicating high pressure are rare and have been recorded only as inclusions in the serpentinite. Glaucophane schist inclusions have been reported by Quodling (1964), Matthias (1967) and Mayer (1972). An eclogite inclusion from northeast of Attunga has been reported recently by Shaw and Flood (1974). Bayly (1974) found inclusions of greenschist and foliated amphibolite within a serpentinite mass at Glenrock, and a small foliated amphibolite inclusion from the Woodsreef area has been reported by Glen and Heugh (1973). Shaw and Flood (*op. cit.*) have estimated that their eclogite inclusion crystallised between 290°C - 600°C at a minimum pressure of 7-12 Kb.

Gunthorpe (1970) considered that a crossite-stilpnomelane-pumpellyite assemblage found overprinting low-pressure metamorphics of the Tia Complex formed at conditions of about 5 Kb and 200 - 250°C, and represents an intermediate-high pressure facies series. Gunthorpe contemplated that this phase of metamorphism developed coincidently with the serpentinisation of the peridotite and increase in pressure resulting from volume increases and tectonic emplacement during serpentinisation.

A zonal scheme of four intermediate-pressure facies series zones has been developed by Leitch (1972) for the Nambucca Slate Belt where greenschist facies conditions of metamorphism associated with severe deformation were reached. Leitch (1974 a, b) attempted to apply this scheme to the whole of the New England region. Details of the locations of the zones have not been published and hence cannot be corroborated here. Mineral assemblages described in unpublished theses rarely have recorded the presence of stilpnomelane and actinolite outside the Nambucca Slate Belt, and the intensity of deformation for that belt is not known from elsewhere in New England. Work for this thesis has shown that the zonal scheme of Leitch cannot be applied to the Rockvale - Coffs Harbour region and much more work will be required to check the validity of the scheme for other regions within New England.

The Coffs Harbour Block (Block II of Leitch 1974) has suffered only low pressure conditions (this thesis). In the Texas Beds actinolite and stilpnomelane have not been recognised although biotite, indicative of greenschist conditions, is developed incipiently in the higher grade rocks

(Butler 1974). Leitch (1974a) considers the metamorphism of the Tia Complex (Block 2 of Leitch *op. cit.*) described by Gunthorpe (1970) to be of a similar series to that of the Nambucca Slate Belt. However conditions outlined by Gunthorpe infer a geothermal gradient of approximately 38°C/km which is significantly higher than the 15 - 25°C/km postulated by Leitch for the Nambucca region, and is more akin to the 40°C/km postulated for M1 from the Coffs Harbour Block (Appendix I, pp.76-77). Low-pressure conditions also existed during metamorphism of the Wongwibinda Complex (Binns 1966). Hence in at least three of the blocks outlined by Leitch the metamorphism was influenced by low pressure rather than intermediate pressure conditions. Apart from the known intermediate pressure conditions of the Nambucca Slate Belt, sufficient data are not readily available to the writer to determine pressure conditions for the remainder of the blocks.

A very low-pressure metamorphism, extremely similar to contact metamorphism, has been found on a regional scale over parts of the Coffs Harbour and Rockvale blocks (see Map 2). The metamorphism is akin to a static thermal event and similar conditions have been reported by Gunthorpe (1970) in the Moona Plains region. H.R. Butler (pers. comm.) has also mapped a large area west of Stanthorpe where similar conditions of metamorphism have occurred.

3. IGNEOUS ROCKS

(a) Granitic Rocks

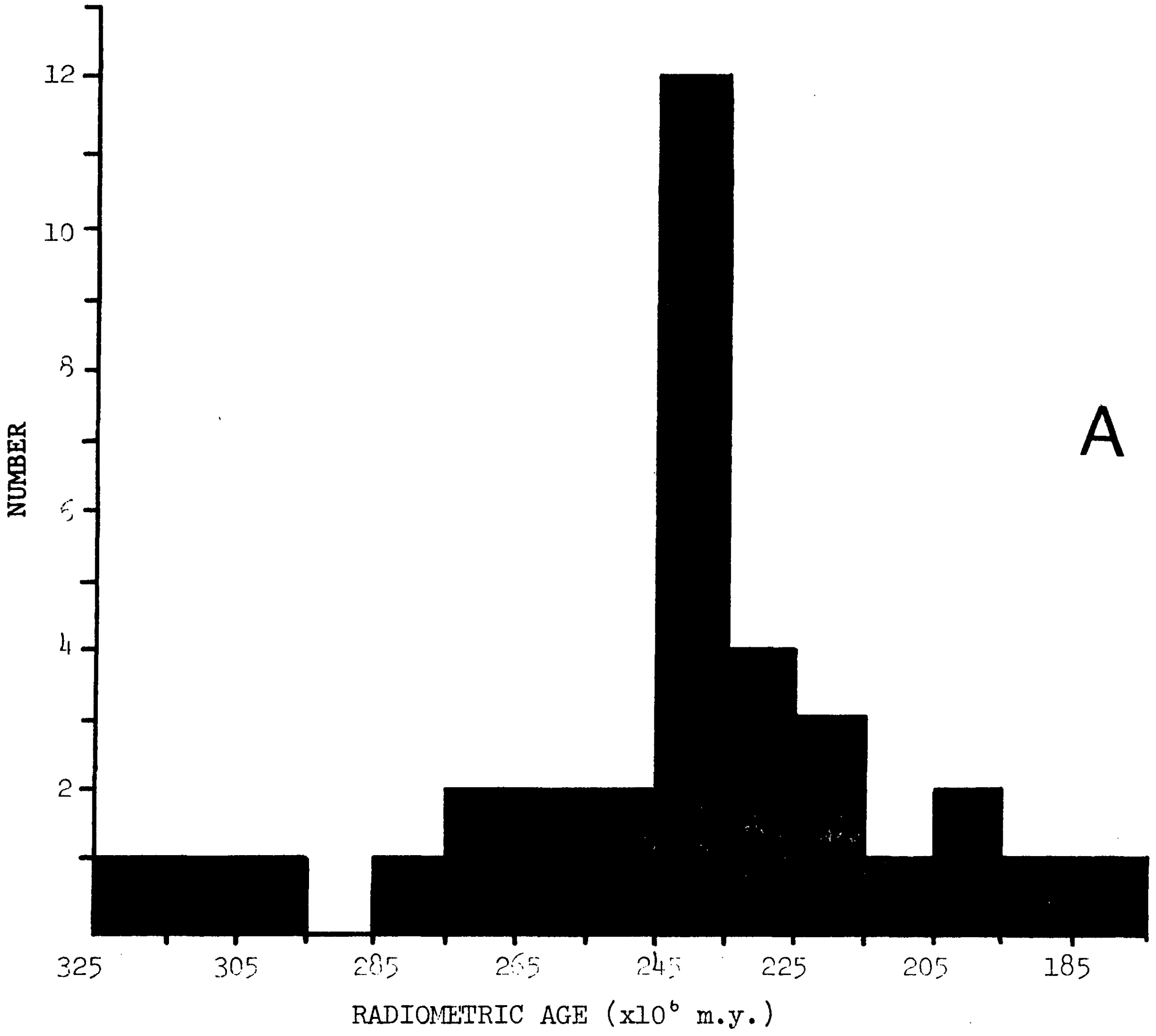
Three separate suites of acid intrusive rocks have been recognised in the Central Complex (Binns *and others* 1967; Flood 1971; Wilkinson 1974a). The main differences between these suites are briefly discussed in Appendix I (p. 89 and Table 16) and summaries of the main petrological and chemical differences have been provided by Wilkinson (1974a) and Leitch (1974a).

The ranges of radiometric ages for the plutonic suites have been modified by recent determinations and a list of known ages is included as Table 10. The distribution of the radiometric ages in geological time is shown in Figure 70.

The Bundarra Plutonic Suite occurs as a narrow north-south trending belt over 220 km in length and is situated to the east of the Peel Fault system. Specimens from this suite collected west of Bonshaw and west of Bukkulla have yielded ages of 304 - 317 m.y. (J.D. Kleeman, pers. comm.). Hence the age of the Bundarra Plutonic Suite ranges from 317 m.y. in the

Table 10: Radiometric ages for plutonic rocks from the New England region

		Age	Method	Pluton	Reference
NEW ENGLAND BATHOLITH (*sensu stricto*)	EASTERN BELT	181	K/Ar	Valla Adamellite	McKenzie 1972
		191	K/Ar	Yarrahapinni Adamellite	McKenzie 1972
		200	K/Ar	Morgans Creek Adamellite	McKenzie 1972
		203	K/Ar	Rivertree Granite	McKenzie 1972
		210	K/Ar	Koreelan Creek Granodiorite	McKenzie 1972
		222	Rb/Sr	Stanthorpe Adamellite	Shaw 1964
		223	K/Ar	Undercliffe Falls pluton	Evernden &Richards 1962
		224	K/Ar	Round Mtn. Leucoadamellite	Binns & Richards 1965
		225	K/Ar	Carrai Adamellite	E.C. Leitch pers. comm.
		225	K/Ar	Botumburra Range Adamellite	E.C. Leitch pers. comm.
		225	K/Ar	Ruby Creek Granite	Phillips 1968
	WESTERN BELT	230	Rb/Sr	Gilgai Granite	Bofiner (*in* Packham 1969)
		236	K/Ar	Mole Granite	J.D. Kleeman pers. comm.
		237	K/Ar	Puddledock Complex	Cooper *et al.* 1963
		237	Rb/Sr	Bungulla Porphyritic Adamellite	Shaw 1964
		238	?	Puddledock Complex	M.J. Neilson pers. comm.
		238	K/Ar	Bolivia Range Leucoadamellite	Evernden & Richards 1962
		239	?	Highlands Monzonite	M.J. Neilson pers. comm.
		239	?	Oban River Leucoadamellite	M.J. Neilson pers. comm.
		240	Rb/Sr	Tingha Adamellite	Bofinger (*in* Packham 1969)
		242	K/Ar	Dundee Porphyritic Adamellite	Evernden & Richards 1962
		242	?	Llangothlin Adamellite	M.J. Neilson pers. comm.
		243	K/Ar	Attunga Creek Adamellite	Cooper *et al.* 1963
		244	?	Mt. Duval Adamellite	M.J. Neilson pers. comm.
		244	K/Ar	Wards Mistake Adamellite	Binns & Richards 1965
		248	K/Ar	Inlet Monzonite	Cooper *et al.* 1963
HILLGROVE PLUTONIC SUITE		252	K/Ar	Abroi Granodiorite	Binns & Richards 1965
		258	K/Ar	Barrington Tops Granite	Cooper *et al.* 1963
		259	K/Ar	Tobermory Adamellite	Binns & Richards 1965
		269	K/Ar	Hillgrove Adamellite	Cooper *et al.* 1963
BUNDARRA PLUTONIC SUITE		270	K/Ar	Bannalasta Adamellite	Chappell 1973
		281	Rb/Sr	Bundarra Plutonic Suite	Bofinger (*in* Packham 1969)
		304	K/Ar	Bundarra Plutonic Suite	J.D. Kleeman pers. comm.
		309	K/Ar	Bundarra Plutonic Suite	J.D Kleeman pers. comm.
		317	K/Ar	Bundarra Plutonic Suite	J.D. Kleeman pers. comm.



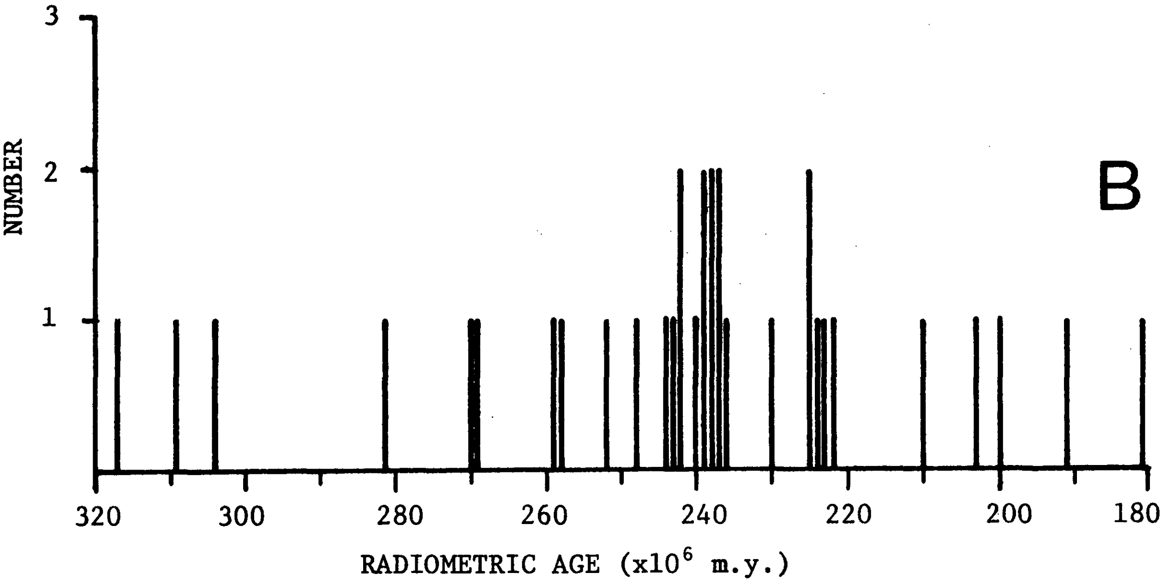


Fig. 69: Distribution of radiometric ages of granitic plutons from the New England region.

north to 270 m.y. in the south (Bannalasta pluton, Chappell 1973).

Three ages from the Hillgrove Plutonic Suite suggest a range of 269 m.y. to 252 m.y. (Binns and Richards 1965). However the 252 m.y. age for the Abroi Granodiorite is considered, on structural evidence, to be too young (see pp. 90-91) and it is suggested that this pluton is possibly the oldest associated with the Hillgrove Plutonic Suite. All ages for this suite are K-Ar and because of the stressed nature of the plutons the ages are not definitive, but should be supplemented with Rb-Sr determinations. The Hillgrove suite trends at 030° in a belt stretching from Barrington Tops in the south to Kookabookra in the north. A small belt trending 120° with Hillgrove Suite affinities occurs to the northeast of Ebor in the Coffs Harbour Block.

Plutons of the New England Batholith (*sensu stricto*) have radiometric ages which range from 248 m.y. to 181 m.y. (Table 10). From an examination of the radiometric ages, with regard to the spatial distribution of the plutons, it is possible to subdivide this suite into a western (older) belt trending NNE (025°) with ages from 248 m.y. to 230 m.y. and an eastern (younger) belt trending 350° with ages from 225 m.y. to 181 m.y.

The western belt has had 15 ages determined so far and 14 of these fall in the range 248 - 236 m.y. The other age of 230 m.y. determined by Bofinger (*in* Packham 1969) using Rb-Sr methods on a sample from the Gilgai Granite should be recalculated using the revised constants listed by Green and Webb (1974). Revision should place the age of this pluton within the range of the others comprising the western belt. A significant time difference (11 m.y., 236 - 225 m.y.) then occurs between the age ranges of the two belts.

Six ages from the eastern (younger) belt fall in the range 225 - 222 m.y. and are remarkably constant. The remaining five ages fall between 210 m.y. and 181 m.y. All these latter ages were determined by McKenzie (1972) who considered that because of alteration products in all specimens dated, the ages of emplacement are actually older than the K-Ar age, which appears to date the alteration event. Hence the ages for these plutons might be close to the ages determined for other rocks from this eastern belt (i.e. about 225 m.y.).

The elongated nature of the suites of plutonic rocks recognised in New England, particularly the Bundarra and Hillgrove Suites, can be explained in terms of diapiric models described by Ramberg (1967). Ramberg outlined the patterns produced during dome formation and growth but problems, such as the control of the initiation of domes from a source layer and the thickness of a dome relative to its dimensions, are still not fully understood.

The first stage after the development of an unstable situation, where the density of the overburden becomes greater than that of the source material, is the formation of a series of waves with horizontal axes. The amplitude of the waves increases until a series of evenly spaced culminations develop on the anticlinal ridges. These culminations soon change into circular domes which rise until their progress is impeded by a feature such as an interface or the land surface. Trusheim (1960, Fig. 4) has shown that the growth and shape of the anticlinal ridge or series of domes is controlled largely by the thickness of the source layer.

It is considered that the Bundarra Suite represents the anticlinal ridge stage and that either (1) the circular domes have been completely removed by erosion so that only the lower ridge part of the source area is now exposed, or (2) the anticlinal ridge has not yet started to break up into culminations because either an enormous quantity of material is present in the source layer or the progress of the ridge has been impeded in some way. The Hillgrove Suite is considered to have reached the stage of formation of rather evenly spaced domes rising from the anticlinal ridge and this is represented diagramatically in Figure 71.

Ramberg (*op. cit.*) found with his models that the anticlinal ridges always formed parallel to the side of the container and it is considered significant that the Bundarra Suite anticlinal ridge is parallel to the Peel Fault which possibly might have acted as a boundary for the source layer. As yet no distinct feature can be postulated as a boundary for the Hillgrove Suite.

It is interesting to note that the Bundarra Suite occurs wholly within a block (or blocks) consisting entirely of rocks of the Sandon Association. The Hillgrove Suite, apart from rare intrusions of uncertain affinity south of Walcha, occurs within fault bounded blocks of the Coffs Harbour Association.

(b) Permian Acid Volcanic Rocks

Recent mapping by the Geological Survey of N.S W. on the Grafton, Dorrigo, Manilla and Inverell 1:250,000 geological maps has shown the presence of a widespread belt of acid volcanic rocks considered to be Late Permian in age. These volcanic rocks consist of ash fall and ash flow tuffs and lava flows.

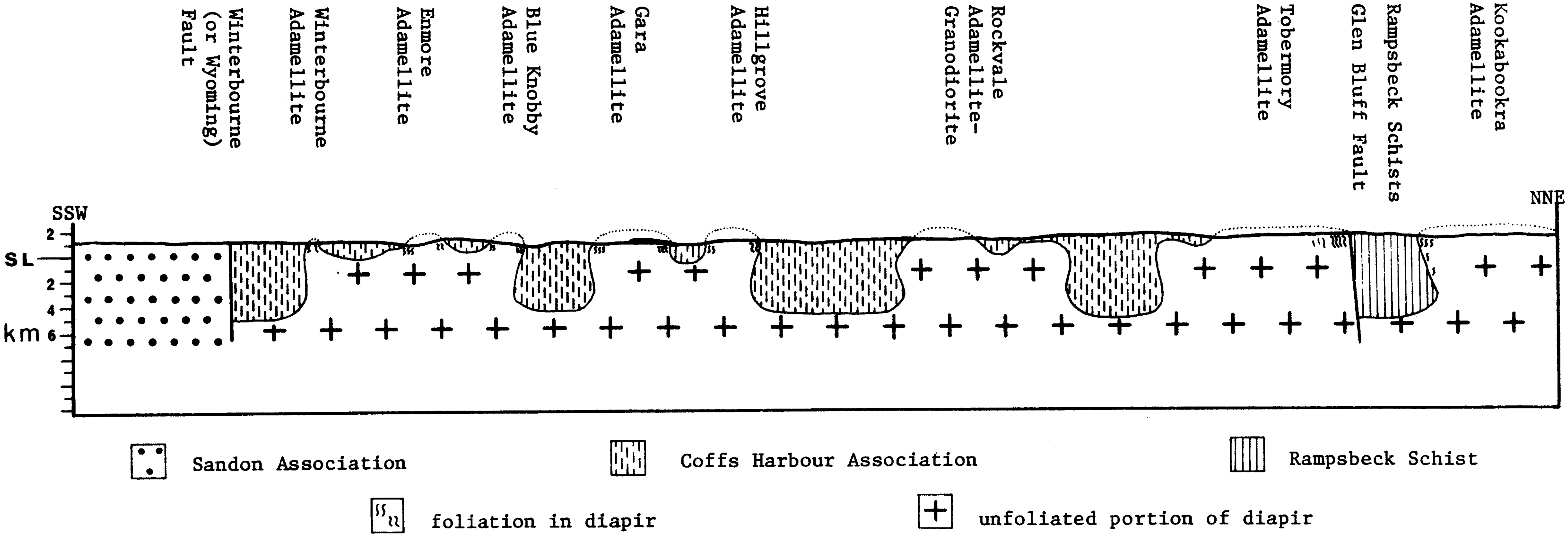


Fig. 70: Schematic cross section from east of Walcha (GR 47501636) to the junction of the Mitchell and Oban rivers (GR 51242832). Horizontal and vertical scales are the same. Diagrams shows development of the Hillgrove PlutonicSuite as an anticlinal ridge with rather evenly spaced culminations developing into domal structures.

In the Drake region the volcanics are at present being examined by H.K. Herbert (pers. comm.) who has been able to subdivide the volcanic pile into an older rhyolitic sequence, consisting mainly of lava flows and minor fragmental material, and a younger andesitic to dacitic sequence, which consists of mainly fragmental rocks with some porphyritic material. The older sequence has been gently folded and disrupted by block faulting and covered by a thick blanket of the andesitic sequence. Herbert suggests that a major disconformity exists between the two sequences but, because of lack of exposure, he has not been able to conclusively determine the relationship. Both sequences are calc-alkaline but are considered by Herbert to be genetically unrelated.

In central New England an extensive volcanic pile termed the Emmaville Volcanics (Brunker *et al.* 1969) unconformably overlies rocks of the Sandon and Nambucca Associations (Map 6) and conformably overlies rocks of the Dummy Creek Association. Little work has been attempted on these rocks, the only detailed studies being by Docherty (1973) and Langham (1973). The southern part of the sequence west of Armidale is at present being examined by R.G. Cuddy.

Docherty and Langham have subdivided the volcanics northwest of Guyra into two formations. The older Tenterden Formation consists of andesitic, rhyodacitic, dellenitic and rhyolitic lavas and ash flows, and is disconformably overlain by the Moredun Creek Rhyolites. which consists of mainly rhyolitic lava flows with some ash flows and associated intrusive rocks. Chemical data presented by both Langham and Docherty suggests that the volcanics are calc-alkaline types associated with a continental margin.

Isolated patches of Permian Volcanics occur throughout New England of which the Gibraltar Ignimbrite (Vickery 1972), Wallangarra Volcanics (Butler 1974) and calc-alkaline varieties associated with the Wildash Group (P.C. Dennis 1974) are documented examples. Other examples occur associated with rocks of the Dummy Creek Association.

Leitch (1974) considered that the volcanics probably represent an early phase of magmatism which provided a blanket beneath which the plutons cooled. The Emmaville Volcanics appear to be associated with the older western belt of the New England Batholith whereas the Drake Volcanics appear to be associated with the younger eastern belt plutons. Preliminary attempts to correlate the Drake Volcanics and the Emmaville Volcanics by H.K. Herbert (pers. comm.) have been unsuccessful, possibly because the volcanics might be associated with the two distinct and separate suites of plutons.

(c) Serpentinites

Serpentinites in New England are here divided into two types: (a) those associated with rocks of ophiolitic affinities, and (b) isolated occurrences with associated subordinate to rare exposures of doleritic rocks.

Ophiolitic rocks with associated serpentinite (type a) have been described in detail from west of Barry by Cross (1974). Other occurrences of serpentinite and associated basic rocks which are here interpreted as being possibly ophiolitic are the Barry Igneous Complex (Heugh 1971) and the Pigna Barney Igneous Complex and localities south of Nowendoc (Mayer 1972).

Numerous bodies of type (b) serpentinite have been reported from the southern part of the New England Geosyncline and occur (1) associated with the Peel Fault system or the Manning Fault system near the western boundary of the Central Complex, and (2) as a large intrusion in the Baryulgil area immediately west of the Clarence - Moreton Basin. The serpentinites, originally described by Benson in a series of papers (e.g. 1914, 1918) have been described again by Wilkinson (*in* Packham 1969) and a recent summary is provided by Wilkinson (1974b).

4. DEFORMATION

The New England region is cut by many faults, but their significance is not clearly understood. Faults have disrupted the Central Complex to produce the present pattern of stratigraphic associations (see Map 6). Contrasts in intensity and style of deformation between adjacent blocks (e.g. differences in structural style between the Rockvale, Dyamberin and Coffs Harbour Blocks discussed in Chapters 2 to 5), coupled with a lack of detailed structural data for much of the Central Complex, make it difficult to generalise on the deformation of the Central Complex as a whole.

Most of the Central Complex appears to have suffered at least one major deformational episode with many areas having suffered a second less intense episode (e.g. Coffs Harbour Block, Chapter 2). Regions where more than two episodes of deformation have been recorded are the Warnes River area (Fisher 1969), Tia Complex (Gunthorpe 1970), Nambucca Slate Belt (Leitch 1972) and Wongwibinda Complex (this thesis). Deformation in the Tia and Wongwibinda Complexes is associated with low pressure metamorphism of greenschist and amphibolite facies whereas in the Nambucca Slate Belt and Warnes River area deformation is associated with intermediate pressure metamorphism of prehnite-pumpellyite, pumpellyite-actinolite and greenschist facies.

The age of deformation in the Rockvale - Coffs Harbour region is considered to be Early to Middle Permian, and agrees well with conclusions of Leitch (1969, 1974a) who showed that a major deformation occurred in the southern part of the New England Geosyncline in the Middle Permian time. Several unconformities have been documented from the Tamworth Belt (see discussion in Leitch 1974a) and a Carboniferous - Permian disconformity has been reported from the Hastings Block by Northcott (1973) and the Emu Creek Beds (McCarthy *et al.* 1974). As yet because of the absence of well defined marker horizons, coupled with poor exposure, it has not been possible to prove the existence of major unconformities in the Central Complex. Localised Permian - Carboniferous unconformities exist in the border rivers region (Olgers and Flood 1970b) although the Tabulum locality is now considered disconformable (McCarthy *et al.* 1974). As discussed previously, doubts still exist as to the nature of the contact at Glenmore (compare Olgers and Flood 1970a with Warner 1970, McCarthy 1971 and Boxall 1972).

Faults

Several major fault systems exist in the southern part of the New England Geosyncline. The Hunter - Mooki Fault system, consisting of east dipping (15° - 50°) thrusts, separates the Tamworth Belt from the Sydney and Gunnedah Basins, and has been discussed by Leitch (1974a).

Of more interest here is the Peel Fault system which separates the Tamworth Belt from the Central Complex. In the north the Peel Fault system is a steeply dipping arcuate structure running from Warialda to Nundle. South of Nundle the system becomes fragmented and is termed the Manning Fault system (Voisey 1939b). The nature of movement on the fault has not been conclusively established and several different interpretations have been put forward. Voisey (1959) and Chappell (1961a) consider it to be a steeply dipping reverse fault. Crook (1963) and Scheibner and Glen (1972) consider the Peel Fault system to be a strike-slip regime with some vertical component and Scheibner and Glen postulated a dextral sense of movement. Rod (1974a) criticised the interpretation of Scheibner and Glen but then postulated a sinistral sense of movement based on inconclusive information such as the general character of the Peel Fault, and its topographic expression. The Peel Fault system is a complex structure, the geology of which is incompletely known. Large masses of serpentinite are associated with the fault and slivers of sedimentary rocks ranging in age from Ordovician to Permian have been found within the fault system.

Ordovician slivers: Conodonts and corals in grey bioclastic to buff-coloured argilliceous limestone from the Trelawney Beds south-east of Tamworth indicate an Eastonian age (Philip 1966, Hall 1970). These rocks are remarkable in that they have suffered virtually no deformation or metamorphism and the fossils are excellently preserved. This contrasts to early Devonian limestones, faulted against the Trelawney Beds, which are marmorised and poorly-preserved due to low-grade burial metamorphism (prehnite-pumpellyite facies). Philip (*op. cit.*) considered that the Ordovician limestones have not been deeply buried at any stage. Hall (1970) described another Eastonian locality northeast of Attunga, which contained abundant corals in grey limestones associated with massive cherts and mudstones. Packham (1969, p.231) described Ordovician graptolites of probable Bendigonian age from a fault block containing sandstones, and these are the only recorded occurrence of graptolites in New England. These are of similar age to graptolites south of Wellington in the Lachlan Geosyncline which are thought to be the oldest known from New South Wales.

Silurian Occurrences: Silurian fossils previously reported as occurring within the Woolomin Beds (e.g. Chappell 1961a; Hall 1970; Lusk 1963) are here considered to be allochthonous fault slivers associated with the Peel Fault system. This is supported by K. Fitzpatrick (pers. comm.) who has recorded several new localities of limestone in the Woolomin Beds between Crow Mountain and Dungowan. In each case the limestones occur close to the serpentinites and where contacts were observed they were faulted. Hall (1970) considers the Silurian corals to be Llandoverian to Wenlockian in age. The limestones have often been recrystallised and have suffered a higher grade of metamorphism than the Ordovician rocks. Heugh (1971) reports Ordovician to Early Devonian limestone lenses in a fault sliver associated with the Peel Fault system in the Barry region.

Devonian to Permian Occurrences: Johnston (1968) described a sliver of Tamworth Group containing limestone lenses adjacent to the Peel Fault in the Upper Bingara area approximately 80 km north of previously known Tamworth Group sediments. Johnston also described a Late Carboniferous or Early Permian sequence adjacent to the Peel Fault south of the Tamworth Group sliver. The Late Palaeozoic sequence is completely bounded by faults and contains conglomerate horizons with radiolarian chert clasts. Johnston suggests that the radiolarian chert fragments indicate derivation from east of the Peel Fault. However the presence of a sliver of Tamworth Group (which contains radiolarian cherts in the Tamworth region), suggests that the possibility of derivation from the Tamworth Group cannot be ruled out.

Work near Woodsreef by Price (1973) has shown the presence of a Permian sandstone sequence truncated to the east by the Peel Fault. To the west this unit (the Ironbark Creek Arenite) conformably overlies a sequence of conglomerates, sandstones and mudstones which Price considered had Carboniferous affinities, although no identifiable fossils have been found as yet. This sequence (Crow Mountain Creek Beds) contains two distinctive conglomerate members. The andesitic volcanic and granodioritic clasts in the Black Mountain type suggests derivation from the west, as this unit is similar to the Rocky Creek Conglomerate. The Eumur Creek type contains radiolarian jasper and basic lava clasts which Price considered was derived from east of the Peel Fault. The relationship of the Crow Mountain Creek Beds with units to the west is unknown.

A narrow Permian fault sliver in the Attunga region has been mapped by Hall (1963). The sequence consists of conglomerate, sandstones, impure limestones and shale and occurs adjacent to the Peel Fault. Clasts of chert and cherty mudstone contain recrystallised radiolaria and Hall thought that these strongly resembled Tamworth Group rocks. Hay (1970) records radiolarian chert, feldspathic sandstone and rhyolitic volcanic clasts from conglomerates in the same sequence. Numerous fossils indicate a Fauna II age (Runnegar 1970). The presence of jasper clasts has not been mentioned by workers from the Attunga locality and hence derivation from either the Woolomin Beds or Tamworth Group is possible.

A fourth Late Palaeozoic fault sliver has been described by Crook (1961c) north of Nundle (Andersons Flat Beds). The unit contains Permian fossils, crops out poorly and only sandstones and conglomerates have been found. Chert containing recrystallised radiolarians is the dominant clast type. Of the four localities of Permian or possible Permian rocks found associated with the Peel Fault system, three are completely fault bounded slivers. In the fourth case the Permian unit appears to pass conformably downwards to Carboniferous lithologies. In each locality conglomerates have been derived predominantly from radiolarian chert or jasper units. T.G. Russell (pers. comm.) considers the Late Palaeozoic rocks adjacent to the Peel Fault reported by Price (1973) from Woodsreef are part of the Tamworth Belt. Other Late Palaeozoic slivers associated with the Peel Fault are also considered to be part of the Tamworth Belt.

Two large linear magnetic anomalies occur over the Hunter - Mooki Fault and Peel Fault systems (Ramsay and Stanley, in press). The anomaly associated with the Peel Fault system is caused by serpentinite masses, and the anomaly associated with the Hunter - Mooki Fault system is due to intermediate to basic igneous rocks of uncertain age associated with the fault system.

The Demon Fault is a major north-south trending structure extending for over 200 km in the eastern part of the Central Complex. Shaw (*in* Packham 1969) proposed a dextral strike-slip movement of 30 km along this fault in the Tenterfield region. A suggested movement of 29 km in the Rockvale - Coffs Harbour region agrees closely with the estimate of Shaw. The amount of movement is based on displacement of plutons and hence the estimate is only a record of movement since the time of emplacement. Leitch (1975) and Runnegar (1974) infer a dextral strike-slip movement of the order of 150 - 200 km. These writers inferred this amount of movement on the basis of lithological similarity of the Texas Beds and Coffs Harbour Sequence. In this thesis these sequences are considered to be related to different associations and hence no support can be given to their hypothesis.

Other faults in the Central Complex such as the Bellinger Fault, Parrabel Fault, Nowendoc Fault and numerous others are major structures, which have been recognised on the basis of contrasting lithologies and style of structural deformation, but insufficient work or poor exposure has not enabled a sense or amount of movement to be determined.

The above synthesis of the geological elements found in the southern part of the New England Geosyncline forms the basis on which a tectonic model of New England has been constructed.

CHAPTER 7: PLATE TECTONIC MODEL FOR THE SOUTHERN PART OF THE NEW ENGLAND GEOSYNCLINE

Special Acknowlegement: For ethical reasons it is stated clearly here that the tectonic analysis in this Chapter is a product of joint working sessions by the candidate and his supervisor. The writing and parts of the analysis are the work of the candidate.

INTRODUCTION

Since the development of the concept of plate tectonics several proposed tectonic models for the New England region attempt to reconstruct the tectonic situation during the Phanerozoic. Those by Oversby (1971), Solomon and Griffiths (1972), Scheibner and Glen (1972) and Marsden (1972) have been criticised severely by Packham and Leitch (1974) although these critics have not hesitated to produce their own models (Packham 1973; Leitch 1975). More recently tectonic models by Scheibner (1973), Harrington (1974) and Runnegar (1974) have appeared, along with a critical but ill-informed paper by Rod (1974a), who also attempted a model (Rod 1974b).

During the compilation of the synthesis of the geology of the New England region (Chapter 6) it became obvious that no existing model accounts satisfactorily for the observed geology. Problems encountered during compilation were that large areas of New England have not been mapped, except in the simplest reconnaissance fashion, and some other areas obviously need remapping. The complexities in tectonic interpretations of present day situations have been neglected by previous workers and consequently their models are far too simplistic and unrealistic.

While accepting the above limitations, the synthesising power of the concept of plate tectonics has enabled the construction of a new model, even though it is incomplete because of the lack of critical information. The model is radically different from its predecessors in its recognition of plate junctions inside the New England region, and in the consideration of the geometry of triple junctions. The plates that are recognised do not coincide with those of earlier writers (Scheibner 1973; Leitch 1975).

The plates have been given the names of aboriginal tribes, because they do not interfere or conflict with pre-existing nomenclature for stratigraphic units and structural features. In appropriate cases the names used are those of aboriginal tribes which formerly lived in a district but have now disappeared. Thus the Aniwan tribe formerly occupied the Armidale region but has now disappeared except for a few remnants, and this name is given to the plate which once existed in the Armidale region but has been subducted in the Peel trench.

In the nomenclature of this Chapter, plates are designated by their capital letters with or without a following lower-case letter (e.g. A = Aniwan, Wi = Wiradjuri) and boundaries between two plates are designated by lower case letters of the plates involved (e.g. Peel trench = Aniwan-Wiradjuri plate boundary = aw_i). Where required, triple junctions (J) between the plates are designated by the letters of the plates involved (e.g. WiAWu, see Fig. 72).

In the preceding synthesis descriptions were given of the sedimentary associations, metamorphic zones and igneous rock types in the region. The descriptions can be applied to the tectonic plates shown in Figure 71. The reader will notice for example that the Rockvale and Dyamberin Blocks (see Appendix I) become part of the Peel outer arc and trench, and that the Coffs Harbour Block is divided into the Coffs Harbour plate and the Jiegera plate.

Some of the plate boundaries (Fig. 71) are sharp and well defined (e.g. Peel Fault, Demon Fault). Some present-day plate boundaries in other parts of the globe, particularly transform faults and trenches, occur as zones rather than as sharp lines and this is also true of some fossil plate boundaries in this region which are difficult to pinpoint exactly (e.g. Wollomombi plate boundary, Baryulgil trench).

The following model outlining the tectonics of the southern part of the New England Geosyncline is incomplete, and in places only very tentative ideas have been put forward. It is likely to be only after several years of careful detailed mapping, with a tectonic approach in mind, that it will become possible to develop a comprehensive tectonic model which will adequately account for all the known geology of the New England region.

PLATE MOVEMENTS AND THEIR TIMING

PRE-DEVONIAN

Very little can be inferred with regard to the tectonic conditions in Pre-Devonian time. Ordovician graptolite-bearing sediments (Packham 1969) and limestones (Philip 1966, Hall 1970) have been recorded as faulted slivers associated with the Peel Fault system. Silurian limestones (Chappel 1961b,

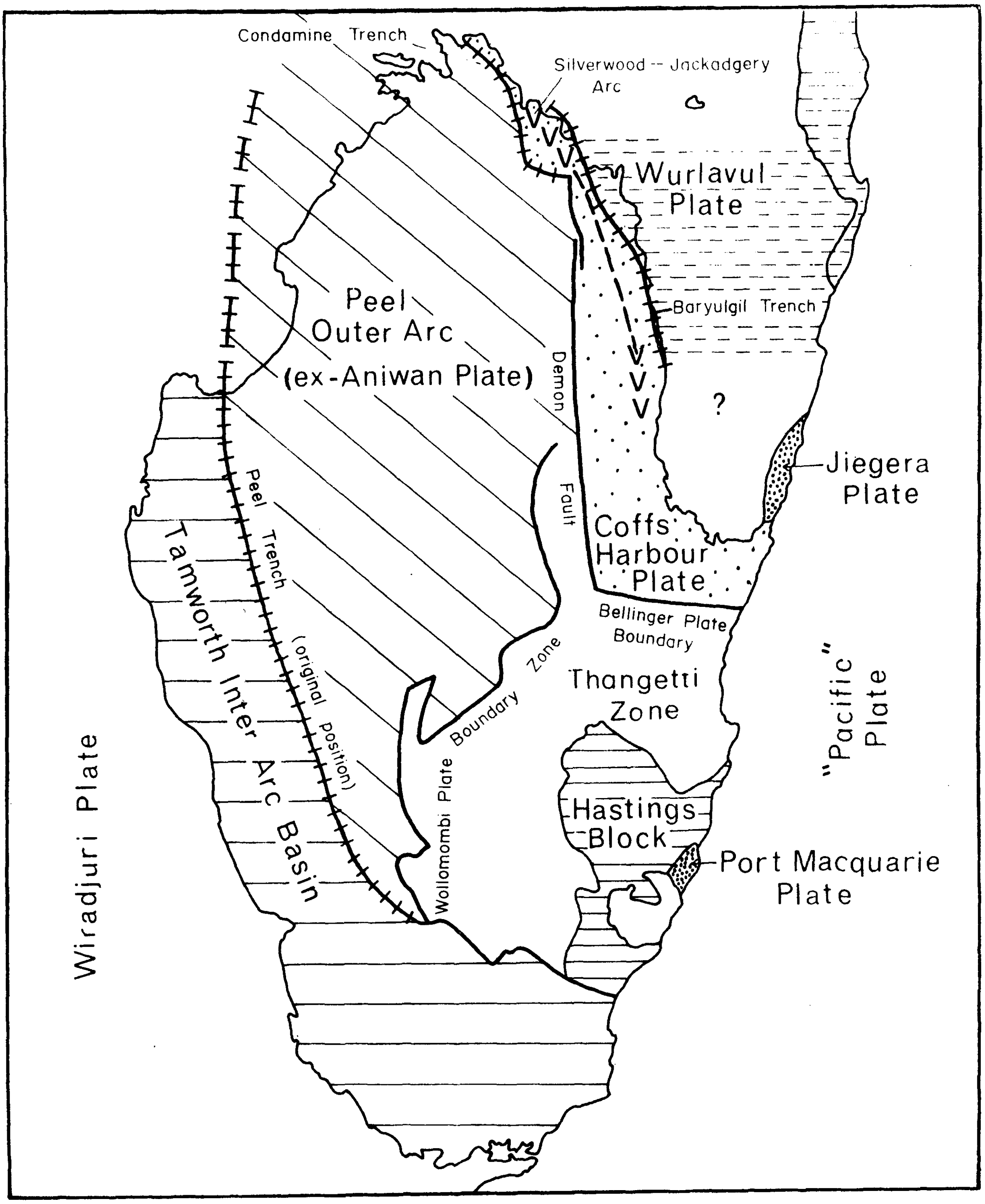


Fig. 71: Location within the southern part of the New England Geosyncline of tectonic elements referred to in the text. The Ngamba plate comprises the Hastings Block and the Thangetti zone. For plutonic suites see Map 6.

Hall 1970) along with some Early Devonian lenses (Heugh 1971) have been found infaulted into the Woolomin Association close to the Peel Fault system. The presence of the above rocks suggests that an oceanic regime, with possibly some abyssal plain sediments existed prior to the Devonian in New England.

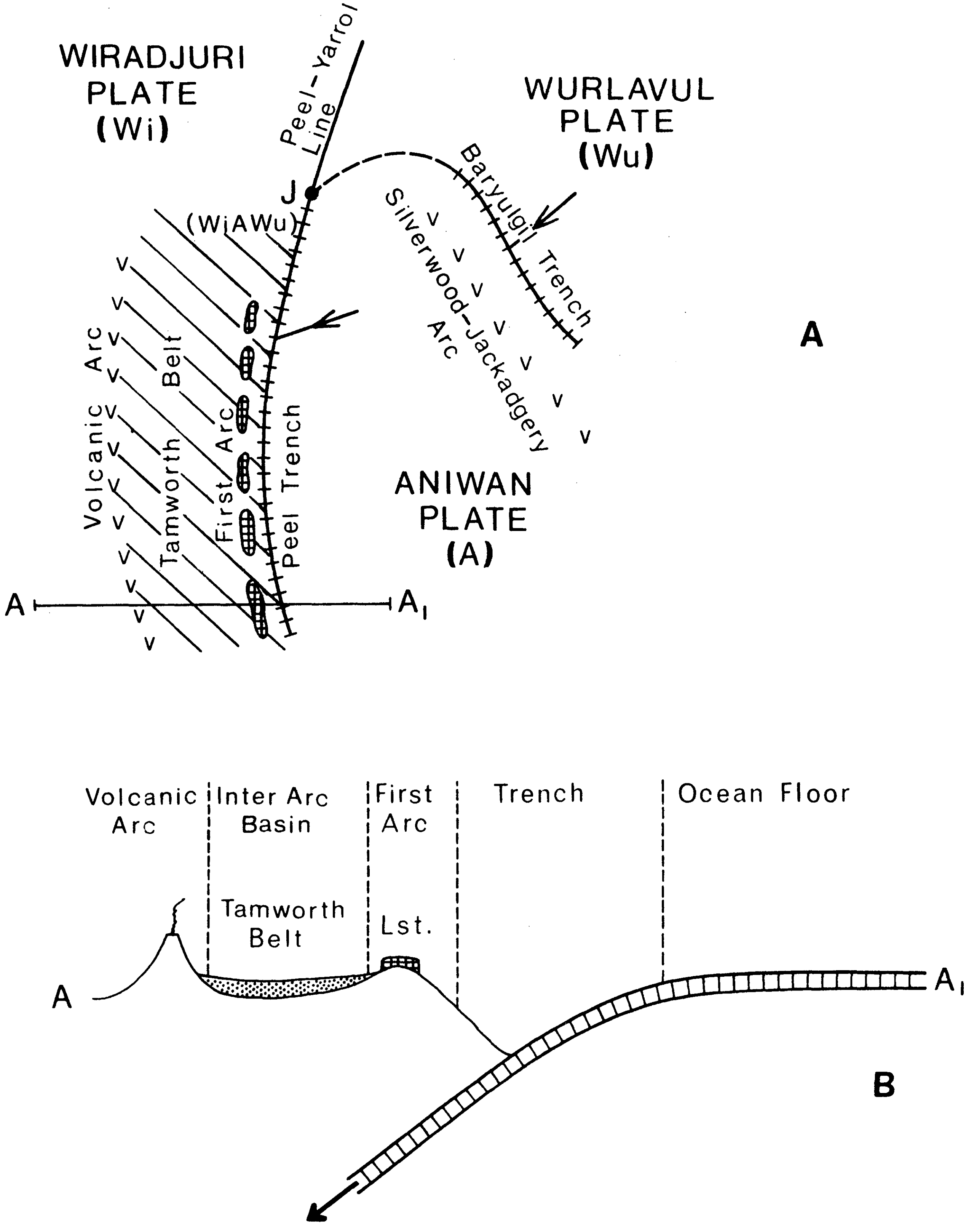
DEVONIAN PLATE GEOMETRY AND KINEMATICS

Early Devonian

The Geological Map of New England published by the Geological Survey of New South Wales (Map 8) is a compilation of published information, of unpublished thesis maps at the University of New England, and data in the files of the Department of Mines. It shows the distribution of Devonian formations. Rocks of known Early Devonian age are the Tamworth Group (Crook 1961a), the Silverwood Group (Olgers and Flood 1970a) and possibly part of the Woolomin Association.

The Silverwood Association is here interpreted tectonically as being a volcanic arc (the Silverwood - Jackadgery Volcanic Arc). However, until future detailed work conclusively proves whether or not the Silverwood Group is part of the same sequence as the volcanics observed by Gutsche (1960) and McQueen (1971) in the Jackadgery area, the inclusion of the Jackadgery rocks as part of this volcanic arc is considered tentative. The Baryulgil Serpentinite represents the position of a trench (Baryulgil trench) which was located to the northeast on the convex side of this volcanic arc. The close proximity of the trench to the volcanic arc suggests that the subduction zone was steeply plunging to subvertical. The Baryulgil trench is tentatively extended to the northwest to meet the Peel - Yarrol Line (a line joining the Peel Fault System and the Yarrol Thrust) at a triple junction.

The Peel Line south of the triple junction is interpreted as the position of a trench, with an accompanying volcanic arc located to the west - a situation similar to that proposed by Leitch (1975). The Early Devonian picture is represented diagrammatically in Figure 72. The volcanic arc located on the Wiradjuri plate contributed andesitic detritus from which much of the Tamworth Group was derived. A "first arc" commenced to develop and was represented by the Nemingha Limestone (Packham 1969, p. 232) near the eastern edge of the Tamworth Belt, the remainder of the Tamworth Group being deposited in an inter-arc basin (Fig. 72B).



DIAGRAMMATIC ONLY
(not to scale)

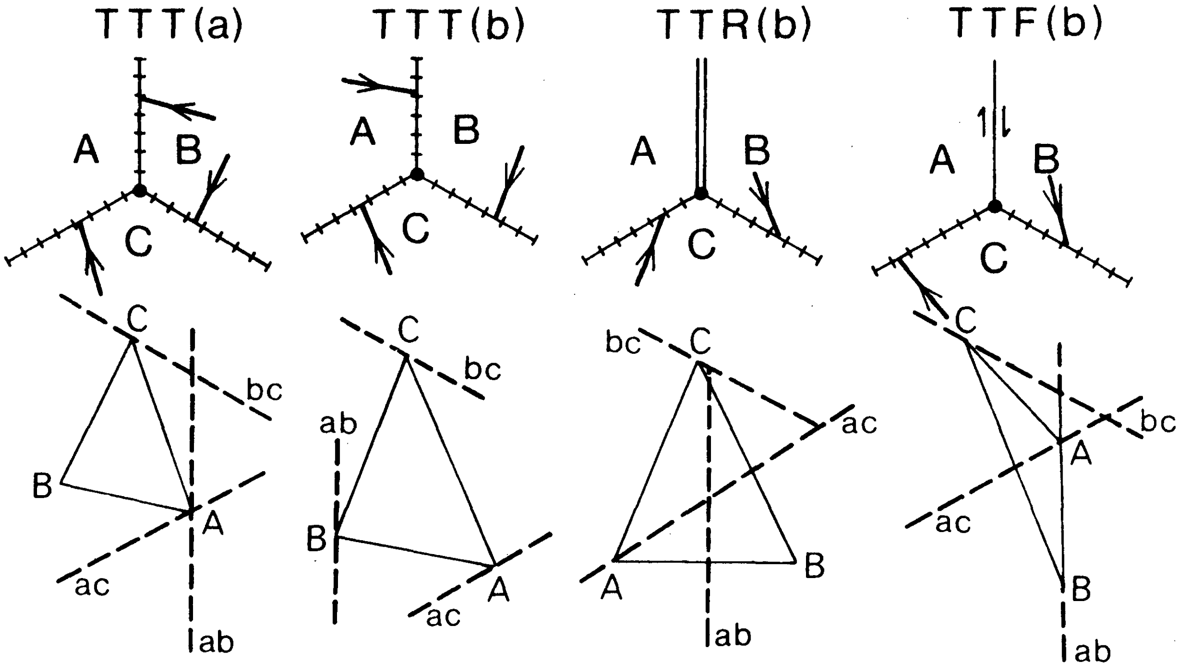
Fig. 72: Diagrammatic representation of tectonic elements present in the southern part of the New England Geosyncline during Early Devonian time.

The triple junction was of the trench-trench-unknown type and several situations based on the geometric possibilities outlined by McKenzie and Morgan (1969) are feasible (Fig. 73). The most likely is either the TTT(a) or TTF(b) situation (where T = trench, F = transform fault, R = spreading ridge). In the case of TTT(a) the triple junction (J) would have migrated northwards along the Peel - Yarrol Line with respect to a fixed Wiradjuri plate. Thus the Silverwood Arc would be migrating northwards and the Tamworth Arc, while maintaining its position relative to the Peel Trench, would be becoming longer in a northerly direction.

The movement of J for the TTF(b) situation (Fig. 73) depends upon the direction of the relative velocity vector ${}_{Wi}V_A$ with respect to the Wiradjuri plate. Let ${}_{Wi}V_A$ make an angle θ with the Peel trench. Then if θ is less than the angle between the Baryulgil trench and the Peel - Yarrol Line north of the triple junction, the velocity vector triangle is as illustrated and the triple junction migrates towards the south, relative to a fixed Wiradjuri plate. This results in the conversion of the trench into a transform fault once the triple junction has passed. However, if θ is greater than the angle between the Baryulgil trench and the Peel - Yarrol Line, the velocity vector triangle would change and the triple junction would migrate northwards, relative to a fixed Wiradjuri plate, converting the transform fault into a trench. Because the geology of New England is not sufficiently well known to predict velocity and direction of plate movements during the Early Devonian, it is not possible at present to determine which of the above situations is the correct one.

Middle to Late Devonian

No evidence has been found for Middle and Late Devonian volcanic rocks associated with the Silverwood - Jackadgery Arc although if the triple junction WuAWi was migrating northwards the Baryulgil trench would also be migrating northwards and consuming the Wurlavul plate. The site at which the volcanics could have formed would now be covered by sediments of the Clarence - Moreton Basin. On the other hand if the triple junction was migrating south the trench would be moving southwards and the volcanics could be located to the south of the Silverwood - Jackadgery Arc. No evidence has been found to the south but the volcanics might have been obliterated by erosion or by the intrusion of the New England Batholith. Another alternative is that subduction ceased. Due to lack of data it is not possible to determine which of the above situations is correct.



Stable (1) if ab and ac form a straight line, or (2) if $_A V_C$ is parallel to bc.

Complicated situation, stable only if ab, bc and ac meet at a point.

Complicated situation, stable only if ab, bc and ac meet at a point.

Stable (1) if bc is parallel to $_A V_C$ or (2) if ab and ac form a straight line.

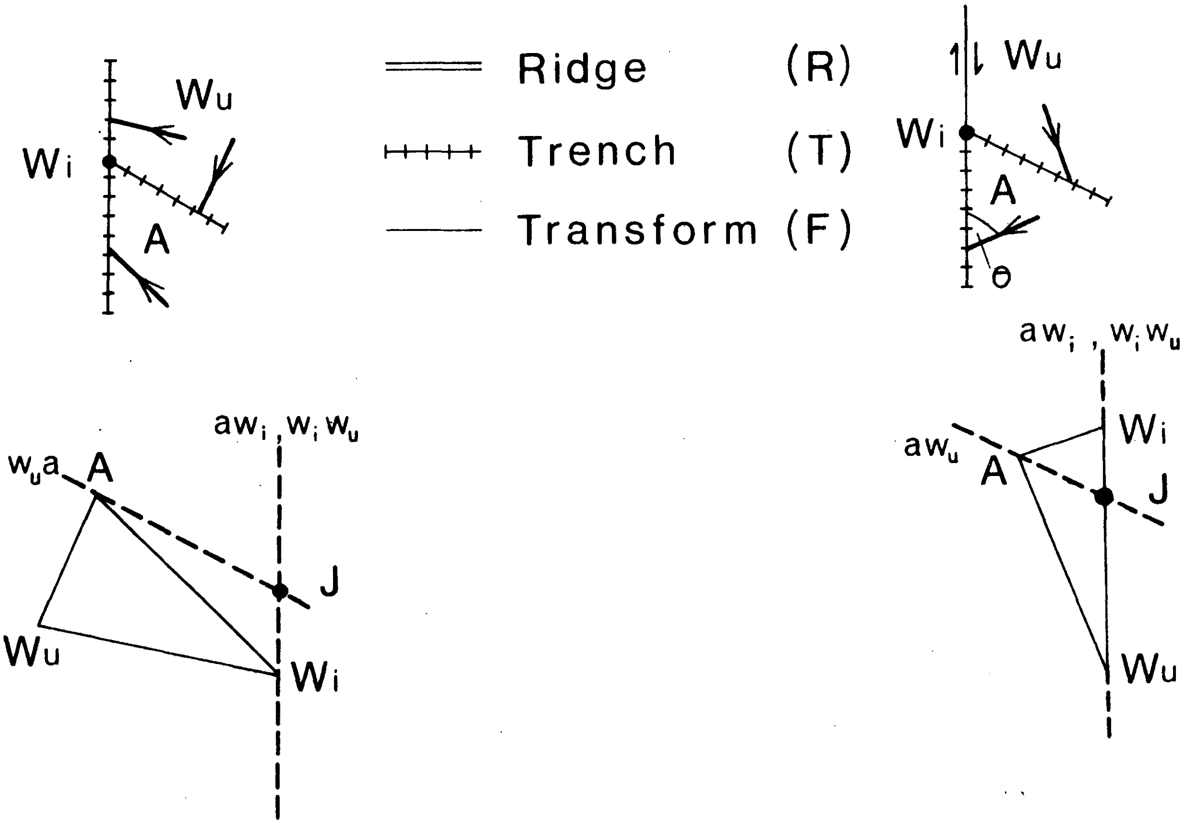


Fig. 73: Possible triple junction situations for intersection of the Baryulgiltrench with the Peel-Yarrol line. The geometries, relative velocity triangles, stability criteria and most likely stable situations for the triple junction are shown.

During the Middle Devonian subduction associated with the Peel trench continued along with growth of the first arc by deposition of thick units of limestone (Sulcor, Loomberah, Moore Creek and Timor Limestones described in Packham 1969, P. 232), Associated Tamworth Group sediments were being deposited in the inter-arc basin.

During the Late Devonian (Frasnian and Early Fammenian time) a volcanic arc was located at the site of the "western" Baldwin Formation now exposed along the western edge of the Belvue and Werrie Synclines. The Tamworth Belt sediments ("eastern" Baldwin Formation, Keepit Conglomerate and younger Devonian formations) were deposited in the inter-arc basin and palaeocurrent data indicate that they have been derived mainly from the west where erosion of a volcanic arc was taking place (White, 1966). The presence of granitic boulders in the Keepit Conglomerate possibly suggests the erosion of plutonics associated with the volcanic arc.

The Peel trench was located to the east of the present position of the Peel Fault system, which marks the initial site of that trench. Ocean floor sediments (the Sandon Association) were being deposited on the Aniwan plate and subducted in the trench. Part of the eastern edge of the trench occurred above sea level (the "outer ridge"). On this high grew Late Devonian (?) plants found to the west of Armidale by Smith (1973). These might have grown on either extensive "Coast Ranges", or on an island of a "borderland" zone, but were subsequently deposited in near-shore conditions. Dr. R.E. Gould (pers. comm.) considers that they are either Late Devonian or Early Carboniferous in age, more probably the former.

Further to the northeast the lower units of the Coffs Harbour Association (Moombil and Brooklana Beds, see Appendix I) were being deposited as distal turbidites, possibly in a back arc basin receiving the products of erosion of the Silverwood - Jackadgery volcanic arc.

CARBONIFEROUS PLATE GEOMETRY AND KINEMATICS

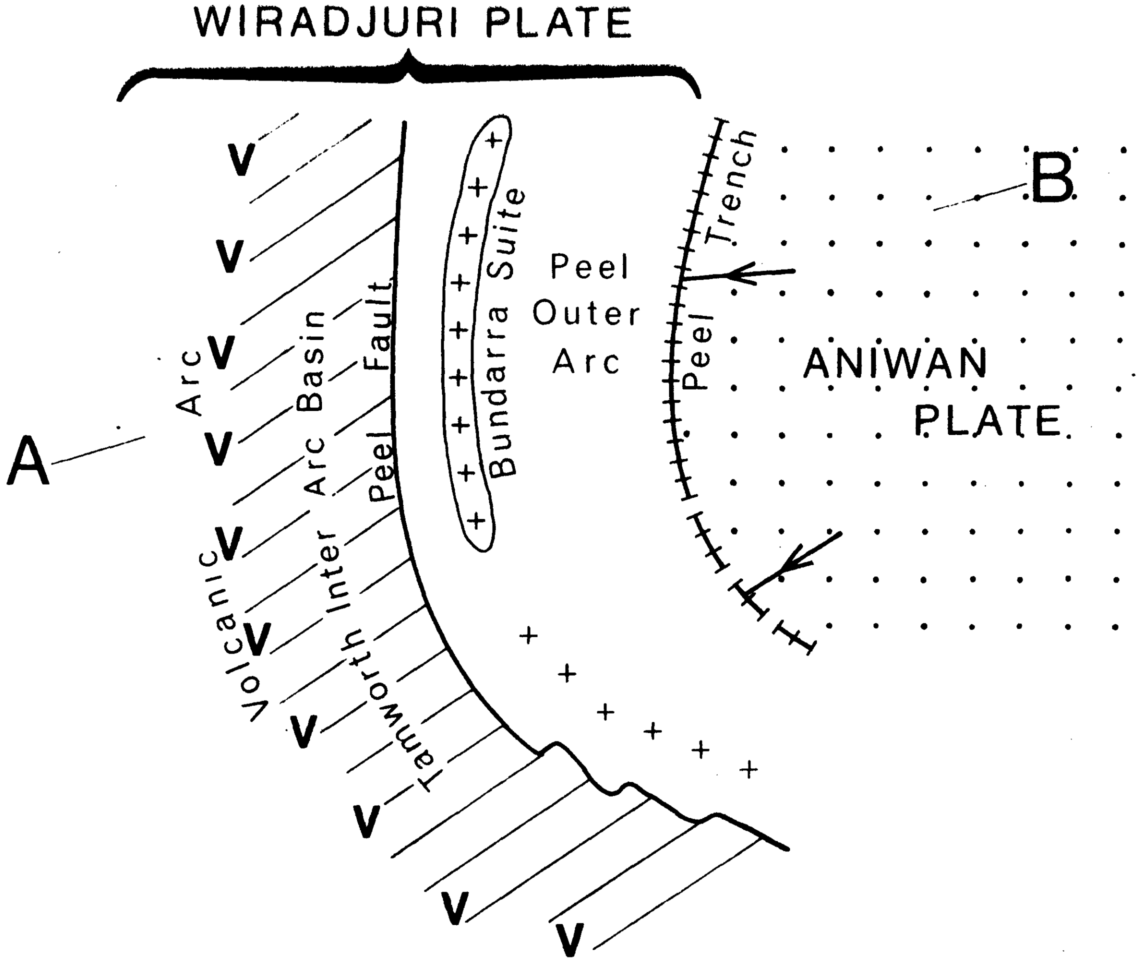
During most of the Carboniferous, plate movements in the New England region were similar to those of the Middle and Late Devonian. There is no direct evidence that subduction was still occurring along the Baryulgil trench, but possibly this trench had migrated further north.

One problem is to account for the presence of Early Carboniferous granitic clasts in conglomerates in the Beenleigh Association. Green (1973) reported that one of these clasts in the Neranleigh - Fernvale Group has an age of 335 m.y., and McCarthy *et al.* (1974) reported that a similar clast in the Emu Creek Beds has an age of 331 m.y. Granitic plutons of this age have not as yet been recorded in the New England region but are known in Queensland. It is postulated here that the Beenleigh Association formed further north in Queensland than its present position and has been moved southwards subsequently. In its quartzose nature the Beenleigh Association is distinctly different from all other sedimentary associations in New England (Fig. 68) which suggests that it had a continental provenance. It is possible that the Beenleigh Association might be related to the Curtis Island Group in northern Queensland (Kirkegaard *et al.* 1970).

In the New England region a trench was located to the east of the Bundarra Suite and granitic material of the Bundarra Magmatic Arc was forming above a west-dipping subduction zone. Further west a continental margin volcanic arc formed above the same subduction zone and was shedding pyroclastic material eastwards to the Caroda Formation (White 1966) and the Isismurra Formation (Roberts and Oversby 1973) of the Tamworth Belt. A schematic representation of the Late Carboniferous situation is shown as Figure 74. The westward-facing convexity of the Peel trench could be used as a polarity indicator and interpreted to mean that the western plate was being subducted. However all other polarity indicators suggest so strongly that there was subduction on the concave side of the plate boundary that this rare situation has to be accepted. The concavity might be one of the causes of the later transformation of part of the subduction zone to a transform fault with accompanying plate reorientation.

In the Ashford region an andesitic flow is conformably overlain by a marine sequence containing a thick limestone horizon of Late Visean age (Northcott 1972). This limestone could have accumulated on an accretionary fault slice in the "coast ranges and continental borderland" of the Peel Outer Arc, or could have formed on a "high" produced by doming associated with the diapiric rise of the Bundarra Plutonic Suite. In this district Visean limestones formed in a mobile environment, for large and small masses of them slumped eastwards into the Texas Beds of the Texas - Stanthorpe region.

The Coramba Beds of the Coffs Harbour Association are postulated to have accumulated north of their present position as proximal turbidites in a back arc basin associated with the Silverwood - Jackadgery arc.



+ + + + + +	Portion of Bundarra Suite subducted later.
⊢⊣ ⊢⊣ ⊢⊣ ⊢⊣	Portion of Peel Trench later subducted. (The northern portion possibly became later the Demon Transform Fault.)

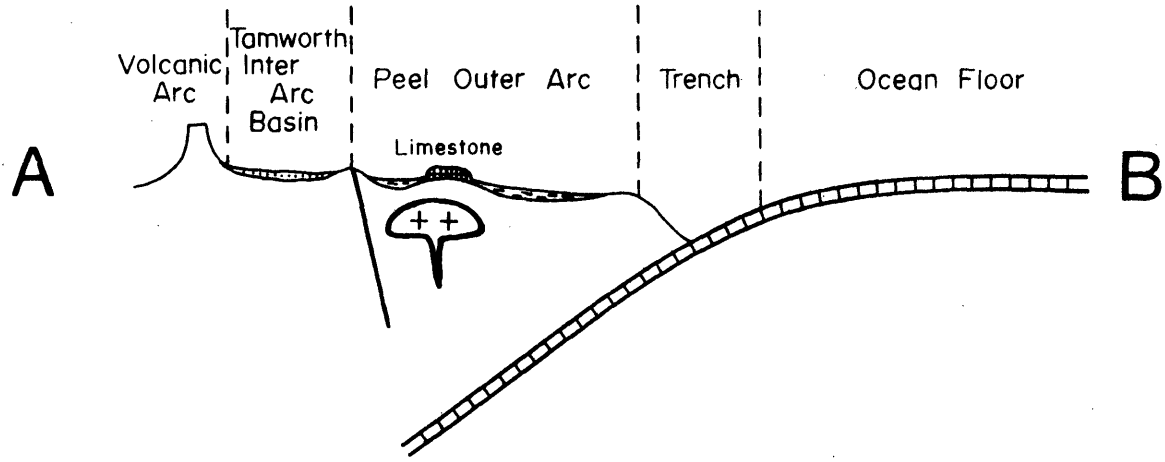


Fig. 74: Diagrammatic representation of tectonic elements present in the southern part of the New England Geosyncline during Late Carboniferous time. Both diagrams are schematic and hence not to scale.

PERMIAN PLATE GEOMETRY AND KINEMATICS

At about the Carboniferous - Permian boundary there were major changes in the shapes and movement patterns of plates in the New England region. As yet, geological information is not sufficient to allow analysis of all the relative movements but it is possible to outline the situation after the major reorientation occurred. An important feature was the development of small plates located between two large plates. The movements of these small plates controlled the evolution of the New England Tablelands in the Permian. Before their role can be discussed a theoretical model of the behaviour of small plates needs to be examined.

THEORETICAL MODEL FOR ROTATION OF A SMALL PLATE BETWEEN TWO LARGE PLATES

Krause (1973) developed a model for the motion of present day plates in the Bismarck - Solomon Seas region. He considered a small plate (Bismarck plate) rotating within a much larger plate (Pacific plate) which was in motion relative to another large fixed plate (Indian plate). In this situation, points on the rotating Bismarck plate describe movement paths through time which are modified trochoids. The curve for each point depends on the rate of rotation and the distance of the point from the centre of the plate. Another factor affecting the rate of movement is the distance of the point from the Pacific - Indian Eulerian pole of rotation.

The analysis by Krause is the basis for the theoretical model presented here (Fig. 75). A small plate (plate A) is rotating sinistrally within a large plate (plate C) which is also rotating in a sinistral direction relative to a large fixed plate (plate B). The Eulerian pole (EP) for the ab boundary (EP_{AB}) traces out a movement path along a great circle about the Eulerian pole for the bc boundary (EP_{BC}).

Assume that point X_0 is the initial position of a point X within plate A. Keeping plate B fixed, point X traces out a prolate trochoid movement path from position X_0 to position X_1 during a 180° revolution of plate A relative to plate B about EP_{AB} and a revolution through approximately 30° of plate C relative to plate B about EP_{BC}. The significance of the prolate trochoid curve is that there are different and rapidly changing effects on the different segments of the boundary of plate A, as discussed below.

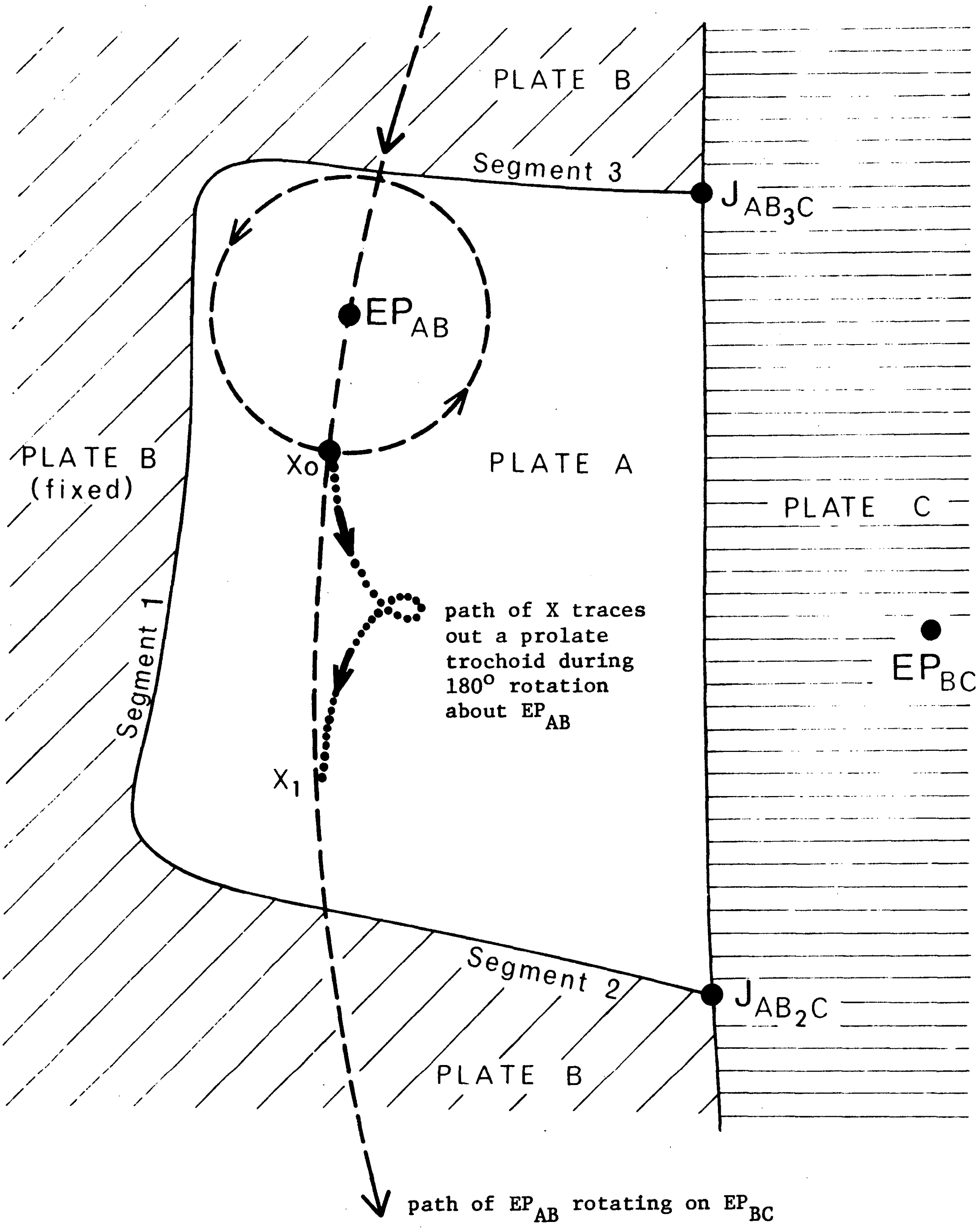


Fig. 75: Theoretical model for the rotation of a microplate (Plate A) between two large plates (B and C). See text for full explanation.

(1) Nature of the plate A - plate B boundary along Segment 1.

Keeping plate B fixed, the plate boundary was initially a dextral transform fault which changed rapidly into oblique dextral rifting which lasted for a considerable period of time. After this the boundary changed rapidly through periods of normal rifting, sinistral rifting, sinistral transform faulting, sinistral subduction, normal subduction and finally through an extended period of oblique dextral subduction which gradually changed into transform faulting at position X_1.

(2) Nature of the plate A - plate B boundary along Segment 2.

The nature of the relative movement on this segment of the boundary changed as follows: initial normal subduction changed rapidly to an oblique dextral subduction which lasted for a protracted period, followed in rapid succession by dextral transform faulting, dextral rifting, normal rifting, sinistral rifting and sinistral transform faulting. Finally a protracted period of sinistral subduction occurred reverting to normal subduction at position X_1.

(3) Nature of the plate A - plate B boundary along Segment 3.

The nature of the relative movement on this segment of the boundary changed as follows: initial normal rifting changed into a protracted period of sinistral rifting. This was followed in rapid succession by sinistral transform faulting, sinistral subduction, normal subduction, dextral subduction and dextral transform faulting. Next come a protracted period of dextral rifting finally reverting to normal rifting at position X_1.

(4) General theory

The movement path of the point X would define a different prolate trochoid if the rotation about EP_{AB} was dextral or if the rotation about EP_{BC} was dextral and consequently the effects along the plate boundaries would also differ. Four situations are possible:

1. EP_{AB} dextral; EP_{BC} dextral
2. EP_{AB} dextral; EP_{BC} sinistral
3. EP_{AB} sinistral; EP_{BC} dextral
4. EP_{AB} sinistral; EP_{BC} sinistral

An infinite number of paths can occur for each of those situations depending on the relative rotation velocities of the two plates. Consequently it can be seen that unless the precise rates and directions of motion for the two plates (A and C) are known it would be virtually impossible to predict the nature of the segments of the boundary of the small plate A.

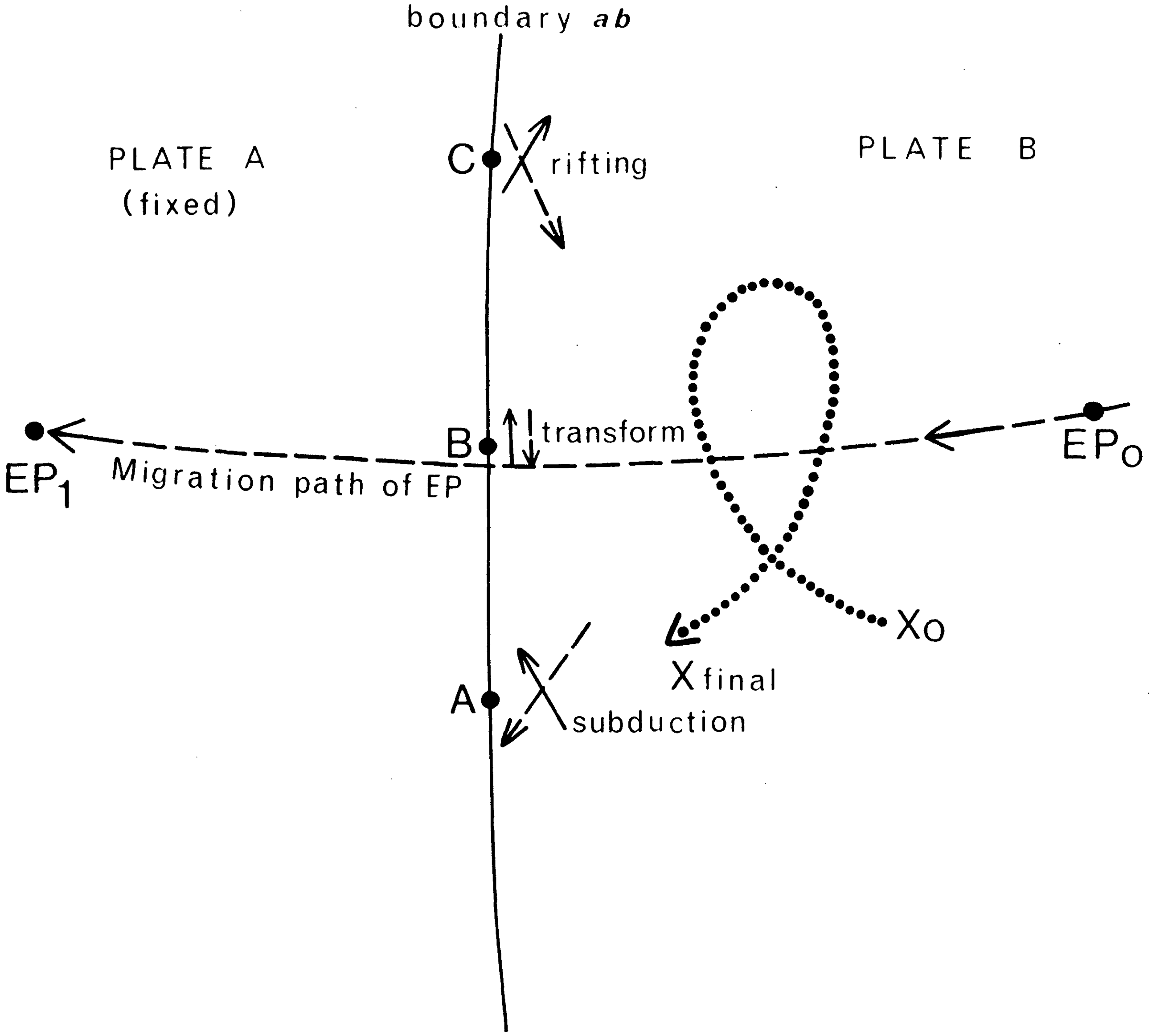
Another method to produce a modified trochoid movement path for points within a plate would be to have the Eulerian pole moving across the plate boundary (Fig. 76). Progressively different conditions would exist along the plate boundary for points A, B and C during the migration of the Eulerian pole. For example, when the Eulerian pole is at position EP_0 there would be sinistral subduction at point A, sinistral transform faulting at point B and sinistral rifting at point C. On the other hand when the Eulerian pole is located at position EP_1 there would be dextral subduction at point A, dextral transform faulting at point B and dextral rifting at point C. Consequently the position and movement of an Eulerian pole relative to a plate boundary can have considerable important implications for the geological processes operating at that boundary.

SMALL PLATES IN NEW ENGLAND

During the Permian small plates developed between the large Wiradjuri plate and the "Pacific" plate. These were the Jiegera, Coffs Harbour, Ngamba (including the Thangetti zone) and Port Macquarie plates which, however, were not all active at the same time. The development of some of these plates will be outlined below but the development of others is complex and the state of present day geological knowledge does not allow the postulation of mechanisms for their evolution. The best example of this is the Thangetti zone (Fig. 77) which, given the existing state of knowledge of its detailed geology, is a "zone of forbidden analysis". This is so even though most of the zone has been mapped carefully by candidates for doctoral and other degrees. When the mapping was being done the zone was known to be complex, but no-one realised the full complexities indicated by the tectonic analysis outlined above.

As outlined in the theoretical model for a small rotating plate between two large plates, changes at plate boundaries can be both rapid and very complex. In the analysis of fossil or "dead" situations such as those in New England, seismic data are not available to determine the directions and amounts of plate movements, and hence movement directions, and the nature of the plate boundaries, have to be inferred from the known geology.

The Thangetti zone is a portion of the Ngamba plate and at times parts of this zone might have been transferred to the Wiradjuri plate. All three main types of plate interaction are considered to have occurred in the belt along the western part of the Thangetti zone. This is here



←——— relative dextral motion of plate B about Eulerian pole at position EP_o

← — — — relative dextral motion of plate B about Eulerian pole at position EP_1

●●●●●●●●●●● migration path of fixed point X from initial position Xo to position X final

Fig. 76: Migration path of a fixed point X within a moving plate B (relative to a fixed plate A) due to migration of the Eulerian pole for the plates A and B across the plate boundary ab.

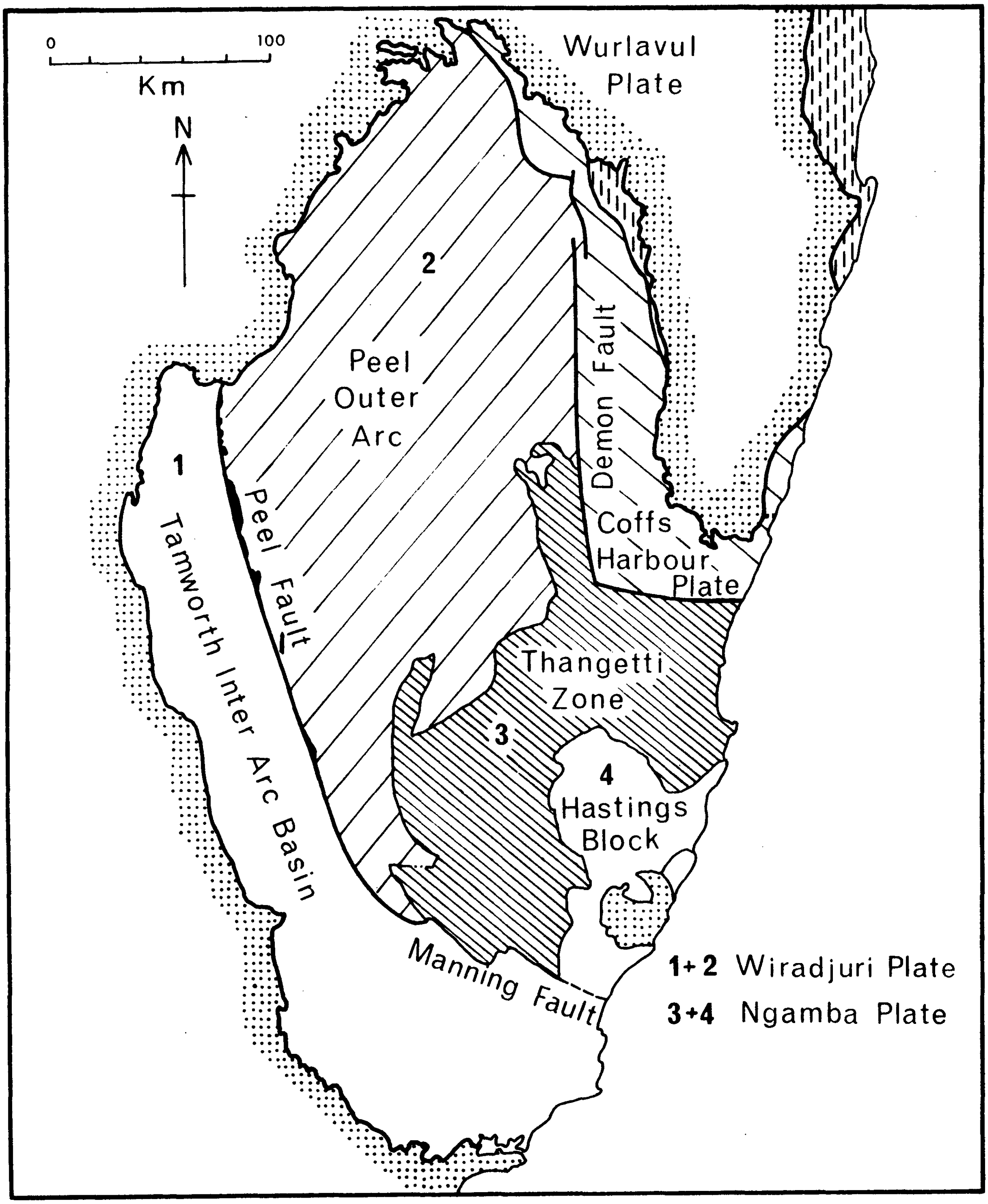


Fig. 77: Sketch map showing important tectonic elements present in New England after completion of movement on the Demon Fault, and location of the Thangetti zone which, given the existing knowledge of the geology, is a "zone of forbidden analysis".

referred to as the Wollomombi plate boundary zone (Fig. 71) because the location of the boundary between the Wiradjuri and Ngamba plates is not precisely known. Fragments of the Coffs Harbour Association (Map 6) occur in the Rockvale Block and around Tia and are separated by areas of the Nambucca Association. This suggests that at some stage segments of the Coffs Harbour Block have been rifted apart, and that diamictites were deposited in the rift or rifts. The timing of this event or series of events is difficult to determine, but some of the movement was prior to the metamorphism of the Tia Complex.

As will be shown later, subduction along the Wollomombi plate boundary was important in the production of the volcanics north of Armidale, the plutons of the Hillgrove Suite and of the western belt of the New England Batholith. The Wollomombi plate boundary is also thought to have been a transform fault at some stage during the Permian for the sense of shearing of plutons by the Chandler Fault zone is sinistral. It can be inferred that subduction (normal or oblique) at the plate boundary caused formation of the Hillgrove Plutonic Suite, which was then disrupted and sheared by a sinistral transform.

Hence, at different stages in the Permian, subduction, rifting and transform faulting have occurred in the Wollomombi plate boundary zone, suggesting the presence of a small plate which has had complex boundary changes, similar to that described by Krause (1973).

Plate movements in New England during the Permian will be divided, for the purpose of discussion, into those associated with the Thangetti zone and those occurring during the development of the Demon Fault.

EVOLUTION OF THE THANGETTI ZONE

Because geological knowledge does not allow a complete interpretation of the Thangetti zone only selected features can be discussed.

Metamorphism

As shown on Map 7, areas of known low-pressure metamorphism extend in an arcuate belt from the Coffs Harbour Block through the Wongwibinda Complex to the Tia Complex. The Nambucca Slate Belt and metamorphics of the Warnes River district form a parallel arcuate zone of intermediate-pressure metamorphic rocks lying to the east of the low-pressure zone. Miyashiro (1972, 1973b) has shown that low pressure metamorphic rocks represent zones of ancient volcanic chains where high heat flow regimes resulted from the rise of granitic magma. He also considered that high pressure metamorphic belts represent ancient subduction zones along trenches. The paired nature of high and low pressure belts has been recognised by Miyashiro (1973b) who also considers that during the Palaeozoic high-pressure belts were rare, possibly because the rate of plate descent was slow, and that medium-pressure metamorphic belts were formed instead.

Hence the two metamorphic zones in New England can be regarded as a paired metamorphic belt related to the subduction of an oceanic plate and the development of a magmatic arc. Remnants of the oceanic plate which were not subducted are represented mainly by sediments of the Nambucca Slate Belt.

Granitic Rocks

The granitic rocks in New England have been divided into four suites (Map 6), two of which can be related to the subduction of the Thangetti zone under the Wiradjuri plate and development of the paired metamorphic belt. This subduction is possibly related to the rotation of the Ngamba plate. An examination of the radiometric ages for the Hillgrove Plutonic Suite and the Western Belt of the New England Batholith (Map 7) shows that the Hillgrove Suite is the older, occurring closest to the trench which was possibly very steeply dipping. Westwards there is a progressive decrease in the ages of the plutons, with the youngest in this western belt occurring furthest from the subduction zone. These are the Mole Granite and Gilgai Granite which are also the two highly acid tin-bearing granites and possibly the most highly potassic.

Subduction along the Wollomombi plate boundary has given rise to the plutonic belts with a north-northeast trend. Subsequent evolution of the Demon Fault, and dextral movement of the Coffs Harbour Block, has transported towards the south those plutons which formed to the east of the present position of the Demon Fault. These plutons, (Chaelundi Complex, Sheep Station Creek Complex and Dundurrabin Granodiorite), along with the Coffs Harbour Sequence, have suffered a late stage sinistral rotation resulting in the present north-west trend in the southwest portion of the Coffs Harbour Block (see Chapter 2).

The intrusion of the plutons was preceded by the extrusion of volcanics with calc-alkaline continental margin affinities (Langham 1973). Extensive remnants of the volcanics occur to the north of Armidale and west of Guyra. The oldest plutons (Hillgrove Suite) which formed closest to the trench were later sheared, either in a sinistral transform zone or in an oblique sinistral subduction zone.

Deformation

The changing nature of the plate boundaries associated with movement of the small plates caught between the large Wiradjuri and "Pacific" plates has led to a complex series of deformations in those small plates, particularly in the Thangetti zone. In the Nambucca Slate Belt, Leitch (1972) has recognised five separate episodes of deformation. The most deformed rocks crop out on the coast in the headlands at Valla and Nambucca Heads and are structurally shredded. The easterly strike of some of the deformations in the Nambucca Slate Belt can be explained most easily as a product of the southward migration of the Bellinger trench; as subduction proceeded the trench-fill sediments were plastered against the trench wall and became deformed.

Other factors that have had considerable influence on the evolution of the Thangetti zone are the deformation associated with movement and changes along the Wollomombi plate boundary and movement of the "Pacific" plate. The orocline-like rotation of the Ngamba plate (see later) was probably accompanied by severe folding and faulting, especially as the Thangetti zone was caught between the sinistral rotation of the southern part of the Ngamba plate and the southwards movement of the Coffs Harbour plate. This idea is similar to that of Scheibner (1973) who nevertheless interprets the Bellinger Fault as an obduction zone and maintained that part of the Ngamba plate (his Kempsey Block) remained rigid at this time.

In the Coffs Harbour Block (Chapter 2) the deformation is most intense closest to the Bellinger trench and progressively decreases northwards. This was a "collision" effect, which decreased in intensity as it was transmitted northwards.

Future analysis of the nature of the triple junctions located in the Thangetti zone due to increased geological knowledge will be extremely important because, as McKenzie and Morgan (1969) have pointed out, sudden changes in tectonic and deformational style in a region are more likely to be caused by movement of triple junctions rather than by changes in the relative velocity vectors of plates.

OBDUCTION AND NATURE OF THE MANNING AND PEEL FAULT SYSTEMS

Late Carboniferous to Early Permian subduction of the Thangetti zone portion of the Ngamba plate along the Peel trench is tentatively correlated with the eruption of the Early Permian Werrie Basalts, and the associated acid volcanics in the Gunnedah - Boggabri region. Subduction of the same elements in a southwest direction can be correlated with the eruption of Early Permian volcanics in the Hunter Valley. Later movement of the trench eastwards, approximately to the position of the Wollomombi plate boundary, subducted the Thangetti zone under the Wiradjuri plate to produce the Hillgrove Suite and under the Tamworth Belt at the Manning Fault system.

Thus the Tamworth Belt, which is underlain in part by an ophiolitic suite (Cross 1974), was thrust (obducted) northwards over the top of the Thangetti zone and the ophiolitic rocks were exposed at the northern edge of the thrust. Therefore the irregular outline of the Manning Fault system represents the overthrust edge of the base of the Tamworth Belt.

Associated with the obduction of the Tamworth Belt over the Thangetti zone was the probable movement of the Wollomombi plate boundary towards the southeast. This might have reactivated the Peel Fault System to produce a dextral strike-slip movement with the Peel outer arc portion of the Wiradjuri plate (Fig. 77) moving south. Early Permian fault slivers caught up along the Peel Fault System (see Chapter 6) indicate that the movement was later than Early Permian time. Movement ceased prior to the intrusion of the Inlet Monzonite which has been dated at 248 m.y. by Cooper *et al.* (1963). Leitch (1969) has shown that folding of the sediments in the Tamworth Belt also occurred at about the same time as movement along the Peel Fault System.

VORTEX PATTERN IN SOUTHERN NEW ENGLAND

As discussed previously, the Tamworth Belt had a curved outline which was concave eastwards during the Carboniferous. It is probable at this stage that the Hastings Block was located to the southeast of the Tamworth Belt and was rotated with a sinistral sense of movement in a northerly direction to be relocated in its present position as part of the Ngamba plate in the Early to Middle Permian. Of major significance here is the Manning Fault System mapped by Voisey (1940) which is here considered to be the northern boundary of the Tamworth Belt around Mt. George but was only given conjectural status in the coastal region south of Taree by Voisey. Two related possibilities can be suggested to produce the observed patterns (Map 6).

1. Development of an Orocline

The Tamworth Belt and Hastings Block developed as an orocline in the method formulated by Carey (1955). For an orocline to develop the plates would need to be in a non-rigid state. The conjectural Manning Fault system of Voisey (1940) is thus relegated in status to a radial fault - one of many located in the Hunter Valley portion of the Tamworth Belt (see Map 6 and Fig. 78). In this case a rift could possibly be opened at the present site of the Sydney Basin between the Mt. Coricudgy Anticline and the present edge of the continental shelf (Fig. 79).

2. Rotation of a small plate

For this model the conjectural portion of the Manning Fault System becomes a major fault which separates the arcuate Tamworth Belt from the Hastings Block. The Hastings Block can be regarded as a portion of a small plate (Ngamba Plate) between the large Wiradjuri plate (which includes the Tamworth Belt) and the "Pacific" plate. Movement northwards of the "Pacific" plate relative to the fixed Wiradjuri plate could easily produce a sinistral sense of rotation of the Ngamba plate.

Present knowledge does not allow approval of one possibility over the other, but future detailed mapping in the vicinity of the Manning Fault System near the coast might help to elucidate the situation.

Associated with the development of the orocline or rotation of the Ngamba plate there appears to have been sinistral movement or rotation along the Wollomombi plate boundary zone. Fragmentation of the Coffs Harbour Association, possibly by rifting and sinistral transform fault movement, has produced a vortex like pattern. The "eye" of the vortex is located in the Nowendoc region near where Gunthorpe (1970) reported a small area of intermediate-high pressure metamorphism. This is also where obduction has occurred of the ophiolitic sequence over sediments of the Thangetti zone. This vortex produced a complex picture, including disruption of the Tia region by concentric and radial faults to give the present lozenge pattern (see Map 6) and detailed field mapping will be required to outline its character.

The rotation and subduction of the Ngamba plate could have been at rates between 0 and 150 mm yr^{-1} but the EP for the rotation was on or very close to the plate, thus giving a very low relative velocity. A rate of about 1 to 5 mm per year on the Wollomombi plate boundary would be acceptable. At

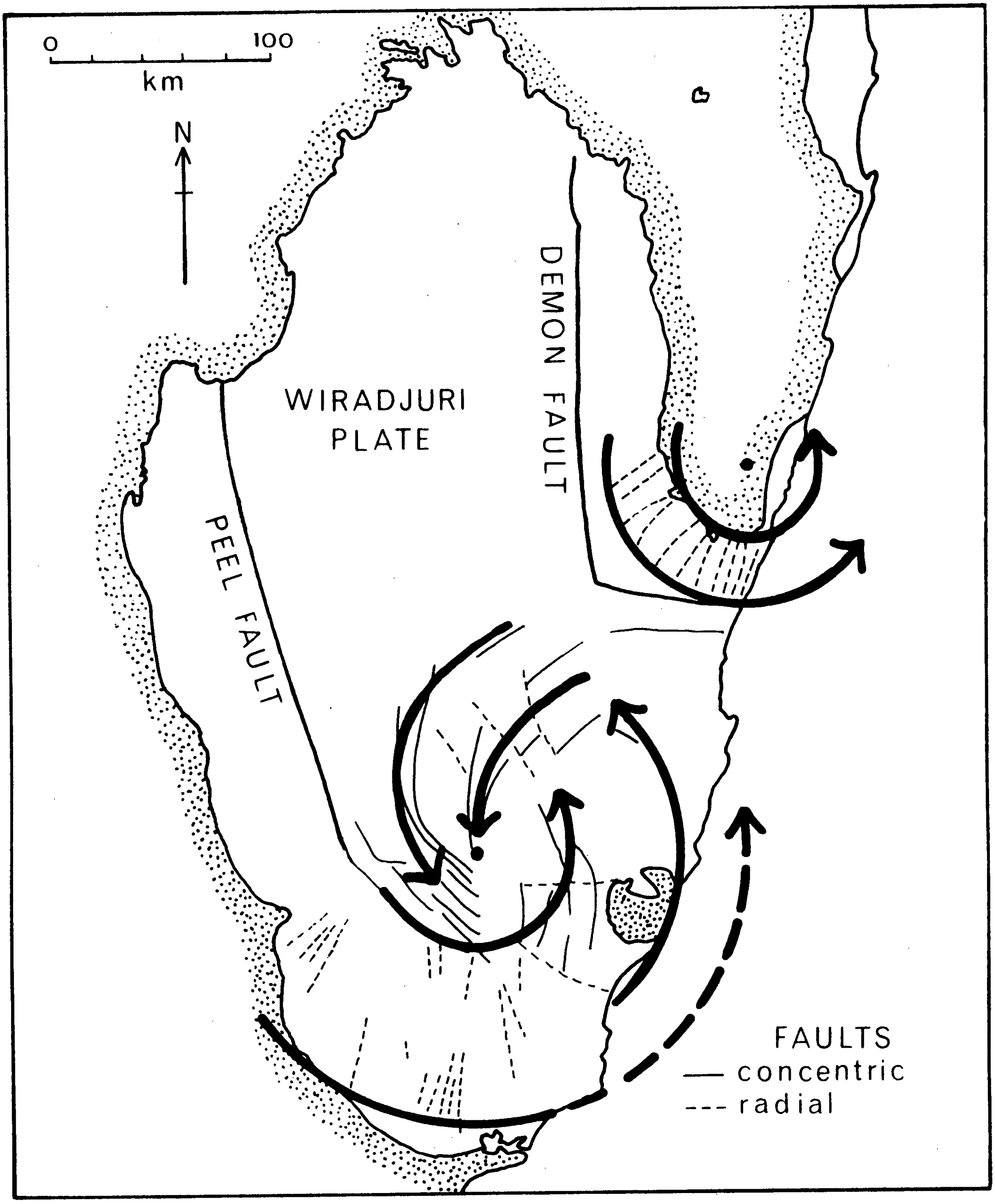


Fig. 78: Vortex arrangement in the southern part of New England produced by either oroclinal folding of the Tamworth Belt or sinistral rotation of the Ngamba plate. See text for full explanation.

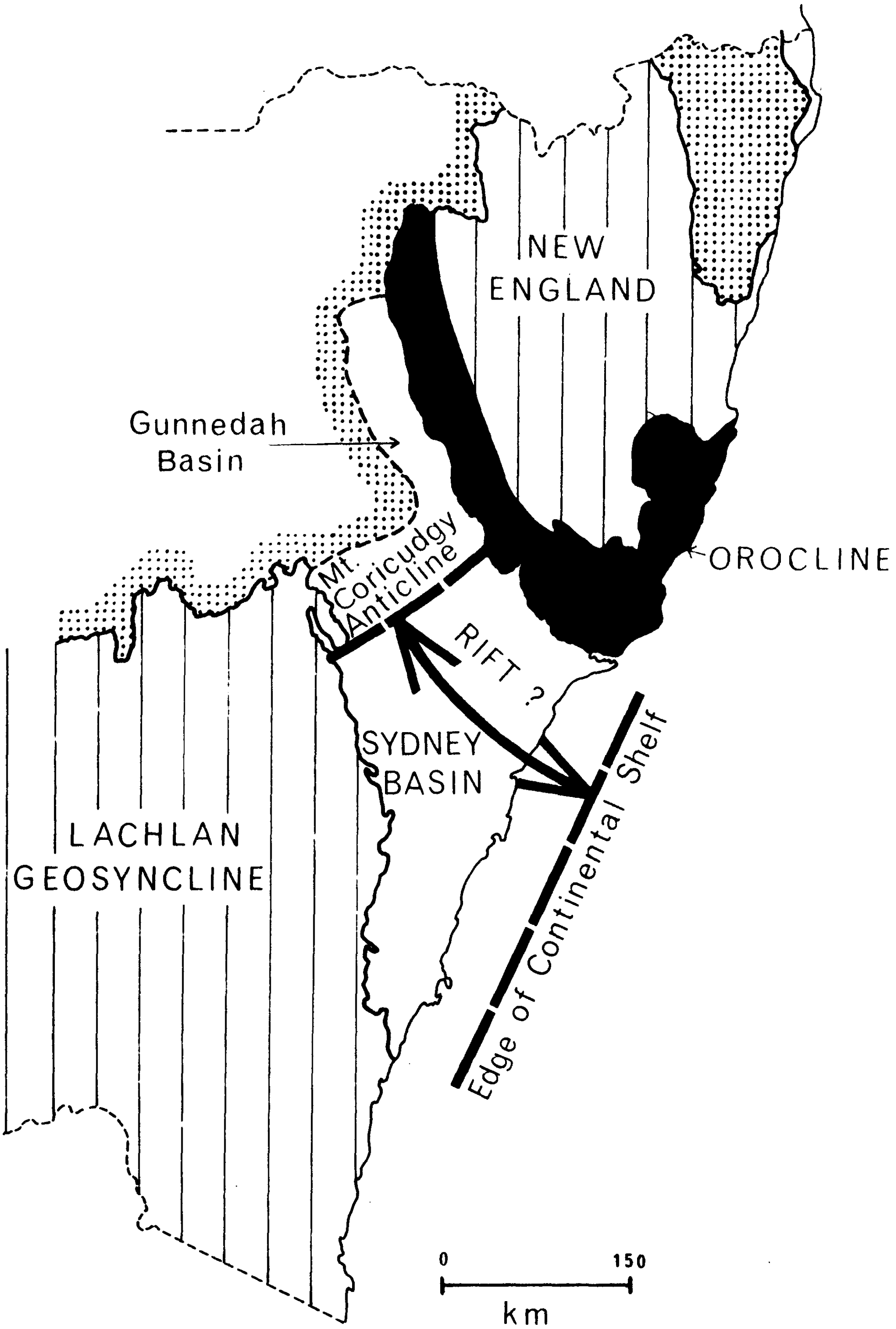


Fig. 79: Possible rifting associated with oroclinal folding of the Tamworth Belt and Hastings Block to produce a rift for deposition of the Sydney Basin.

that angular distance from EP_{WiN} the distance travelled by a point X on the Wollomombi plate boundary was about 300 km and the time involved was about 30 m.y. to 6 m.y. A rate of 1 mm yr^{-1} for 30 m.y. would mean that movement occurred through most of the Permian, and this is likely because the plutons of the Hillgrove Suite and Western belt of the New England Batholith span a time interval of 33 m.y. (269 - 236 m.y.) in the Middle to Late Permian.

Assuming the granitic diapirs formed at a depth of 25 km and rose at the rate of 1 mm yr^{-1} then the time taken to rise would be 25 m.y. Therefore it is necessary to add on approximately 25 m.y. to all K/Ar dates to get the time of formation of the plutons at a depth of 25 km. Using a rise rate of 1 mm yr^{-1}, another one m.y. should be added for every kilometre increase in the depth of origin of the granitic material. Thus the batholiths could have formed 25 m.y. earlier than their cooling dates, giving ages of formation of 294 - 261 m.y. (i.e. Earliest to Middle Permian). The higher rate of 5 mm yr^{-1} on the Wollomombi plate boundary therefore seems unlikely.

DEVELOPMENT OF THE DEMON FAULT

The sudden end of the Demon Fault in both the north and the south indicates that it must be a transform. Its southern end (Bellinger plate boundary, Fig. 71) is against the Thangetti zone of trenches and other complexities. There are basically only three transforms that can exist, namely R-R, T-T and R-T, and hence at the northern end of the Demon Fault there must have been either a trench or a spreading ridge. There is no evidence whatsoever for a spreading ridge so the palaeo-feature must have been a trench, which is here termed the Condamine trench (Fig. 80).

Therefore the Demon Fault is interpreted as a T-T transform of lengthening, not shortening, type. This type of transform can occur only where trenches have opposed polarity which, in this case, means that the Thangetti zone is being subducted under the Coffs Harbour Block and the plate on the northern side of the Condamine trench must have been subducted under the Wiradjuri plate.

This new trench (Condamine - Bellinger trench) divided the Aniwan plate (see Figs. 72 and 74) into the Coffs Harbour plate north of the trench and the Thangetti zone of the Ngamba plate south of the trench (Fig. 80A). The subsequent dextral sense of movement (Fig. 80B) along the Demon Fault has produced a situation similar to that on the New Zealand Alpine Fault as outlined by McKenzie and Morgan (1969).

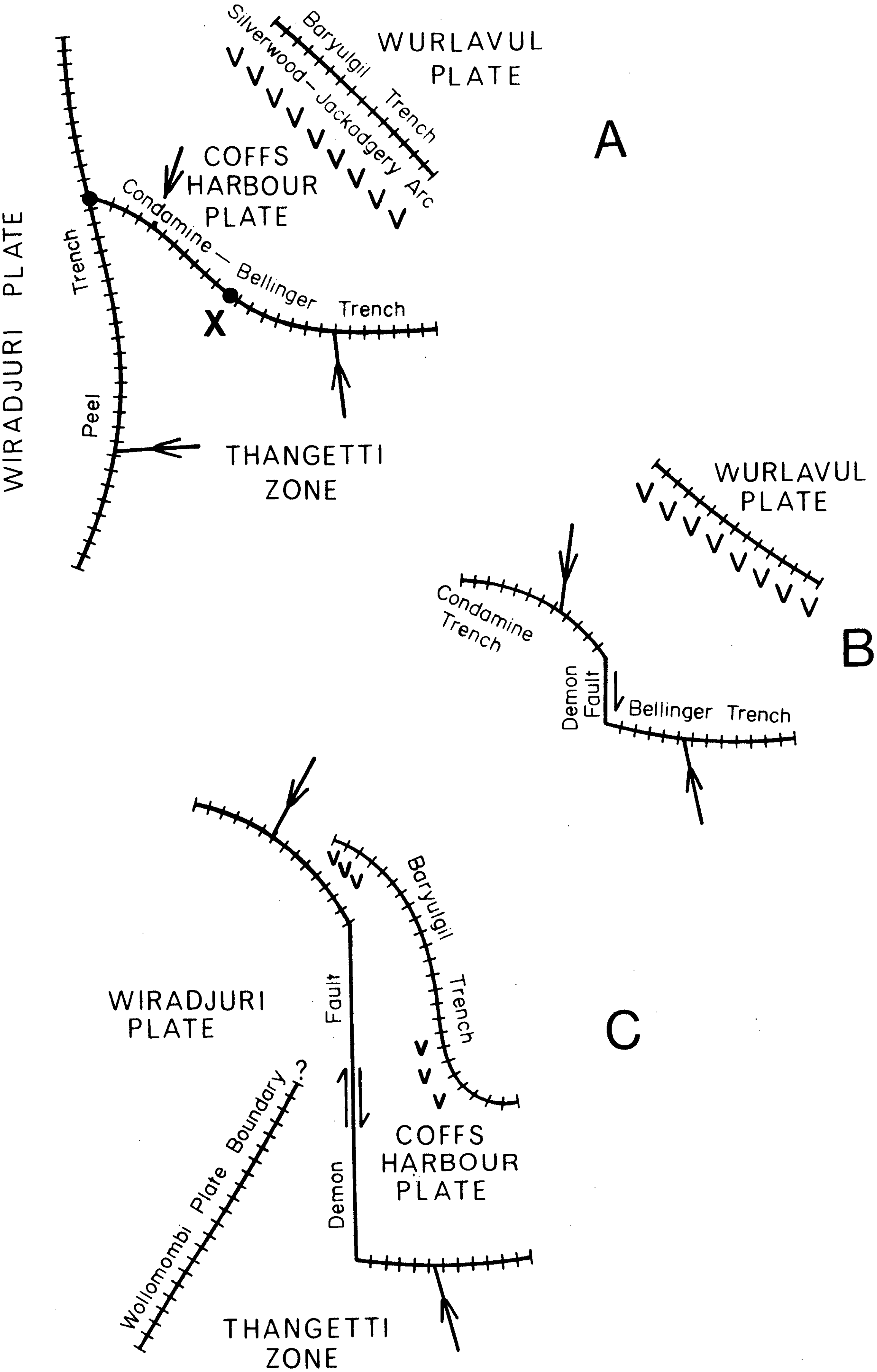


Fig. 80: Diagrammatic representation for the development of the Demon transform fault from initiation (Fig. A) to final position (Fig. C).

The Demon transform could have lengthened at any rate between 1 mm and about 150 mm yr^{-1}. At the highest rate of 150 mm yr^{-1}, the approximate 180 km length of the Demon Fault could have formed in about 1 m.y., and at 30 mm yr^{-1} it could have formed in about 6 m.y. Even at the lower rate it was a rapid event. If a Late-Permian - Early-Triassic pluton (Stanthorpe Adamellite) is really displaced dextrally on the fault, then the Coffs Harbour plate moved south in the Late Permian to Early Triassic.

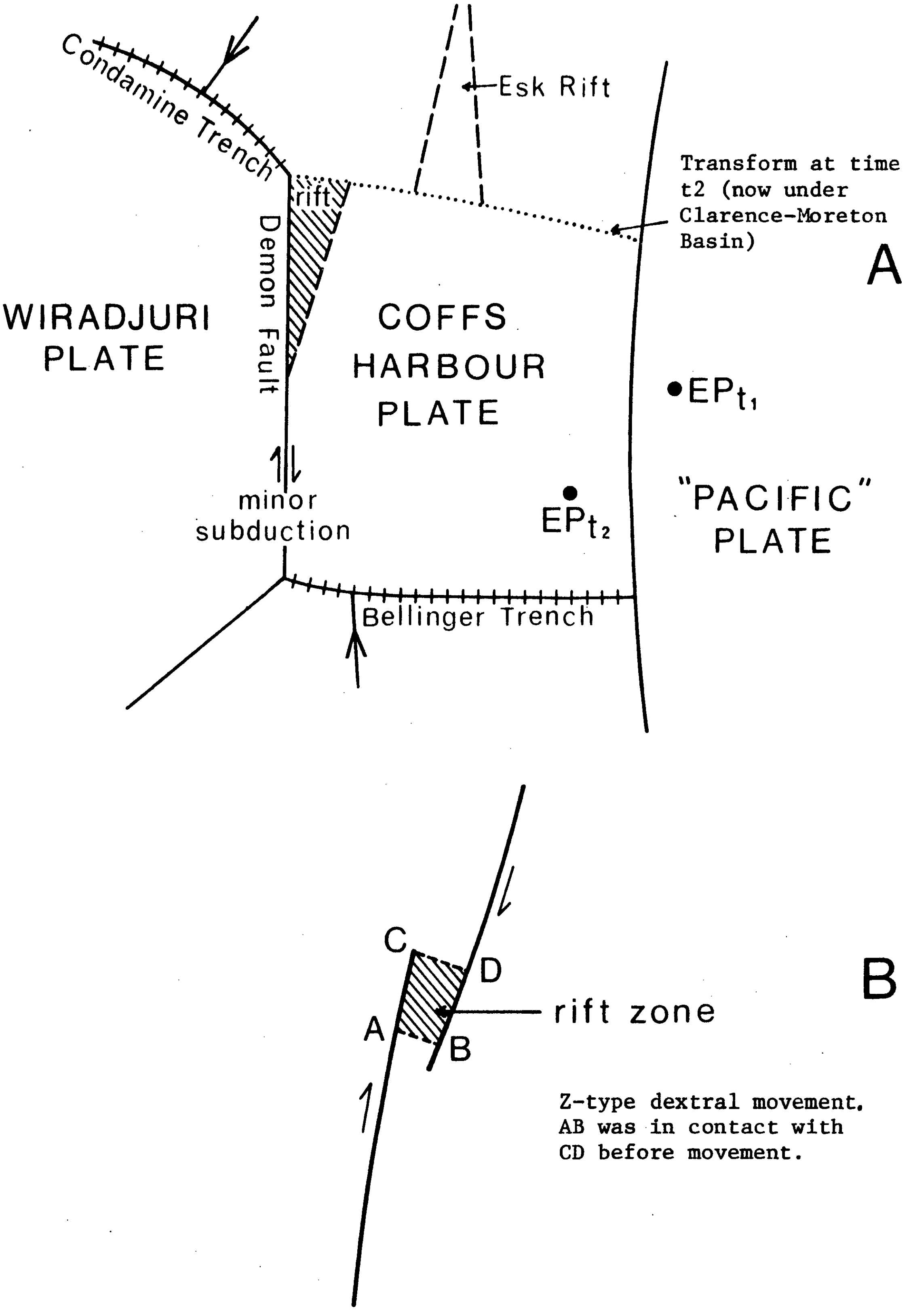
The Coffs Harbour plate was subducted under the Wiradjuri plate along the Condamine trench but was conserved to the east and moved south along the Demon transform (Fig. 80C). Subduction of much of the Coffs Harbour plate along the Condamine trench might have produced a volcanic arc in the Wiradjuri plate, remnants of which could be the Emmaville volcanics and associated porphyritic rocks. A large part of the Coffs Harbour Sequence (see Appendix I) could have been lost by subduction at the Condamine trench leaving cherts (Leyburn Beds of Butler 1974) and the Silverwood Group on the north side of the subduction zone between Leyburn and Stanthorpe.

Part of the Wollomombi plate boundary and Thangetti zone east of the present position of the Demon Fault has been overridden by the Coffs Harbour plate. Intense compression and deformation occurred in the Nambucca Slate Belt of Leitch (1972). In the northern part of the Nambucca Slate Belt a pile of metabasaltic rocks known as McGraths Hump Member (Leitch *op. cit.*) is here considered to be a remnant seamount, and not the base of an obducted plate as suggested by Scheibner (1974).

Rift situation for the Drake Volcanics

Along the northern part of the Demon transform there is a rift valley infilled with the Late Permian Drake Volcanics. Two processes for the formation of the rift are outlined below.

Process 1. This process is based on an analysis of the New Zealand Alpine Fault by Christoffel (1971) and depends on the changes of relative motion on a plate boundary when its Eulerian pole is moving. The model is illustrated in Figure 81A and the requirements for it are that the Eulerian pole for $time_1$ (EP_{t1}) must fall on a great circle perpendicular to the Demon Fault, to either the west or the east, and that EP_{t2} is moving. For the time at which movement on the transform changes to rifting there are an infinite number of positions of the Eulerian poles EP_{t1} to EP_{tn} and hence an infinite number of modified trochoid paths could be defined. Hence the only requirement is that the EP is moving. In Figure 81A the Eulerian poles are shown to the east of the Demon Fault; they could have been west of the fault in



Z-type dextral movement. AB was in contact with CD before movement.

Fig. 81: Possible mechanisms to produce rifting in the Drake Volcanic Zone, associated with movement on the Demon Fault. A - movement of Eulerian pole based on method of Christoffel (1971); B - strike-slip fault method (after Clayton 1966).

Wiradjuri plate.

Process 2. The second process involves rifting between en echelon strike-slip faults within a transform zone and no movement of an Eulerian pole is required. This process was first described by Clayton (1966). ERTS-A images of northern New South Wales suggest that the Demon Fault in detail consists of en echelon faults and splay faults with a Z-type overlap. Since the movement appears to have been dextral the correct solution would require a Z-type dextral rifting situation as illustrated in Figure 81B. This second process is closely related to the first process, both being products of plate rotation.

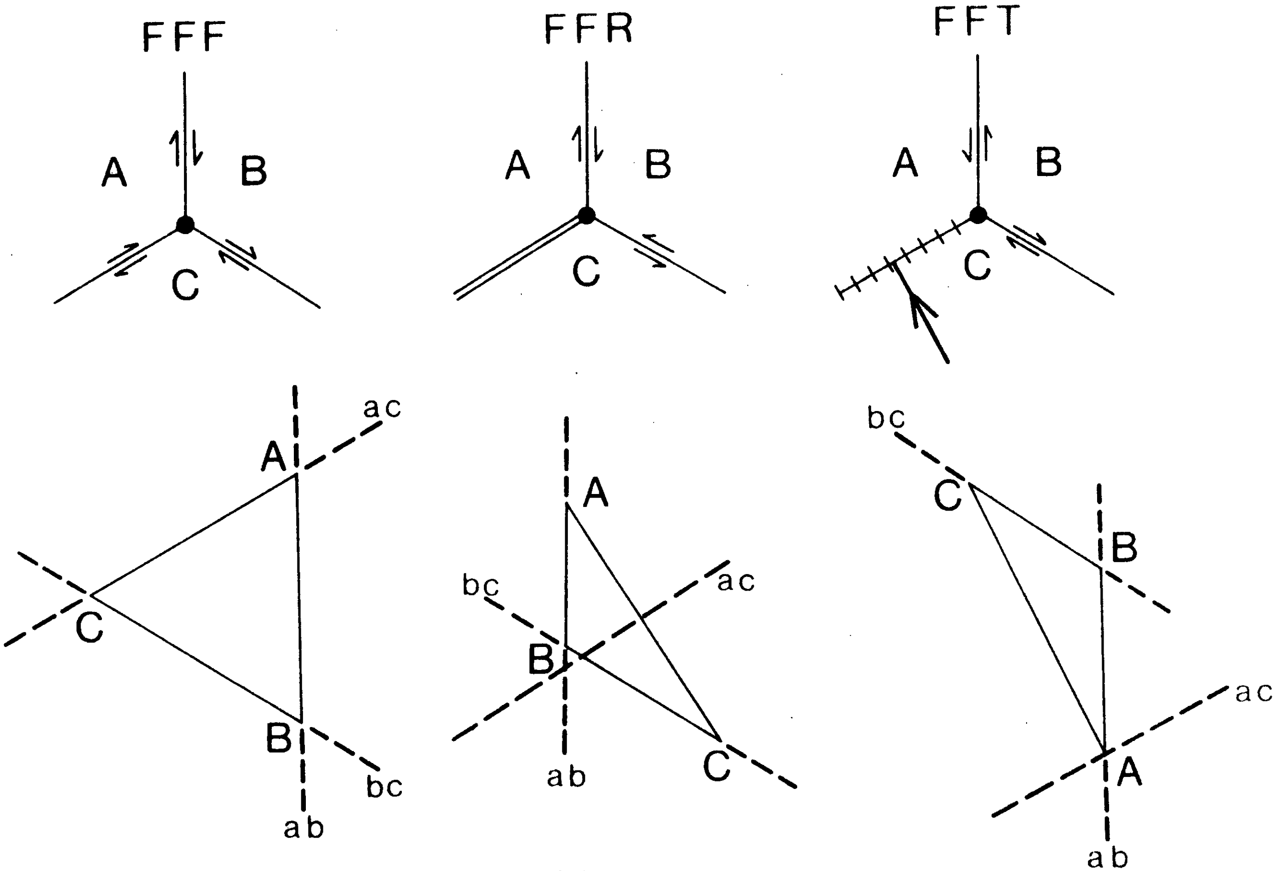
The Drake rifting situation and development of a microplate (Coffs Harbour plate) is analogous to the New Zealand situation recognised by Wellman (1973).

POSSIBLE TRIPLE JUNCTION SITUATIONS

During the Permian several triple junction situations occurred and it is possible to examine some of these in the light of known geology although many others, particularly those associated with the Thangetti zone or the "Pacific" plate, cannot be postulated at the present time due to lack of sufficiently detailed geological data.

A triple junction between the Peel - Yarrol Line and the Condamine trench was of trench-trench-unknown type; geometry of this type of situation has been analysed previously for an Early Devonian situation where the Baryulgil trench met the Peel - Yarrol Line (Fig. 73). The possible solutions for the present situation are that the unknown plate boundary is either (1) a trench, in which case the triple junction migrates northwards relative to the fixed Wiradjuri plate, or (2) a transform, in which case the triple junction can migrate in either direction depending on the direction of the relative velocity vector of the Thangetti zone with respect to the Wiradjuri plate.

Another situation is where the Wollomombi plate boundary possibly meets the Demon transform and hence three plates: Wiradjuri (Wi), Coffs Harbour (Ch) and Thangetti zone (Th), meet at a triple junction. The nature of the Wollomombi boundary zone changes through time and hence all possible situations need to be examined. Because dextral movement has occurred on the Demon transform, three possible situations exist (Fig. 82) of which FFF is unstable. In the FFR situation the motion of the ridge must parallel the



Unstable

Stable (1) if B lies on ac, or (2) if ab and bc form a straight line.

Stable (1) if ac and ab form a straight line, or (2) if ab and bc form a straight line.

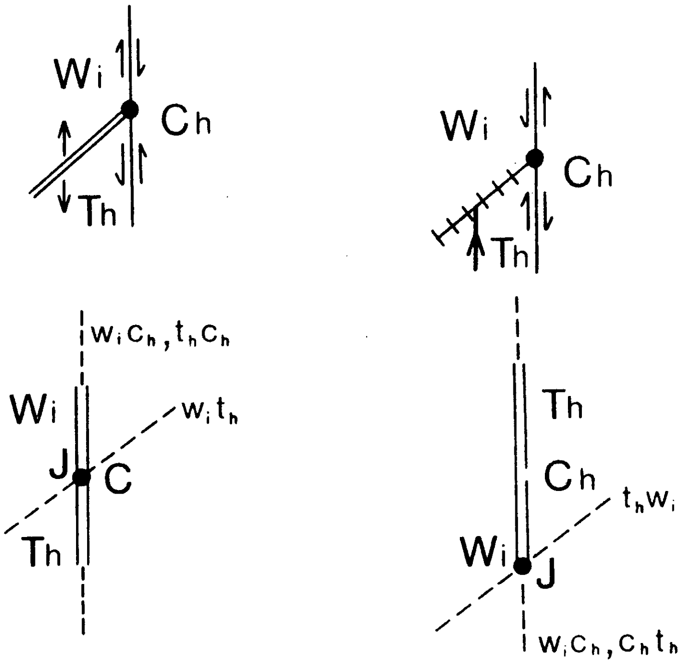


Fig. 82: Possible triple junction situations for the Demon transform-Wollomombi plate boundary intersection. The geometries, relative velocity triangles, stability criteria and most likely stable situations are shown.

transform. If the ridge is not normal to the transform then oblique rifting must occur. J moves southwards relative to a fixed Wiradjuri plate.

In the FFT situation oblique subduction parallel to the transform must occur to ensure stability. In this case J is at rest relative to the Wiradjuri plate but migrates southward relative to a fixed Coffs Harbour plate.

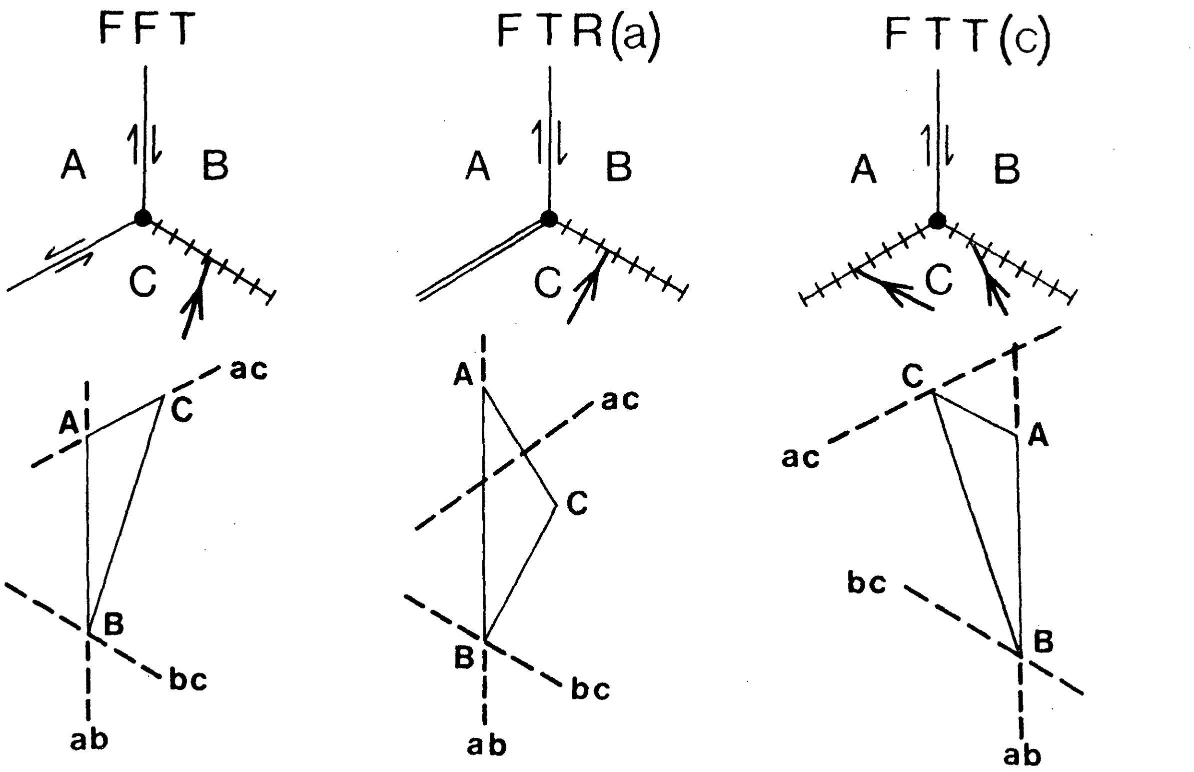
If the triple junction formed by the intersection of the Demon transform and the Wollomombi plate boundary migrated south relative to the Coffs Harbour plate eventually a new triple junction would form at the position where the Demon transform, Bellinger trench and Wollomombi plate boundary met. Attempts to produce a stable situation for this triple junction are shown in Figure 83. According to stability criteria for triple junctions developed by McKenzie and Morgan (1969) it is not possible for a stable triple junction to exist given the present orientations of the Demon transform, Bellinger trench and Wollomombi plate boundary. As a consequence this unstable triple junction existed only instantaneously and must have evolved to a stable situation such as one of those illustrated in Figure 83.

Of some interest is the FTR(a) case where, for a fixed Wiradjuri plate, the triple junction is migrating eastwards converting the Bellinger plate boundary from a trench to a transform. In the FFT and FTT (c) cases the triple junctions are migrating south relative to a fixed Wiradjuri plate and are at rest with respect to the Coffs Harbour plate. For these two cases to occur a southern extension of the Demon transform (either as a trench or a transform) to the south of the Bellinger plate boundary is required.

It must be remembered that triple junction geometry is only applicable on plane surfaces in the immediate vicinity of the triple junction. Once the geometry is applied to a situation on a sphere, and away from the triple junction, the plate boundaries can behave in a manner completely different to that indicated by the stability conditions at the triple junction.

MESOZOIC EVENTS

Analysis of plate geometry for the Mesozoic is beyond the scope of this thesis except for a few events which have implications for the New England region. During the Early Triassic several events took place but were mainly confined to the vicinity of the present day coastline, and



Stable (1) if bc and ab form a straight line, or (2) if ab and ac form one.

Stable (1) if ac goes through B, or (2) if ab and bc form a straight line.

Stable (1) if ab and bc form a straight line, or (2) if ab and ac form a straight line.

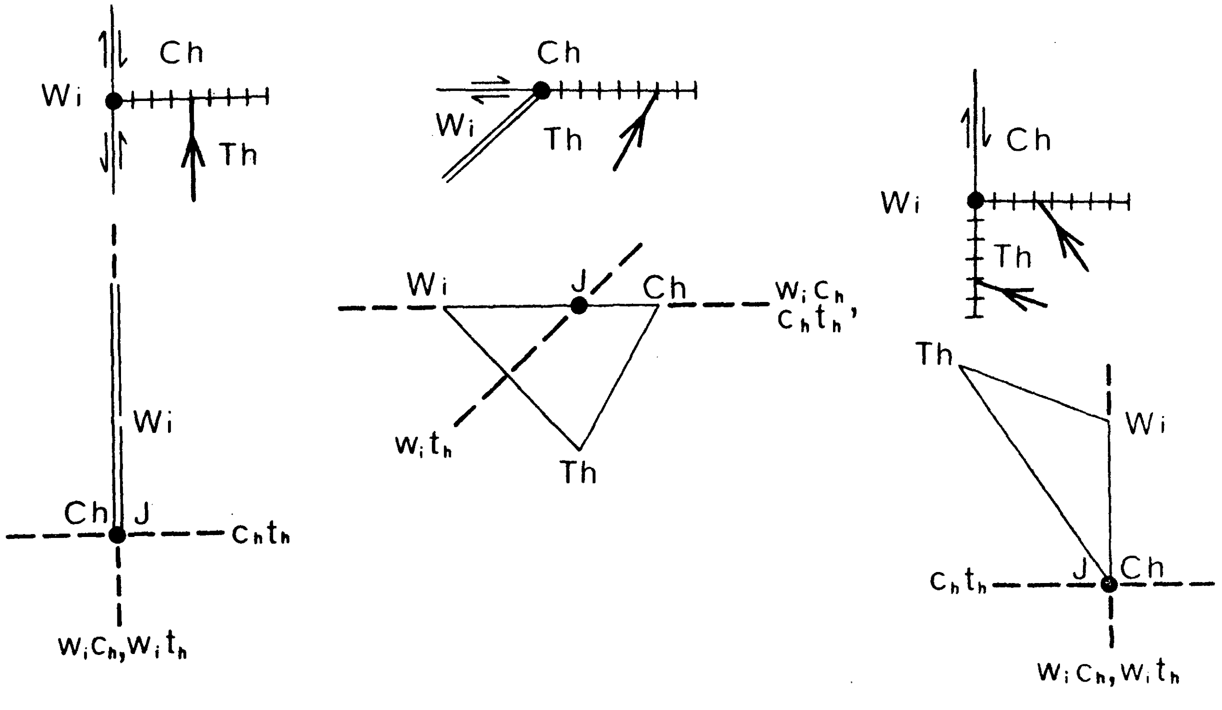


Fig. 83: Possible triple junction situations for the Demon transform - Bellinger trench - Wollomombi plate boundary intersection. The geometries, relative velocity triangles, stability criteria and possible stable situations are shown.

appear to be associated with movement of the "Pacific" plate. Movement of the western plates appears to have ceased, resulting in one major plate (the "Australian" plate).

The most important event was the intrusion of the north-south trending Eastern Belt of the New England Batholith at about 225 m.y. which is now considered to be Early Triassic (Green and Webb 1974). It is postulated here that the Eastern Belt is a product of a west dipping subduction zone located at the "Pacific" plate boundary just off the present New South Wales coast. Intermittent volcanic activity has been recorded by McElroy (1962) in the Clarence - Moreton Basin during the Triassic (Copes Creek Tuff, Chillingham Volcanics) and Jurassic (Towallum Basalt) and this activity is also considered to be related to subduction at the "Pacific" plate margin located to the east of the basin. This plate margin was mainly transform in character but minor oblique subduction occurred intermittently.

Movement of the "Pacific" plate and fragmentation along the boundary with the "Australian" plate has produced at least two small plates and has had a marked impact on parts of the "Australian" plate. In the Coffs Harbour Block a very late stage macroscopic deformation resulted in a pronounced swing in strike of the northern portion of the Coramba Beds (see Chapter 2). This swing might have resulted from the development of an oroclinal fold similar to the one tentatively postulated for the Tamworth Belt, or might be due to rotation of a small plate caught between the large "Australian" and "Pacific" plates. The presence of the distinctly different jasper-rich Redbank River Beds, at the position where the change in strike occurs, suggests preference for the rotation of a small plate (here called the Jiegera plate) over the oroclinal hypothesis. Some rotation has also occurred in the southern part of the Coffs Harbour Block.

Due to the presence of the Clarence - Moreton Basin and Quaternary alluvium no possible relict plate boundary features have been observed and hence no further analysis can be attempted. It will suffice to say that points within the Jiegera plate might possibly trace out modified trochoid paths during their rotation. A likely trochoid path is a flattened cycloid path with the cusp pointing towards the west. Movement of the "Pacific" plate is essentially northwards and rotation occurred when the motion was towards the cusp of the cycloid.

An anomaly in the coastal geology is the Port Macquarie Block consisting of serpentinite and cherty rocks similar to the Woolomin Beds near the Peel Fault. It is tentatively suggested that this block is a separate plate (the Port Macquarie plate) which has been rotated into its present position by movement of the "Pacific" plate northwards relative to a fixed "Australian" plate.

Intense deformation at Nambucca Heads and Valla does not extend much further inland but is coupled with thrust sheets which moved towards the west, suggesting that a "collision" with the "Pacific" plate occurred at one stage in the deformational history of that portion of the Nambucca Slate Belt.

From the above tectonic analysis it can be seen that the western and southeastern edges of the Clarence - Moreton depositional basin are tectonically controlled. In the west the basin is bounded by the Baryulgil plate boundary (trench) and to the southeast by the Jiegera plate. Detailed work to the northeast might also possibly show that the margin of the basin in that region is tectonically controlled.

CONCLUSION

For a first primary analysis, the southern part of the New England Geosyncline has been affected mainly by three different sets of plate movements which were partially coincident in both space and time. These plate movements are considered to be associated with three separate major deformations or orogenies affecting New England during the Palaeozoic.

The first orogeny is associated with the Peel trench and possibly took place over a considerable period of time in the region east of the Peel Fault during subduction of the Aniwan plate and accretion of the Peel outer arc portion of the Wiradjuri plate.

Plate movements associated with the rotation and subduction of the Ngamba plate are regarded as the cause of the second orogeny which took place in Early to Middle Permian, mainly influencing rocks now located to the east of longitude 151°30'E.

Initiation and evolution of the Demon Fault during the Late Permian to Early Triassic was the cause of the third orogenic episode observed in New England. The main region affected now lies to the north of latitude 32°S and to the east of 150°E longitude.

In the Nambucca Slate Belt Leitch (1972) recorded multiple deformations which are here considered to have been the products of the three orogenies with the two younger ones being superposed on rocks already affected by the first orogeny.

A postulated fourth orogeny, possibly resulting from movements associated with the "Pacific" plate, could have been simultaneous with the other orogenies, or possibly overlapped them in space and time. The effects of this orogeny are limited to localised areas on the present coastline.

The classical orogenies for eastern Australia (that is, Kanimblan and Hunter - Bowen) are not correlated with the orogenies outlined here because it is considered that in the light of plate tectonics, orogenies are confined in time to the duration of the plate interactions, and in space to the specific region where the effects of the interactions are now observed. If names are to be given to the three major orogenies in New England, they should be called the Peel, Ngamba and Demon orogenies respectively.