CHAPTER 2

SEDIMENTARY ROCKS : GENERAL COMMENTS

The petrology of sedimentary rocks in the Woolomin Association and in the Tamworth Group has been described in some detail by earlier workers. In particular, Mayer (1972) and Rigby (1980) described the petrography of sedimentary rocks in, and adjacent to, the Pigna Barney-Curricabark area. Similar studies on the Tamworth and Parry groups and/or the Woolomin beds to the north of this area include those by Crook (1960a,b), Chappell (1968), Ellenor (1972,1975), Paull (1975), Rose (1978), Cuddy (1978), Cawood (1980,1982b, in press) and numerous additional unpublished theses and reports held at the University of New England (see Korsch, 1977, for a summary of some of these studies). All these studies show that clastic rocks in the Tamworth and Parry groups, and in the Woolomin Association, were derived almost entirely from a predominantly intermediate-silicic, and occasionally basic (especially in the Early Palaeozoic succession; Cawood 1982b, in press) volcanic source, presumably in the form of at least one relatively immature, relatively undissected volcanic arc. It is generally believed that, with few exceptions (e.g. the Drik-Drik Formation; see Crook, 1960a; Cawood, in press), the volcanogenic detritus in the Tamworth Belt was derived from an active Palaeozoic volcanic arc lying along the western margin of the belt (e.g. Crook 1960a,b; Leitch 1974,1975; Cawood 1982a,b, in press). As yet it is unclear whether any volcanogenic detritus in the Myra beds was ultimately derived from the same source area as that in the Tamworth Belt.

During the course of this study approximately 230 samples of various clastic rocks in the Pigna Barney-Curricabark and Morrisons Gap-Nundle areas have been examined petrographically. This investigation was almost entirely qualitative and reconnaissance in nature to determine: (i) whether any of the Tamworth Belt and Woolomin Association rocks concerned contain a significant non-volcanogenic component; (ii) whether these rocks contain detritus which might have been derived from the associated basaltic rocks* and/or from the PBOC; (iii) whether any

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* At least some detritus in the Drik-Drik and Bog Hole formations appears to have been derived from intercalated keratophyric volcanics or their lateral equivalents (Crook, 1960a; Cawood, in press).

particular rock units in the Glen Ward beds might be sufficiently distinctive in their petrography to enable them to be used as a marker horizon for stratigraphic and structural investigations; and (iv) to select for analysis those samples whose mineral and bulk chemistries might best reflect the gross magmatic affinities of their source area(s) i.e. matrix-poor samples largely consisting of comparatively fresh volcanic fragments (e.g. 401).

The investigations outlined in (i)-(iii) above produced negative results and as such simply reinforce the general petrographic observations of earlier workers (cited above). Planned investigations of the bulk chemistry and mineral chemistry of the Devonian and (?) older volcanogenic sandstones proved to be too ambitious a project in the time available. Some preliminary data are presented in Table 2.2.

For the most part, therefore, the following brief comments on pertinent aspects of the petrology of sedimentary rocks in the Pigna Barney-Curricabark, and Morrisons Gap-Nundle areas are based on qualitative observations on a fairly representative spectrum of samples (samples and thin sections stored and catalogued in Geology Department, U.N.E.). Some chemical analyses of fine-grained siliceous sedimentary rocks from the Myra beds are listed in Table 2.3. These rocks were initially analysed during attempts to apply a quantitative XRD modal analysis technique (Flinter, 1975) to assist in identifying rocks of possible ash-fall origin in the Myra beds (Mayer, 1972, p.268; *cf.* Leitch, 1981). Difficulties in calibrations for albite and other plagioclases led to it being largely abandoned. Some 'XRD modes' are listed for comparison with the chemical analyses. The XRD Qz value is believed to be accurate to within ± 2% and the low values relative to normative *qz* probably reflect the presence of significant amorphous SiO_2 in the rocks concerned. Secondary quartz ± carbonate veins are almost ubiquitous in the siliceous rocks.

2.1 Myra beds

Jasper, chert and siliceous argillite are the most conspicuous lithologies in the Myra beds. Massive and bedded siltstone are more abundant than previously recognized, even in the type section (*viz.* Curricabark River, see Fig. 1.3, *cf.* Mayer, 1972), but for the most part they are highly sheared and/or highly fractured and they crop out extremely poorly (see Chapter 1). Clastic rocks are exceedingly rare although, to some extent, these too might be occult in the sheared matrix.

Jasper and chert may be massive or well-bedded. Some bedded jaspers display extremely fine lamination (e.g. 193,194). All highly siliceous lithologies contain abundant recrystallized radiolaria and these are most easily recognized in the bedded jaspers (e.g. 194). Sheared jasper (e.g. 189) and chert (e.g. 188) are sometimes slightly phyllitic and betray the presence of a trace of argillaceous material in the pristine sediment. Many jaspers are intermittently interbedded with thin (< 1 cm) manganiferous or relatively ferruginous laminae (e.g. Fe_2O_3 ~22 wt%, Table 2.3, analysis 6). These laminae are presumably hydrothermal in origin, although the relatively high Al_2O_3 content of the sample analysed (Al_2O_3 ~6.8%) suggests some contamination by terrigenous or volcanogenic silicates (*cf.* Bonatti, 1981). In the Myra beds these Fe-Mn-rich sediments are volumetrically negligible, but nevertheless widespread. Similar lithologies are locally significant elsewhere in the Woolomin Association (e.g. Fitzpatrick, 1975) and, overall, their presence suggests that significant submarine volcanism and related hydrothermal activity may have accompanied Woolomin and Myra jasper deposition (see Chapter 3; *cf.* Bostrom, 1970; Leggett and Smith, 1980; Bonatti, 1981). Jasper and Fe-free chert may be intimately interbedded (e.g. 388), perhaps reflecting some intermittent hydrothermal activity.

In the Myra beds it would appear that every compositional gradation occurs from relatively pure chert, through impure chert to siliceous argillite and ultimately, argillite. The moderate *ab + an* contents of some of these rocks (e.g. analyses 8-10, Table 2.3) might suggest that they contain a significant tuffaceous component. However, they are typically too fine-grained and/or too recrystallized to provide any textural evidence which might reinforce this suggestion. Although many of the relatively argillaceous rocks display an incipient- and sometimes well-developed phyllitic foliation sub-parallel to bedding, they are fissile only where strong shearing is evident.

Limestone is relatively rare in the Myra beds. In the Pigna Barney-Curricabark area small blocks (tens of metres or less) of recrystallized limestone crop out between GR 664,824 and GR 672,825, and at

GR 712,863. Samples from both localities were dissolved in acetic acid and they appear to be devoid of age-diagnostic conodonts (J.W. Pickett, pers. comm.).

In addition to being negligible in overall abundance, outcrops of sand- and coarser-clastic rocks in the Myra beds are usually highly localized. Individual outcrops seldom can be traced for distances in excess of several tens of metres. They are most abundant in the vicinity of GR 652,818 and near locality 3.5 (see Fig. B-1). With one exception (195) which contains approximately 30% intraformational (originally poorly lithified)siltstone fragments, detritus in Myra sandstones is predominantly volcanogenic in origin.

Most of the Myra clastics largely consist of intermediate to silicic volcanic fragments and discrete plagioclase grains. Modal abundances of these components vary antipathetically, plagioclase being more abundant in the finer-grained sandstones where it may be accompanied by up to 20% quartz (e.g. 197). In general, however, quartz constitutes less than 5% of the mode. Pyroxene is usually rare in all but a small number of samples containing relatively abundant mafic-intermediate volcanic fragments (e.g. 241, 410). Secondary phases include chlorite, albite, quartz, pumpellyite, prehnite and carbonate. Samples 408 and 410 almost entirely consist of silicic and mafic volcanic fragments respectively. Their respective bulk chemistries (Table 2.2) reinforce these petrographic observations and illustrate broad spectrum (? basaltic-?rhyodacitic) of volcaniclastic lithologies present in the Myra beds (*cf.* Rose, 1978; analysis 9, Table 2; Cawood, in press).

Detrital pyroxenes in two Myra volcanogenic coarse-grained sandstones (241, 242) are mainly augites and relatively Ca-rich augites (see Fig. 3.1; Table E-8). These pyroxenes display considerable variation in their minor element chemistries (TiO_2 = 0.3%-1.9%; Al_2O_3 = 0.8%-5.2%; Na_2O up to 0.63% and MnO up to 0.7%; Table E-8) and in their overall TiO_2:MnO:Na_2O ratios (Fig. 2.1). With the possible exception of several relatively Al-rich variants (Table E-8), the general chemical characteristics of these pyroxenes (e.g. Fig. 2.2) suggests that they were largely derived from subalkaline hosts. Cawood (in press) suggests that the relatively more Ti-rich pyroxenes (TiO_2 ~0.9%) in Woolomin volcanogenic sandstones may have been derived from Woolomin basaltic rocks. Although volcanic fragments similar in texture to the Myra basaltic rocks have not been found in Myra epiclastics, pyroxenes similar to those in the basaltic rocks do occur in some of these sediments (compare Tables E-6 and E-8).

In summary: on present exposures, sedimentary rocks in the Myra beds are almost entirely hemipelagic in origin. Some of the siliceous argillites may contain a significant silicic ash-fall component, but proximal volcaniclastics and volcanically-derived epiclastics are relatively rare. However, intermediate volcanic breccias are locally abundant in the vicinity of locality 3.5 (Fig. B-1) and these are described briefly in Chapter 3. Compared with the Woolomin beds, the relative abundance of hemipelagic sedimentary rocks and the rarity of clastic variants in the Myra beds suggests that the latter largely accumulated in an oceanic environment somewhat more remote from terrigenous influences.

2.2 Tamworth Belt

Glen Ward beds and Tamworth Group

The principal Glen Ward and Tamworth Group lithologies in the areas studied are siliceous argillite, argillite, limestone, and volcanogenic sandstones and conglomerates. Coarse-grained clastic rocks predominate in the Pigna Barney-Curricabark area but these are subordinate to laminated argillites and siliceous argillites in the Morrisons Gap area. In both areas the argillites are intermittently interbedded with thin plagioclase-rich laminae which may contain up to ~20% quartz. On rare occasions these laminae are exceedingly quartz-rich (e.g. 197, ~70% quartz, 15% plagioclase, 15% matrix + opaque oxides). Thinly-bedded lithic sandstones are relatively uncommon. Where present, they usually display well-developed turbidite characteristics such as graded bedding, internal parallel- and convolute lamination and, on occasion, diffuse low-angle cross-bedding (Plate 2.1A,B).

The majority of clastic rocks in the Glen Ward beds are massive, coarse-grained, poorly-sorted, and are usually relatively impoverished in silty or finer-grained matrix components (Table 2.1, Plate 2.1C). In fact, most have relatively closed frameworks of angular to sub-rounded

TABLE 2.1

Modal Analyses of Sandstones from the Glen Ward beds

SAMPLE	Lv	Pl	Py	Qz	Op	O+	Mx	No.	Q	F	Lv
401	80.5	10.2	6.8	0.5	-	0.2	1.8	2246	0.5	11.2	88.3
402	76.5	17.4	0.7	0.4	1.3	-	3.7	1291	0.4	18.5	81.1
411	74.2	15.9	1.1	0.3	-	0.1	8.4	1331	0.3	17.6	82.1
418	73.7	23.0	1.6	0.3	-	-	1.4	1596	0.3	23.7	76.0
415	71.6	22.1	3.2	1.2	-	-	1.9	1396	1.3	23.3	75.4
371	61.9	9.6	0.3	0.3	0.3	4.5	23.1	1512	0.4	13.4	86.2
416	61.4	13.7	-	12.4	0.2	-	12.3	1308	14.1	15.7	70.2
417	61.2	29.4	7.1	-	-	-	2.3	1304	-	32.4	67.6
405	60.6	26.1	4.8	5.3	0.1	1.7	1.4	1364	5.7	28.4	65.9
372	56.0	17.1	-	12.9	0.4	0.3	13.3	2519	15.0	19.9	65.1
370	55.9	18.4	3.8	0.2	0.9	0.5	20.3	2358	0.3	24.7	75.0

Lv = volcanic fragments (predominantly intermediate-silicic)
Pl = discrete detrital plagioclase grains
Py = discrete detrital clinopyroxene grains
Qz = discrete detrital quartz grains
Op = discrete detrital Fe-Ti oxide grains
O+ = other framework components; includes argillite (405) and limestone
Mx = silty and finer-grained matrix, cement
No. = number of points counted

clasts which typically fall within the range 1mm-5mm in size. Larger volcanic fragments are commonly dispersed throughout most of these relatively thick (metres to tens of metres) sedimentation units (Plate 2.1C). Many contain angular pebbles, small blocks and large slabs (up to several metres in length) of intraformational laminated argillite (Plate 2.1D,E) and, on occasion, metre-sized boulders of limestone (Plate 2.1F,G). The argillite fragments usually display some plastic deformation, especially on mesoscopic and microscopic scales. Limestone pebbles (typically 1cm-5cm in size) are present in trace amounts in a large number of the coarser-grained Glen Ward and Tamworth Group epiclastics in the areas studied. Relatively coarse-grained (<5 cm) intermediate-silicic volcanic breccias (e.g. 185, 404) are locally abundant. Volcanic fragments in these rocks are often conspicuously plagioclase- and clinopyroxene—phyric, and are commonly amygdaloidal. Basaltic volcaniclastics are only of localized significance in the Glen Ward beds and are rare in the Morrisons Gap area (see Chapter 3).

Modal analyses of a range of fairly typical coarse-grained Glen Ward sandstones and some relatively uncommon quartz-rich variants (372, 416) are listed in Table 2.1. Apart from the relatively minor but locally abundant argillite and limestone components mentioned above, almost all of the detritus in these sandstones and coarser-grained rocks is of volcanic derivation. Volcanic fragments display a considerable diversity of textures including; vitric, vitrophyric hyalopilitic, microlitic, pilotaxitic and rare intergranular types. Fragments consisting almost entirely of medium- to fine-grained felted plagioclase are relatively abundant. Clinopyroxene may occur as discrete framework component (e.g. 401, Table 2.1) and as phenocrysts in pilotaxitic clasts (e.g. 400). Clasts with intergranular textures are relatively rare (e.g. 199). Plagioclase is the dominant phenocryst type in practically all porphyritic clasts where it may be accompanied by quartz or clinopyroxene phenocrysts. All of the Glen Ward and Tamworth Group epiclastics examined are apparently devoid of Ca-poor pyroxene and primary amphiboles and micas. K-feldspar is exceedingly rare and appears to occur only as a devitrification product of some silicic fragments. Secondary phases include: chlorite, albite, carbonate, quartz, prehnite, pumpellyite and epidote. Pumpellyite is generally rare or present only in trace amounts in most of the Glen

PLATE 2.1

A. Well-developed parallel lamination and graded bedding in Glen Ward volcanogenic turbidites. A layer of poorly-defined low-angle cross-bedding overlies the graded layer. The former lies between 10mm - 16 mm below the top of the photograph, and its curved base is sharply-defined [GR5871,8213].

B. Parallel and convolute lamination in a Glen Ward fine-grained volcanogenic sandstone sequence. These are closely associated with coarser-grained turbidites and massive (? mass flow) sandstone [GR5900,8206].

C. Massive, coarse-grained, poorly-sorted Glen Ward volcanogenic epiclastic unit. Note sub-rounded intermediate volcanic cobbles dispersed in the coarse-grained lithic matrix [GR7263,8056].

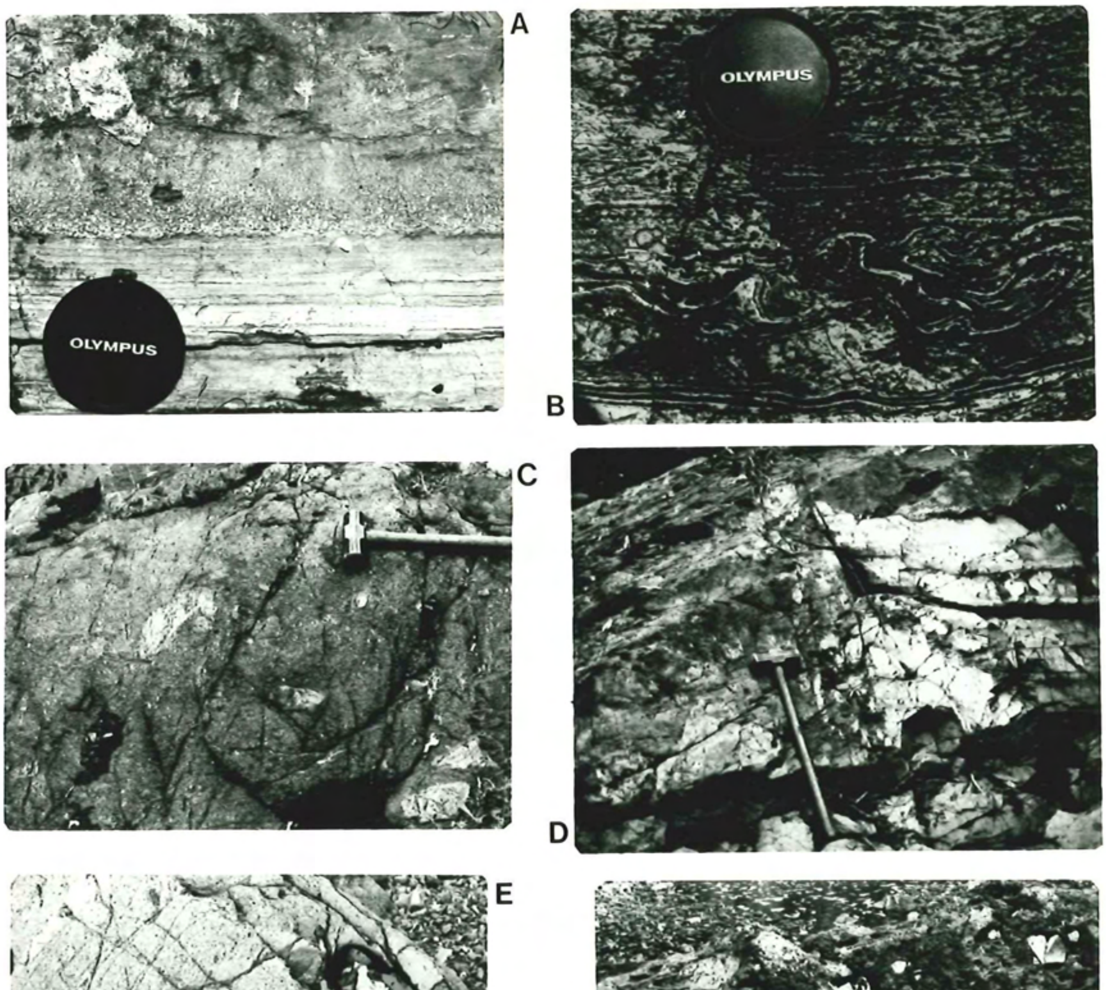
D. Part of a relatively large angular slab of intraformational siliceous argillite (light coloured) included in a Glen Ward massive coarse-grained volcanogenic epiclastic unit [GR6199,8063].

E. Part of a massive Glen Ward volcanogenic epiclastic unit containing a plastically deformed block of intraformational laminated argillite (below hammer) [GR5860,8412].

F,G. Sub-rounded limestone boulders in a poorly-sorted Glen Ward (? see p. 25 and p. 34) volcanogenic cobble conglomerate [GR5954, 9395].

H. Rounded and sub-angular silicic volcanic pebbles in a massive Manning Group diamictite. In this example the matrix is coarse-grained lithofeldspathic sandstone. Similar dispersed-pebble fabrics are also typical of massive siltstones in the Manning Group [GR8238,9294; ∿ 2 km east of locality 3.5, *cf.* Figs B-1 and 1.1].

PLATE 2·1



Ward epiclastics although it is relatively conspicuous towards the (?) upper parts of the section to the south and southeast of the Pitch Creek Volcanics (e.g. 184, 185, 403).

In the areas studied, the Tamworth Belt epiclastics do not display clear-cut systematic petrographic variations related to their apparent stratigraphic position. Texturally diverse volcanic detritus may be intercalated or even mixed within individual sedimentation units (e.g. 198, 199). On the basis of general petrographic characteristics the source area for these rocks appears to have been largely andesitic to rhyodacitic in composition with an almost negligible (?) basaltic component. Relict plagioclases are usually oligoclase-andesine (optical determinations) and, on occasion, labradorite (Table E-4). Framework pyroxenes are typically normally-zoned, Ti-poor (<0.6% TiO_2) augites (Table E-4, Fig. 3.1) whose overall chemistry including: (i) $SiO_2:Al_2O_3$ relations (*cf.* Fig. 3.6); (ii) Ti, Al, Ca, Na and Mn abundances (*cf.* Figs 3.7-3.9, see Fig. 2.1); and (iii) chemical discriminant characteristics (Fig. 2.2), suggest that they were largely derived from subalkaline (? tholeiitic) hosts. On average, detrital augites in the Glen Ward epiclastics (Table E-4) contain less TiO_2 than augites in the associated basaltic extrusives (Table E-2) and intrusives (Table E-3). However, there is considerable overlap in the overall ranges of pyroxene compositions displayed by these rocks. Although these data do not preclude the possibility that some of the detrital pyroxenes might have been derived from basaltic rocks similar- or related to those which are intercalated with the Glen Ward epiclastics, the rarity of clasts with basaltic textures in the latter renders this possibility unlikely.

Whole rock analyses of two Glen Ward coarse-grained, matrix-poor sandstones containing abundant pyroxene-phyric clasts (analyses 2 and 3, Table 2.2) suggest that the general source area included at least some relatively mafic andesitic volcanics. In the absence of a large and detailed data-base, it is probably unwise to assign specific magmatic affinities to volcanogenic sedimentary rocks, even those which appear to contain minimal 'foreign' components. However, it may be commented that abundances of the relatively "immobile" minor and trace elements (e.g. Ti, Zr, P, Y; see Chapter 3) in samples 400 and 401 (Table 2.2) are not inconsistent with a dominantly subalkaline source area. Sample

399 displays some anomalous chemical characteristics (e.g. unusually high P_2O_5/Nb and TiO_2/Y ratios) and the extent to which its present chemistry might resemble that of its ultimate volcanic 'parents' is conjectural.

For the most part, limestones in the Glen Ward beds are largely recrystallized, especially those in the general vicinity of Limestone Creek (Map 1). These limestones are relatively isolated massive blocks in coarse-grained volcanogenic epiclastics which contain relatively abundant limestone pebbles and cobbles. This suggests that the larger blocks also might be allochthonous. On the other hand, at least some of the limestones forming a discontinuous horizon along the southern and eastern margins of the Pitch Creek Volcanics (Map 1), i.e. the Bennys Creek Limestone Member (Mayer, 1972), include bedded clastic variants and may possess marginal interbedded calcarenite-clayey calcilutite facies (e.g. GR 723,808). It is perhaps more likely that these limestones are *in situ* although it is possible that Emsian and slightly older limestones are mixed in this horizon (Mayer, 1972, p.48).

In summary: The Glen Ward beds contain voluminous coarse-grained, almost exclusively volcanogenic epiclastics. These appear to have been deposited in a proximal environment under conditions sufficiently turbulent to incorporate large blocks of the intercalated argillite. Comparatively thin-bedded, finer-grained, lithofeldspathic sedimentation units commonly display relatively proximal turbidite characteristics (e.g. pronounced graded bedding). As a general rule, Tamworth Group clastic rocks in the Morrisons Gap area display a more distal aspect than those in the Glen Ward beds.

2.3 Nambucca Association

The elongate fault block of Nambucca Association in the Morrisons Gap area (see Map 2) largely consists of friable, weathered lithofeldspathic sandstone and siltstone. It contains a poorly-preserved Early Permian fauna which includes *Trigonotreta stokesei*, Koenig 1825. Related Early Permian fault blocks (Barnard beds of Heugh, 1971) largely consisting of conglomerates, pebbly sandstones and siltstones are relatively common in the Tamworth Group and Woolomin beds to the east of the Morrisons Gap area.

Manning Group lithologies in the Pigna Barney-Curricabark area include black, thinly-bedded and massive pebbly siltstones, friable brown-olive pebbly siltstones, massive pebbly sandstones (Plate 2.1H), poorly-sorted conglomerates, well-bedded impure bioclastic limestones and, locally, silicic volcanics. The sandstones and coarser-grained lithologies largely consist of silicic volcanic fragments with comparatively minor, but locally abundant, radiolarian chert and argillite, quartzo-feldspathic sandstone and intermediate- (?) mafic volcanic fragments. Silicic volcanic pebbles and detrital quartz may be locally abundant in the limestones. In general, lithic fragments in all lithologies are well-rounded and are usually very poorly sorted. However, angular silicic volcanic breccias do occur in close association with apparently equivalent silicic volcanics in the vicinity of GR 575,940.

The lithologies listed above largely belong to the Glory Vale Conglomerate and Colraine Mudstone of Mayer (1972). Elsewhere these two units are underlain by a thick (?5-?7km, Mayer, 1972) sequence of sedimentary breccias (Wards Creek beds), turbidites and diamictites (Giro Diamictite), and are overlain by mudstones, sandstones, tuffs and andesitic volcanics of the Kywong beds (~1.6km thick). Mayer (1972) considers the Manning Group as a whole to be a regressive sequence of marine debris flows and turbidites initially deposited in deep marine grabens between uplifted Myra lithologies. Up-section, there is a progressive decrease in detritus derived from the Myra beds and an increase in silicic volcanic detritus as the environment deposition shallowed. Mayer's (1972) suggestion that the Manning Group might have been deposited in grabens formed during subduction-related accretion and uplift of the Myra beds warrants further evaluation in the light of more recent concepts related to the evolution of trench-slope basins (e.g. Moore and Karig, 1976) and basins related to strike-slip faulting (see Chapter 1, Section 1.4). Perhaps one or other of these mechanisms might be applicable to various parts of the Nambucca Association.

TABLE 2.2

Major and Trace Element Analyses of Sediments from the Glen Ward beds and Myra beds

ANALYSIS No.	1	2	3	4	5	6		8	9
SAMPLE	399	400	401	409	LKBA	LKAA	410	408	Wb
SiO_2	59.93	52.98	54.83	85.48	55.8	60.1	51.53	70.77	62.7
TiO_2	1.19	0.58	0.59	0.01	0.82	0.75	1.92	0.69	1.21
Al_2O_3	16.19	15.21	15.40	0.21	17.7	16.8	14.94	14.67	15.1
V_2O_3	0.03	0.05	0.05	-	n.d.	n.d.	0.04	0.01	n.d.
Fe_2O_3	1.97	4.37	1.49	12.95	3.4	3.2	7.74	2.61	8.5
FeO	3.12	5.93	8.67	0.23	6.2	4.8	7.92	2.57	n.d.
MnO	0.08	0.20	0.18	0.02	0.21	0.15	0.08	0.15	0.14
MgO	3.22	7.54	7.30	0.11	4.3	3.1	3.35	2.08	3.4
CaO	5.09	7.01	5.07	0.14	9.2	7.1	11.71	1.08	4.5
Na_2O	3.41	5.43	5.00	0.10	2.7	3.2	0.16	2.20	3.4
K_2O	3.43	0.32	0.88	0.65	0.43	0.59	0.04	2.64	1.6
P_2O_5	0.60	0.14	0.13	0.05	0.16	0.15	0.09	0.10	0.22
TOTAL	98.26	99.76	99.62	99.85	100.9	99.9	99.52	99.57	100.8
ΣVol.[1]	1.50	4.66	3.77	0.50	0.8	0.8	4.07	2.69	3.2
ΣFeO/MgO	1.52	1.31	1.97	-	2.1	2.4	4.44	2.36	2.25
TRACE ELEMENTS (μg/g)									
Rb	44	<2	9	<2	n.d.	n.d.	<2	90	n.d.
Ba	1776	111	316	<5			<5	424	
Sr	1860	723	260	7			375	164	
Li	4.5	10.4	10.3	1.1			5.7	25	
Zr	131	49	38	2			111	173	
Nb	<3	4	5	<3			14	14	
Y	4	16	15	2			28	47	
Cu	69	58	133	3			67	34	
Zn	66	87	99	10			104	80	
Ni	22	26	37	6			39	20	
Co	<52	66	66	32			49	44	
V	207	312	349	10			280	94	
Cr	60	128	181	n.d.			48	36	
La	n.d.	9	5	n.d.			15	n.d.	
Ce	n.d.	n.d.	n.d.	n.d.			20	n.d.	
Nd	n.d.	n.d.	n.d.	n.d.			14	n.d.	

[1] See Appendix G

n.d. = not determined.

Analyses 1,2,3: Glen Ward epiclastics

Analysis 4 : Glen Ward siliceous inter-pillow umber

Analysis 5 : Average Low-K orogenic basic andesite (Gill,1981)

Analysis 6 : " " " acid " (")

Analyses 7,8 : Myra volcanogenic epiclastics

Analysis 9 : Average 8 Woolomin 'feldspathic litharenites' (Rose, 1978).

TABLE 2.3

Major Element Analyses, XRD Modes† and Partial CIPW Norms of Siliceous Sedimentary Rocks from the Myra Beds

ANALYSIS No.	1	2	3	4	5	6	7	8	9	10
SAMPLE	389	390	391	392	393	394	395	396	397	398
SiO_2	98.25	97.87	93.72	93.63	60.86	97.94	97.65	87.58	83.80	75.35
TiO_2	0.03	0.04	0.02	0.05	0.41	0.05	0.04	0.21	0.08	0.44
Al_2O_3	0.78	0.88	0.95	1.90	6.84	1.31	1.48	4.65	7.05	9.29
ΣFe_2O_3	0.46	0.78	2.37	2.62	21.77	0.35	0.62	2.99	0.64	4.84
MnO	0.22	0.20	0.44	0.41	1.38	0.03	0.16	0.07	0.05	0.09
MgO	0.00	0.00	0.00	0.01	0.80	0.00	0.00	0.66	0.01	1.36
CaO	0.36	0.07	0.17	0.40	1.37	0.04	0.10	0.36	1.91	0.87
Na_2O	0.14	0.02	0.09	0.10	0.69	0.05	0.03	1.64	2.99	1.99
K_2O	0.17	0.18	0.22	0.46	1.83	0.29	0.31	0.48	0.22	1.83
P_2O_5	0.04	0.03	0.02	0.06	0.42	0.01	0.05	0.01	0.03	0.03
C	-	tr.	-	-	-	tr.	tr.	-	-	-
LOI	0.48	0.04	1.37	1.00	3.96	0.49	0.36	1.39	3.31	3.19
TOTAL	100.93	100.44	100.38	100.65	100.34	100.56	100.79	100.03	100.08	99.29
C.I.P.W.*										
qz	96	97	92	90	47	97	96	75	62	53
ab+an	2.2	0.3	1.5	2.5	9.9	0.5	0.4	15.6	30.5	20.9
c	-	0.6	0.3	0.7	2.2	0.9	1.0	0.8	-	2.5
XRD MODE†										
Qz	89	93	88	61	33	90	87	76	59	56
PLAG.	-	-	-	-	-	-	tr.	2	7	2
ILL/SER.	-	-	0.5	tr.	1.2	0.8	0.5	1.4	1.0	3.2
CHL.	-	-	-	-	-	0.2	0.4	2.2	0.4	3.1
HEM.	+	+	+	+	+	-	-	-	-	-
CALC.	-	-	-	-	-	-	-	+	+	+
**An(mol.%)	-	-	-	-	-	-	-	8	6-9	10-13

* CIPW normative *qz,ab,an* and *c* calculated assuming wt % FeO = wt % TiO_2.

** Mole % anorthite in plagioclase estimated following the method of Smith (1956).

tr. = trace amount. + = significant amount present.

Analyses: 1-4 = jaspers; 5 = ferruginous material interbedded with jasper (392);
6-7 = massive and thinly bedded (respectively) grey-green chert; 8 massive grey chert;
9 = grey-green siliceous argillite interbedded with thin (?) mafic tuffaceous laminae;
10 = diffusely bedded grey argillite.

ILL/SER = illite + sericite, CHL = chlorite, HEM = hematite, CALC = calcite.

† see text.

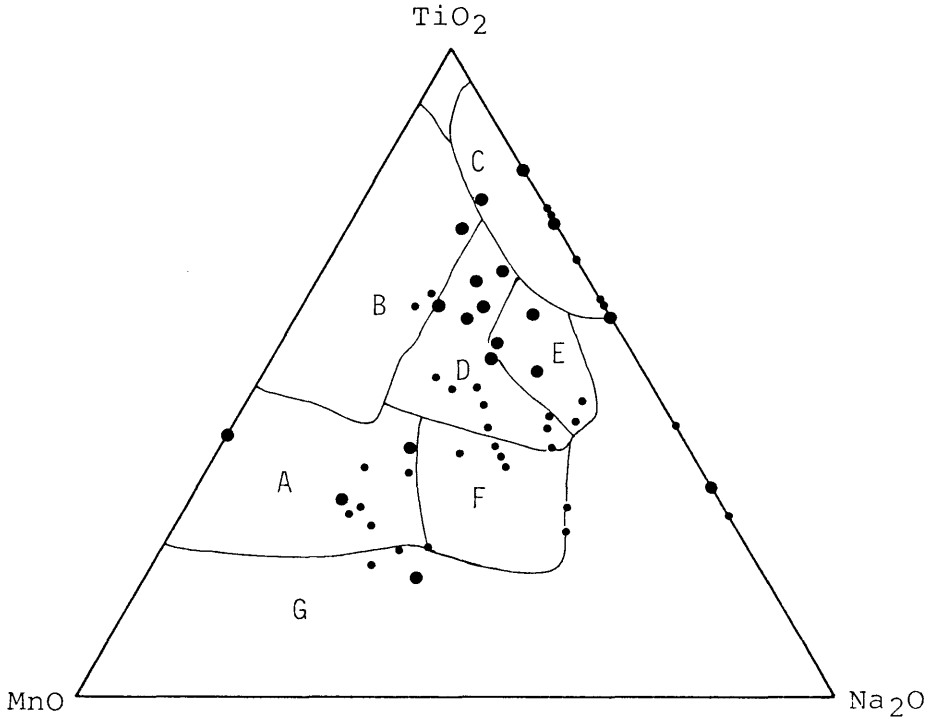


Fig.2.1: TiO_2:MnO:Na_2O relations in detrital Ca-rich pyroxenes from Myra (●) and Glen Ward (•) epiclastics. Fields as in Fig. 3.15.

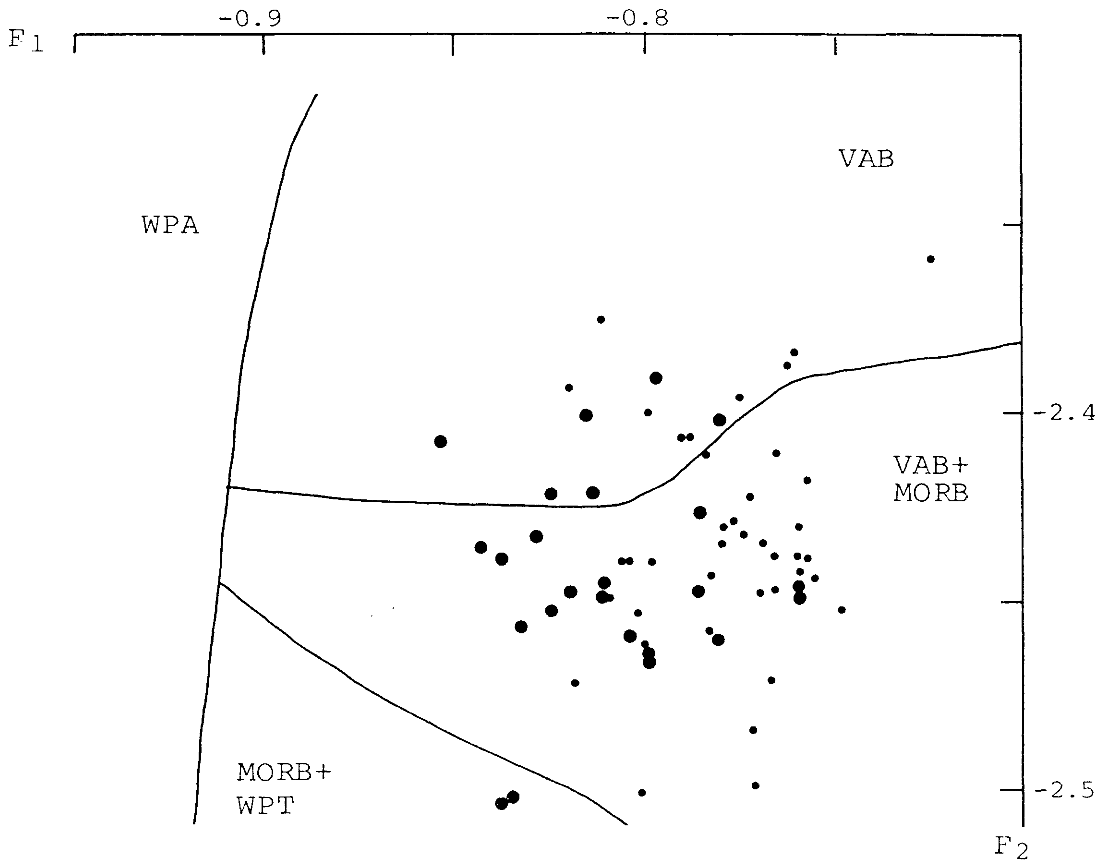


Fig. 2.2: F_1:F_2 relations in detrital Ca-rich pyroxenes from Myra (●) and Glen Ward (•) epiclastics. Fields as in Fig. 3.14.

CHAPTER 3

SOME BASALTIC ROCKS OF THE WOOLOMIN ASSOCIATION AND TAMWORTH BELT

3.1 INTRODUCTION

Basaltic rocks are widespread throughout the mid-Palaeozoic and (possibly) older rocks of the New England Orogen (Leitch, 1974,1979a; Korsch, 1977; Korsch and Harrington, 1981a). They commonly occur as (i) localized intrusive-extrusive piles interbedded with clastic and pelagic sediments of the Tamworth Group and its equivalents (Benson, 1914a,1915; Crook, 1960a; Vallance, 1969a,1974; Crook and Felton, 1975); and (ii) as localized intrusive-extrusive piles and isolated units interbedded with, or tectonically incorporated in, predominantly pelagic sediments of the Myra beds and Woolomin beds (Glen and Heugh, 1973; Fitzpatrick, 1975; Cuddy, 1978; Offler, 1978,1979; Scheibner and Pearce, 1978; Herbert, 1978,1982). Isolated thin flows and intrusives are also present in both the Tamworth Group and the Woolomin Association.

The only basaltic rocks from the Woolomin Association examined in detail during this study are those from the Myra beds in the Pigna Barney - Curricabark area (Map 1). These have been investigated previously in a reconnaissance fashion by Mayer (1972) but otherwise are poorly known. Many other basalt localities within the Woolomin Association were examined briefly for comparative purposes and, where possible, the rock thin sections of some previous workers were examined.

Basaltic intrusives and subaqueous extrusives are locally abundant in the Tamworth Group and its correlatives from Nemingha in the north, through Nundle and the Pigna Barney - Curricabark area, to the Mount George area (Fig. 0.2) in the southeast. In this study these rocks have been examined in detail in the Pigna Barney - Curricabark area (Fig. 0.1; Glen Ward beds, Map 1) and in the Morrisons Gap area (Fig. 0.2; undifferentiated Tamworth Group, Map 2). Field observations were also made in the Bowling Alley Point - Hanging Rock, Barry Station and Glenrock Station areas. Rock thin sections of some previous workers were also examined.

Mafic intrusives and extrusives have been described from the

Tamworth Group and Woolomin Association in the Nemingha - Hanging Rock area by Benson (1913,1915); Crook (1961a); Vallance (1960,1965,1969a,b, 1974) and Cawood (1980); in the Morrisons Gap - Barry Station area by Heugh (1971), Glen and Heugh (1973) and Cross (1974); in the Glenrock Station area by Bayly (1974) and Offler (1978,1979); and in the Bundook district (south of Mount George, Fig. 0.2) by Benson (1916), Sussmilch (1922) and Mayer (1972).

Basaltic rocks in the Tamworth Belt and Woolomin Association invariably show some degree of textural, mineralogical and chemical reconstitution following varying degrees of hydrothermal alteration and low-grade metamorphism. These have overprinted the effects of halmyrolysis and deformation. Most are typical spilites of the type described by Hughes, (1973), Coombs, (1974) and Battey, (1974); that is, weakly metamorphosed or hydrothermally altered basalts. Those in the Tamworth Group near Nundle were studied in some detail by Vallance (1960,1965,1969a,b, 1974) as part of an extensive review of spilitic lithologies. The ubiquitous occurrence of relict basaltic mineralogy with igneous textures precludes any consideration of the origin of these basaltic rocks from primary spilitic magmas (*cf.* Amstutz and Patwardhan, 1974; Lehmann, 1974).

The term "basaltic" *s.l.* is used here in a broad sense referring to rocks which originally were basalts, basic andesites or their coarser-grained equivalents. The terms doleritic or gabbroic are often used to loosely refer to these latter types (see below). The widespread development of secondary disequilibrium mineral assemblages and the variable and patchy responses of these rocks to low-grade metamorphism did not warrant the use of the terms metabasalt and metabasite and hence the qualifier 'basaltic' is preferred in their place.* The distinction between aphanitic, doleritic and gabbroic rocks is made here solely on the basis of average grainsize - aphanitic less than 1mm, doleritic 1-5mm, and gabbroic greater than 5mm.** The terminology of Honnorez and Kirst (1975) and

* The terms 'metabasalt' and 'metabasite' are best applied to basaltic rocks which show pervasive textural and mineralogical reconstitution more typical of higher grades of metamorphism.

** The term basaltic is used throughout this thesis to refer generally to rocks of 'basaltic' composition as defined above - regardless of grainsize.

Dimroth *et al.* (1978) is followed for the description of fragmental basaltic deposits.

In the past, basaltic rocks in the Myra beds and Glen Ward beds have received little attention. The principal objectives of this investigation are:-

(i) To describe the range of basaltic types in the Myra beds and Glen Ward beds from textural, mineralogical and chemical viewpoints.

(ii) To examine the field relations and petrography of these rocks in an attempt to elucidate the mechanism and environment of their emplacement. Textures typical of each petrographic type are described in detail and qualitatively compared with those described in experimental studies (e.g. Lofgren, 1971,1974,1975; Gibb, 1974; Donaldson, 1976,1979; Cameron and French, 1977; Augustithis and Kostakis, 1980; French and Cameron, 1981; Corrigan, 1982; Schiffman and Lofgren, 1982) and natural basaltic associations (e.g. Wilkinson, 1967; Bryan, 1972; Furnes, 1973; Frey *et al.*, 1974a; Liou, 1974; Gelinas and Brooks, 1974; Baragar *et al.*, 1977; Swanson and Schiffman, 1979; Schiffman and Lofgren, 1982) in an attempt to characterize these rocks in terms of cooling rate and order of crystallization. The implications of these data for the mode of emplacement of the various basaltic types are evaluated.

(iii) To obtain mineralogical and chemical data which might define intrinsic magmatic affinities.

(iv) To compare and contrast these basaltic rocks with those described from elsewhere in the Woolomin Association and Tamworth Belt, and those in the PBOC. Most of the latter comparisons are made in Chapter 5.

Clinopyroxene chemistry, whole rock trace element abundances and, to a lesser extent, whole rock major element chemistry are the main parameters applied to evaluate the original magmatic affinities of these basaltic rocks. Studies of this type are subject to some important constraints, and many of these constraints are discussed in some detail in the relevant sections.

Little attention has been paid to secondary alteration products in these rocks, except where these might be relevant to the interpretation of intrinsic magmatic affinities.

This chapter is divided into six Sections. Sections 3.2 to 3.5 describe the field relations, petrography, relict mineral chemistry, and whole rock chemistry respectively of basaltic rocks from the Myra beds and Tamworth Belt. Section 3.6 presents an overall synthesis of the preceding sections and some conclusions.

Sample numbers referred to are:-

040-059 : Tamworth Group (undifferentiated), Morrisons Gap area.

060-130 : Glen Ward beds

200-250 : Myra beds

Representative analyses of clinopyroxenes and some other phases from Myra and Tamworth basaltic rocks are listed in Appendix E. Appendix E also includes comments on the selection of grains suitable for analysis and the procedure used to determine representative analyses of the clinopyroxenes which are believed to most closely approximate equilibrium compositions.

Some important localities of basaltic rocks in the Pigna Barney - Curricabark area are marked on Figure B-1 (localities 3.1-3.5).

3.2 FIELD RELATIONS

3.2.1 Myra beds

Prior to this study few data were available on the basaltic rocks in the Myra beds. In particular, the fact that they occur in a tectonic melange was not previously recognized.

The Myra beds form a terrane of broken formations and autoclastic melange (see Chapter 1, Section 1.1). However, as this melange may contain exotic components* it is conceivable that some of the basaltic rocks in the Myra beds, and elsewhere in the Woolomin Association, in fact might be exotic to the environment of deposition of the associated sedimentary rocks, and unrelated to other Woolomin Association basaltic rocks outcropping nearby. Consequently the varied microscopic and macroscopic characteristics and the field relations of these basaltic rocks are described in detail below. The implications of these as they relate to interpretations of the original environments of extrusion (or intrusion) are summarized and discussed in Section 3.6.1.

With the exception of several areas mapped as predominantly intrusive dolerite or intrusive-extrusive complexes (Map 1; localities 3.1-3.5, Fig. B-1) basaltic rocks in the Myra beds typically occur as small isolated outcrops with dimensions of up to tens of metres. They crop out poorly away from watercourses. Few units are traceable for more than 50m along strike, and many of these lens out abruptly.

Contacts of thin sills and dykes with enclosing jaspers or siliceous argillites can be seen at several localities in Mernot Creek (e.g. GR 7250,9330 and GR 7415,9415, Map 1) but in the great majority of cases contact relationships are not exposed. This is primarily a consequence of the shearing which prevails throughout much of the Myra beds, especially at contacts between rock types contrasting significantly in ductility (see Chapter 1).

All basaltic outcrops show some degree of cataclasis, with evidence of strain usually increasing towards the margins. Outcrops are almost invariably riddled with carbonate- and epidote-rich veins and chloritic microshears. Many are pervasively sheared (Plate 1.2G) and these tend to be highly weathered and outcrop extremely poorly. Consequently, in most instances contact relationships between basaltic rocks and the surrounding sediments are equivocal. Apart from a few small basaltic dykes all outcrops are broadly conformable, but it is difficult to establish whether this is a stratigraphic feature or simply a product of the style of deformation (i.e. most shearing is sub-parallel to bedding so phacoids and blocks tend to be elongate in that direction).

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* Many, possibly all, of the limestones in the Woolomin Association are most probably exotic blocks - see Chapter 1.

(1) Basaltic Extrusives

Most outcrops are massive but pillowed lavas and autobreccias are common in the two units near Bennys Top (localities 3.3,3.4, Fig. B-1), at the junction of Mernot Creek and the Curricabark River (locality 3.5, Fig. B-1) and at least five localities along Mernot Creek, east of Mooney Ground. Massive outcrops predominate in these areas but often contain scattered small vesicles, amygdales and disseminated sulphides - features generally absent from massive outcrops not closely associated with pillows or autobreccias. If the pillows and autobreccias delineate the upper portions of flows, as is usually the case in the Tamworth Belt and many other ancient and modern localities (Carlisle, 1963; Ballard and Moore, 1977; Dimroth *et al.*, 1978; Hargreaves and Ayres, 1979; Wells *et al.*, 1979)*, some of the flow units face WSW in opposition to the predominantly ENE facing of the rest of the sequence.

Conflicting facing directions based on pillow morphology from within closely associated flow units in Mernot Creek might be the result of initial dips radially arranged around small extrusive centres such as those photographed from the Galapagos Rift (Ballard *et al.*, 1981,1982), young seamounts (Lonsdale and Batiza, 1980), or where massive lava passes radially into pillowed lava (Moore *et al.*, 1971; Ballard and Moore, 1977; Dimroth *et al.*, 1978). Nevertheless, the possibility of local tectonic overturning cannot be rejected (see Chapter 1). Pillows resting directly on a massive basaltic unit at locality 3.5 (Plate 3.1A) face SW. These appear to have a much steeper dip than the nearby sediments and may constitute part of an overturned block.

Aphyric pillows occurring at localities 3.3,3.4 and 3.5 are commonly vesicular, and sometimes highly so. At locality 3.3 vesicles and amygdales in some fine-grained pillows have flattened ellipsoidal disc shapes forming a lineation sub-parallel to the pillow margins (sample 238, Plate 3.4D). These vesicles reach 4 cm in longest dimension, the larger ones tending to be shaped more like tapered cylinders. In other pillows at this locality the long axes of elongate vesicles are arranged radially away from the pillow core (Plate 3.4C). There is a tendency for vesicle

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* Exceptions do occur (e.g. Snyder and Fraser, 1963a; Glassley, 1974; Hargreaves and Ayres, 1979).

size to increase towards the pillow core in those pillows with concentrically aligned vesicles, and towards the rim in those with radially aligned vesicles (Plate 3.4C,D). Large drainaway cavities and hollows (Ballard and Moore, 1977; Wells *et al.*, 1979) were not observed. The outcrop form suggests that these pillows represent a nest of lava tubes with abundant subsidiary budding (*cf.* Moore, 1975).

Duffield (1969) described tabular phenocrysts aligned parallel to the margins of elongate pillows in California. He ascribed this to laminar flow through cylindrical conduits. Similar alignment of stretched vesicles (and pilotaxitic groundmass) in the Myra pillows may result from the same mechanism, those pillows having radially aligned vesicles being formed by budding from the main lava tubes. Breccia or interpillow material was not observed at this outcrop but exposed vesicles at the pillow margins suggests that some spalling of the outer chilled selvages took place.

Pillows at locality 3.5, by contrast, are coarsely plagioclase phyric, commonly have sub-circular cross sections ranging in diameter from 10 cm to 1m, and contain variable abundances of highly spherical and radiating pipe-like vesicles (Plate 3.1B,C,D). The spherical vesicles are generally 1-3mm in diameter, tend to cluster around the pillow margins (Plate 3.1A) and in some cases form up to three concentric zones subparallel to the upper pillow margins (Plate 3.1C). Similar concentric zones of vesicles have been described from sub-glacial pillows (Jones, 1969; Wells *et al.*, 1978) where they are most intensely developed at relatively shallow water depths (less than 450m). Moore and Schilling (1973) also found concentric zones of vesicles occurring in conjunction with radial pipe vesicles in Reykjanes Ridge pillows erupted at depths less than 700m. However, concentric zones of vesicles have been described from mid-ocean ridge basalt (MORB) pillows from depths in excess of 2 km (Bideau *et al.*, 1977), but the vesicle size (less than 0.1 to 1.7mm) is much smaller than those in the Myra pillows at this locality (0.5-3mm). The implications of vesicle size for the depth of eruption of Myra basaltic rocks is discussed in Section 3.6.1.

Many of the Myra pillows also show concentric colour banding from a dark green outer selvage (usually highly epidotized) up to 1 cm thick, to a paler grey-green inner selvage of similar thickness, followed by a dark green-black zone 2-4 cm thick which passes through a colloform-textured zone to a lighter green interior (Plate 3.4A). The petrography of these zones is discussed in Section 3.3.1.

Small amounts of pillow breccia containing highly vesicular fragments are associated with these Myra pillows (Plate 3.1E) and those at locality 3.4, but in general the amount of interpillow material is low or negligible. This may be milky-green to cream highly siliceous material or, on occasion, post-eruptive maroon to purple fine-grained carbonate (see Part (3), this section). Interpillow limestone clasts (see Garrison, 1972 for a discussion of inter- and intrapillow limestones) were not observed in the Myra beds.

(2) Pyroclastic Rocks

Highly vesicular pillow lavas, commonly associated with pillow breccias, hyaloclastite breccias and possible hyalotuff (after the nomenclature of Honnorez and Kirst, 1975) units have been described from numerous localities in the Woolomin beds (Fitzpatrick, 1975; Cuddy, 1978). In comparison with those areas, very little hyalotuff or proximal volcanic breccia has been recognized in the Myra beds. Only at locality 3.5 are these features well developed, albeit on a small scale.

Small (several sq.m.) patches of pillow breccia (Plate 3.1E) and several localized outcrops of sheared mafic (?) pyroclastic material occur within the intrusive-extrusive complex at locality 3.5. Also, intermittent outcrops (several sq.m. to several tens of sq.m.) of mildly to highly sheared mafic-intermediate (?) pyroclastics (e.g. 248) occur among sheared siliceous argillites for several hundred metres structurally above and beneath this basaltic complex. Some of this pyroclastic material is relatively fine-grained and well-bedded but much is coarse, poorly-sorted volcanic breccia. The latter may contain abundant angular, highly-vesicular fragments (406, Plate 3.1F), but much of it is relatively free of vesicular material.

Judging by the high degree of strain displayed by the more competent rocks in the Myra beds, mafic pyroclastics are likely to be highly sheared, deeply weathered and may in fact be more extensive than is suggested by the relatively few outcrops observed. While it is possible that the intrusive-extrusive complex at locality 3.5 is a remnant of a disrupted subsea volcanic edifice which was mantled by pyroclastic deposits, at least some of the pyroclastics are chemically unrelated to the nearby basaltic pile (see Section 3.5.3). More convincing evidence for the occurrence of such features in the Woolomin Association is provided by Cuddy's (1978) descriptions of extensive volcaniclastic units in the Wollomin beds.

Cuddy (1978) described relatively shallow water (but below wave-base) deposits of hyalotuff and highly scoriaceous and pumiceous basaltic material from the Woolomin beds near Woodsreef. In the Myra beds basaltic (?) tuffaceous material also occurs as rare, several millimetre thick, horizons in laminated chert-siliceous argillite sequences near locality 3.5 (Plate 2.1, sample 412). As already noted, several outcrops of coarse scoriaceous breccia occur near this locality.

Hyalotuff and scoriaceous deposits are generally considered typical of basaltic eruptions at shallow water depths (McBirney, 1963; Bonatti, 1967; Tazieff, 1972; Walker and Croasdale, 1972; Honnorez and Kirst, 1975; Pickerill *et al.*, 1981). However, at all localities in the Woolomin Association these shallow-water tuffaceous volcanics are closely associated with presumed deep-water sediments (see Chapter 2). In many cases this may be the result of tectonic mixing, but evidence exists for at least semi-contemporaneous volcanism and sedimentation at some localities.

(3) Volcano-Sedimentary Relations

The very thin hyalotuff horizons interbedded with the cherts and siliceous argillites, and the nearby vesicular coarse volcanic breccias, suggest that volcanism at locality 3.5 may have been coeval with sedimentation. Other evidence includes the occurrence of jasper fragments (at various stages of lithification) incorporated in basaltic flows at a number of localities in Mernot Creek between locality 3.5 and Mooney Ground (e.g. GR 7750,9405; GR 7445,9410; and at several localities between GR 7305,9365 and GR 7210,9340). These pillowed and massive flows* contain weakly recrystallized blocky fragments of jasper ranging in size

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* Massive basaltic flows are more common on the sea floor than previously thought, especially near fast-spreading ridges (Normark, 1976; Bryan *et al.*, 1977; Crane, 1978; Fisher and Dimroth 1978; Ballard *et al.*, 1979,1981,1982; Wells *et al.*, 1979).

from several millimetres to several metres. They are most abundant in zones of flow breccia, but are not uncommon as xenoliths. The latter often have thin maroon or purple slightly recrystallized outer margins; whereas jasper fragments in the flow breccias appear to be unaltered. These features suggest that the jasper fragments were incorporated during extrusion and their textural reconstitution was minimized by rapid chilling of the host magma. However, at several localities (e.g. GR 7305, 9365 and GR 7190,9335) tectonic mixing of jasper and basaltic rocks is evident (see Chapter 1).

Basaltic extrusives containing jasper fragments have been reported from elsewhere in the Woolomin Association by Fitzpatrick (1975) and Cuddy (1978). Cuddy (1978) describes both jasper and argillite fragments included in basaltic volcanics and volcaniclastics. Many of these rocks are highly sheared but at least some sedimentary fragments appear to have been incorporated by flows during extrusion (observations of the author while accompanying Cuddy in the field). Fitzpatrick (1975) records jasper fragments in Woolomin basaltic rocks resulting from both tectonic mixing and incorporation during extrusion.

Jasperoidal inclusions in massive and partly-pillowed basaltic flows at some localities in the Myra beds (e.g. GR 7210,9340) and Woolomin beds (Fitzpatrick, 1975) have a wispy or highly attenuated form and larger blocks appear to have been plastically deformed. It is likely that these jasperoidal rocks were only poorly lithified prior to incorporation in the volcanics.

Some massive basaltic units exposed in Mernot Creek (e.g. GR 7210, 9340) also contain jasper xenoliths and these may have incorporated appreciable amounts of the ferruginous material which is often interbedded with jasper in the Myra beds (see Chapters 1 and 2). These outcrops show considerable iron staining, which in some cases is related to carbonate veining. Elsewhere the iron staining is delineated by liesegang bands (202, Plate 3.1G,H or mottled patches). The iron staining is likely to be largely hydrothermal in origin, but may also involve the mobilization of some Fe and other elements derived from ferruginous sedimentary xenoliths and the metasomatic dispersal of these throughout the cooling basaltic units (see Section 3.5.3). Hematite-filled fractures and shears also occur (206, 225), suggesting some secondary remobilization of iron.

PLATE 3.1

NOTE: Photographs A to E (inclusive) were taken in the vicinity of GR8025,9305, locality 3.5 (see Fig. B-1).

A. Myra *Type* 2 pillows overlying a massive *Type* 2 basaltic unit. Note concentric zones of small vesicles (e.g. centre, and upper centre). This outcrop appears to be overturned although, on the whole, structural attitudes of the various basaltic units at this locality are ambiguous (see text). For scale comparisons a camera lens cap is situated near the upper right corner of this photograph.

B. Radial pipe vesicles and cooling cracks in a Myra *Type* 2 basaltic pillow. Note vesicular pillow fragments in the adjacent breccia (*cf.* E).

C. Concentric zones of vesicles in a Myra *Type* 2 basaltic pillow. Creamy-green epidote-rich interpillow matrix adheres to the lower surface of this pillow. Matchbox is 5 cm in length.

D. Abundant coarse albitized plagioclase phenocrysts in a Myra *Type* 2 basaltic pillow. Compass is 7 cm in width. Less conspicuous albitized and/or chloritized plagioclase phenocrysts are present in lower abundances in pillows displayed in photographs A, B, C and E.

E. Minor highly vesicular pillow-fragment breccia associated with Myra *Type* 2 basaltic pillows. The chloritized matrix appears to have been largely very fine-grained vitric fragments.

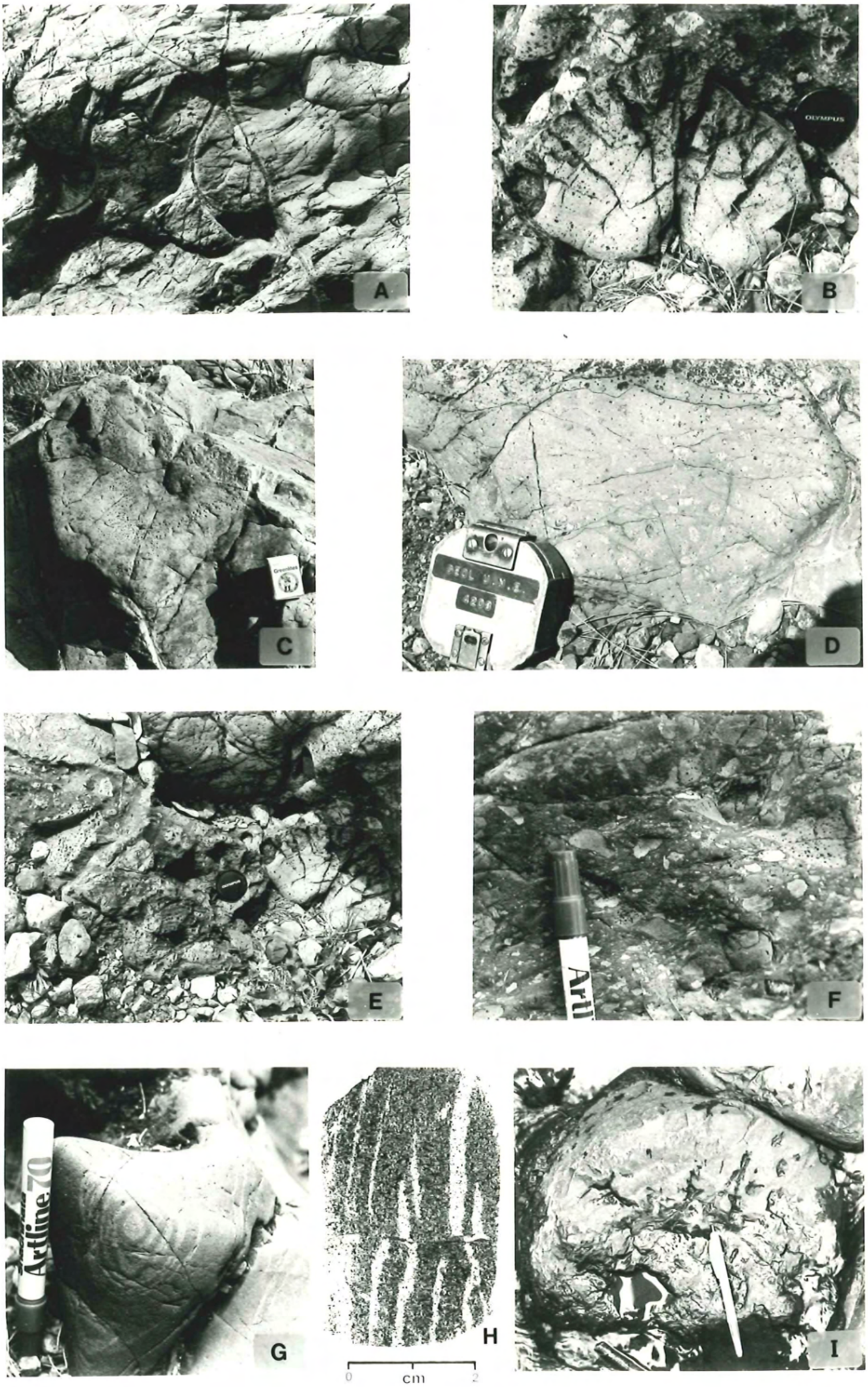
F. Incipiently sheared, coarse-grained Myra andesitic breccia (see p. 135) containing abundant highly vesicular fragments. Pen is 1.5 cm in diameter [GR7925,9340].

G. Liesegang-like iron-staining in a massive Myra *Type* 1 basaltic extrusive [sample 202, GR7218,9360].

H. As above, in thin section. Clear bands are comparatively unstained altered basalt (transmitted tungsten light).

I. Sparse, radially oriented cavities in a Tamworth Group basaltic pillow from the Morrisons Gap area [GR2810,0698].

PLATE 3·1



Rare angular carbonate patches were also found in some of the jasper-bearing lavas (e.g. GR 7520,9495; GR 7680,9360). It is not known whether these are xenoliths or cavity fillings. The latter interpretation is favoured because limestones are not associated with jasper elsewhere in the Myra beds.

(4) Basaltic Intrusives

The field relations of most Myra basaltic units are poorly known. Intrusive contacts are rarely seen (e.g. locality 3.5) but, because of their relatively coarse grainsize and massive form, most doleritic rocks are believed to be intrusive units. Substantial doleritic masses crop out at localities 3.1 and 3.2 (Fig. B-1) and coarse often plagioclase-phyric doleritic rocks (e.g. samples 210-213) are intimately associated with basaltic extrusives at locality 3.5 (Fig. B-1). Other small (tens of metres or less) isolated aphanitic and doleritic outcrops are sparsely scattered throughout the Myra beds and some of these might be intrusive into the enveloping sediments.

Internal and marginal (especially) shearing in most of the doleritic outcrops suggests that these, and possibly all Myra basaltic units, were emplaced prior to melange formation (see Chapter 1).

(5) Summary

Basaltic rocks are present in the Myra beds as:

(i) Phacoids of unknown original field relations occurring in a matrix of sheared sediment.

(ii) Tectonically brecciated and highly sheared horizons among less deformed blocks of sediment.

(iii) Thin dykes, often truncated by shear zones.

(iv) Isolated massive and pillowed flows (and some sills), or groups of several flows, some of which show evidence of volcanism contemporaneous with sedimentation. These basaltic rocks are essentially free of vesicles or amygdales and have negligible associated pyroclastic material.

(v) Intrusive-extrusive complexes, sometimes with associated relatively shallow-water tuffaceous deposits. Highly vesicular and amygdaloidal pillowed flows and breccias are locally abundant.

Three principal types of volcanic activity have been recognized in the Myra beds and elsewhere in the Woolomin Association.

(i) Relatively passive effusion of massive sheet and pillowed flows (probably at abyssal water depths), with minor associated intrusives. These basaltic rocks are scattered throughout the Woolomin Association.

(ii) The building of intrusive-extrusive piles with some associated explosive activity and hyalotuff development. These volcanic piles are probably remnants of submarine volcanoes whose edifices sometimes reached sufficiently shallow depths for phreatic explosive eruptions (probably less than 500m, depending on the volatile content of the magma - see discussion in Section 3.6.1). Basaltic rocks of this type are best seen at locality 3.5 (Map 1) and east of Kootingal (Fitzpatrick, 1975; Map 0.2).

(iii) Relatively shallow water effusion of moderate to highly vesicular pillowed and massive flows with considerable attendant brecciation (e.g. localities 3.3,3.4, Fig. B-1).

Type (i) volcanism was, at least in part, coeval with the accumulation of jasper and presumably other pelagic sediments in the Myra beds and elsewhere in the Woolomin Association. Phacoids of this basalt type are also present in areas of sheared argillite but might not be indigenous to the environment of sedimentation of that argillite. *Type* (ii) volcanism is probably similar in age to *Type* (i) although it has not been possible to demonstrate a direct genetic relationship between these volcanics and the spatially associated proximal volcaniclastics and hyalotuff horizons.

The history of *Type* (iii) volcanism in the Myra beds is equivocal.

It might represent discrete shallow-water volcanism or may be simply the shallow-water portion of a dismembered *Type* (ii) volcanic pile. Cuddy (1978) described a terrane of mixed *Type* (ii) and *Type* (iii) volcanism in the Woolomin beds near the Peel Fault System in the Woodsreef area (Fig. 0.2). In the Myra beds, however, the two types show some petrographic differences (see Section 3.3.1) and might not be closely related.

3.2.2 Tamworth Belt

Tamworth Group and Glen Ward beds

South of Bowling Alley Point (Fig. 0.2), the Tamworth Group has been considerably disrupted by faulting and its stratigraphy is poorly known. Basaltic rocks are usually more abundant lower in the section (or in more general terms, closer to the Peel and Manning Fault Systems) but thin basaltic intrusives(?) are also found high in the section in the Morrisons Gap area (GR 2563,1313, Map 2) and to the south of the Pigna Barney - Curricabark area (082, 113).

Vallance (1969c) noted that in the Nundle area, dolerites tend to occur at lower stratigraphic positions than the basalts. While this is generally the case in that area, many exceptions exist elsewhere. In the Glenrock and Pigna Barney - Curricabark areas Tamworth Belt basaltic extrusives occur at all levels throughout the Lower to mid-Devonian section. It must be noted, however, that much of the lower Tamworth Belt stratigraphy recognized north of Nundle (Crook, 1961a; Cawood, 1980) is not in evidence to the south of Nundle, where rocks of Silver Gully age (see Chapter 1) or slightly older abut the Peel and Manning Fault systems.

Some doleritic rocks closely resembling those in the Glen Ward beds intrude, or are faulted amongst, low Ti basalts of the PBOC (contacts are not exposed - Map 1).

(1) Basaltic Extrusives and Pyroclastics

The basaltic extrusives form massive, partly-pillowed and entirely-pillowed flows. Many are single flow units interbedded with sediments (usually laminated siliceous argillites with some interbedded feldspathic and lithofeldspathic sandstones) but piles of several successive flows, sometimes intruded by dolerite, are not uncommon (e.g. Happy Valley and

Burrows Creek near Nundle (Fig. I-1), McDivitts Creek (Map 2) and Sheepstation Creek, Map 1). Individual flow units range in thickness from several metres to several tens of metres.

It is often difficult to establish whether massive outcrops are parts of flows or intrusives, especially where contacts are faulted. Faulted contacts are quite common in the Glen Ward beds and more common in the Nundle area than indicated by previous workers. The degree of faulting and internal shearing increases towards the Peel and Manning Fault Systems and is especially prevalent in the valley of the Pigna Barney River (Map 1). Where unfaulted contacts are exposed (Limestone Creek, Sheepstation Creek, Longera Creek (Map 1); McDivitts Creek, Stockyard Creek and Brayshaws Creek (Map 2), and numerous localities in the Nundle area) the majority of aphanitic and some microdoleritic units are seen to be flows and the great majority, if not all, of the doleritic rocks are intrusive.

The upper portions of many otherwise massive flows are often partly pillowed but some exhibit minor blocky autobrecciation. Depositional contacts of overlying sediments (most commonly highly siliceous argillites) on these irregular surfaces are by far the most reliable indicators of an extrusive origin. The few basal contacts observed are relatively sharp with little recrystallization or disturbance of the underlying siliceous argillites. Furthermore, thin (often less than 1m thick) inter-flow horizons of finely laminated siliceous argillite (e.g. GR 2848,0695, Map 2) are rarely disturbed by the overlying flows. These features suggest fairly passive, fluidal extrusion of the basalts. The thicker massive flows, especially those thicker than 10m, show a gradual increase in grainsize towards their interiors, where textures are then microdoleritic or doleritic. The thinner flows are typically aphanitic throughout.

Although distinctly amygdaloidal lavas and sills have been reported from the Nundle area (Benson, 1915; Vallance, 1969c), they are uncommon in the Tamworth Group and the Glen Ward beds to the southeast of Nundle. There, except for some amygdale-rich patches (see Section 3.3.2) and occasional scattered amygdales near the upper surfaces of some massive flows and margins of pillows, most lavas and intrusives are essentially free of vesicles and amygdales. Nevertheless, a thick section (*ca.* 70m) of poorly-pillowed basaltic rocks with abundant carbonate amydales (up to

5mm in diameter but mostly 2-3mm - often one or more per sq.cm.) overlies low-Ti basalts of the PBOC in Tomalla Creek (Map 1). These amygdaloidal basaltic rocks also contain abundant jasper - or hematite-filled cavities and fractures.

Some otherwise vesicle- and amygdale-poor pillows have sparse small radially oriented cavities resembling pipe vesicles (Plate 3.1I) and others contain similar cavities elongate sub-parallel to the upper and lower pillow margins (Plate 3.2A). These features are rare, however, and no large intrapillow gas cavities or drain-away cavities (*cf.* Jones, 1968; Hargreaves and Ayres, 1979; Wells *et al.*, 1979) were observed. Pillows also show no evidence of such cavities having been filled by later lava pulses (*cf.* Ui, 1981).

Most pillows are tightly packed and there is very little inter-pillow material (Plate 3.2A,B) except for occasional thin accumulations of chloritized hyaloclastite (aquagene tuff *cf.* Carlisle, 1963) spalled off the outer pillow surfaces (069, 112). Pillow breccias are common near flow tops but almost invariably constitute only a minor, often negligible, proportion of these flows. Most pillow breccias have very little fine-grained matrix. Although some isolated-pillow breccia occurs, it typically contains only a sparse matrix of chloritized shard and microlitic hyaloclastite with a carbonate-prehnite-quartz cement (Plate 3.2C, 111) pillow-fragment breccia (Plate 3.2D) and broken pillow breccia (Plate 3.2E), although not uncommon, are trivial in overall extent.

A substantial horizon of basaltic fragmental material is intercalated with siliceous argillites, litharenites, and basaltic intrusives and extrusives in the Tomalla Creek section of the Glen Ward beds (Map 1). This horizon is highly sheared and most outcrops are foliated chlorite-carbonate limonite ± zeolite rock (118) which can be traced intermittently over a strike length of approximately 1.2 km. The less pervasively sheared material shows a dispersed framework of angular pebble and rare cobble-sized chloritized basaltic fragments in a matrix which is almost entirely replaced by carbonate and zeolites (116, 117).

Rare undeformed blocks of closed-framework microlitic hyaloclastite (Plate 3.2F, 089) occur as small (less than 1 metre) lensoidal phacoids in the highly sheared material. Basaltic fragments forming this hyaloclastite are highly angular and often have delicate outlines. They are unsorted, amygdale-free, often plagioclase phyric, rarely sub-variolitic, and are cemented by a carbonate poor stilbite-epidote-chlorite assemblage. Although this hyaloclastite is obviously a proximal type, its field relations unfortunately are not conducive to the identification of its source. It was presumably a precursor to much of the associated sheared volcaniclastic material and this suggests that the carbonate of the latter is largely secondary in origin. Microtextural evidence supports this conclusion (116, 117). Several small outcrops of similar carbonated volcaniclastic rocks have been found elsewhere in the Glen Ward beds (GR 6633,8105; sample 090) and associated with limestone lenses at GR 6770,8241; sample 247) in the Myra beds.

No scoriaceous breccia was found among the Tamworth Belt rocks examined, but a highly amygdaloidal flow breccia (114) of limited extent occurs in the Glen Ward beds at GR 6715,8000 (Map 1). Basaltic agglomerate with amygdaloidal (carbonate- and chlorite-filled) and amygdale-free plagioclase phyric fragments cemented by pink carbonate (115) is also common at this locality.

Small interpillow patches of finely laminated siliceous argillite (Plate 3.2G) occur near the tops of flows in McDivitts Creek (Map 2). The bedding in this argillite is of similar attitude to that in the overlying sediments suggesting that these flows had open interpillow cavities into which sediment filtered from above. Some similar interpillow cavities in Glen Ward (GR 6305,8040) and PBOC (see Chapter 5) extrusives have been filled by jasperoidal material which often extends into the pillows along cooling cracks. Basaltic breccia at GR 5765,8395 contains angular jasperoidal fragments which are speckled with iron-free patches of chalcedony (Plate 3.2H) and large irregularly-shaped jasperoidal masses (409, Plate 3.3A). The latter have been deformed during incorporation in the breccia and at that time may have been considerably less lithified than the angular fragments.

Interpillow or incorporated (xenolithic) jasper has not been observed in the Tamworth Belt basaltic lavas in the Nundle or Morrisons Gap areas, but the uppermost basaltic flow in McDivitts Creek (Map 2) is directly overlain by a ~25 cm thick diffusely laminated jasper horizon (413). This unit was traced along strike (*via* jasper fragments in the

<u>PLATE 3.2</u>

Tamworth Belt Basaltic Rocks

A. Tightly-packed basaltic pillows in the Glen Ward beds. Note small elongate cavities in the pillow to the lower left of centre, and the slightly darker margins of most pillows. Hammer head is 16 cm in length [GR5781,8478].

B. Large, tightly-packed bulbous pillows in a Glen Ward basaltic extrusive [samples 065 and 067, GR5776,8413].

C. Glen Ward basaltic isolated-pillow breccia and minor interpillow hyaloclastite. The hyaloclastite (pale grey) contains chloritized basaltic fragments dispersed in a carbonate + prehnite + quartz matrix [GR5784,8438].

D. Glen Ward basaltic pillow-fragment breccia. Hammer handle rests on a pillow which appears to be isolated in the breccia. The matrix of this breccia is incipiently sheared [GR6315,8186].

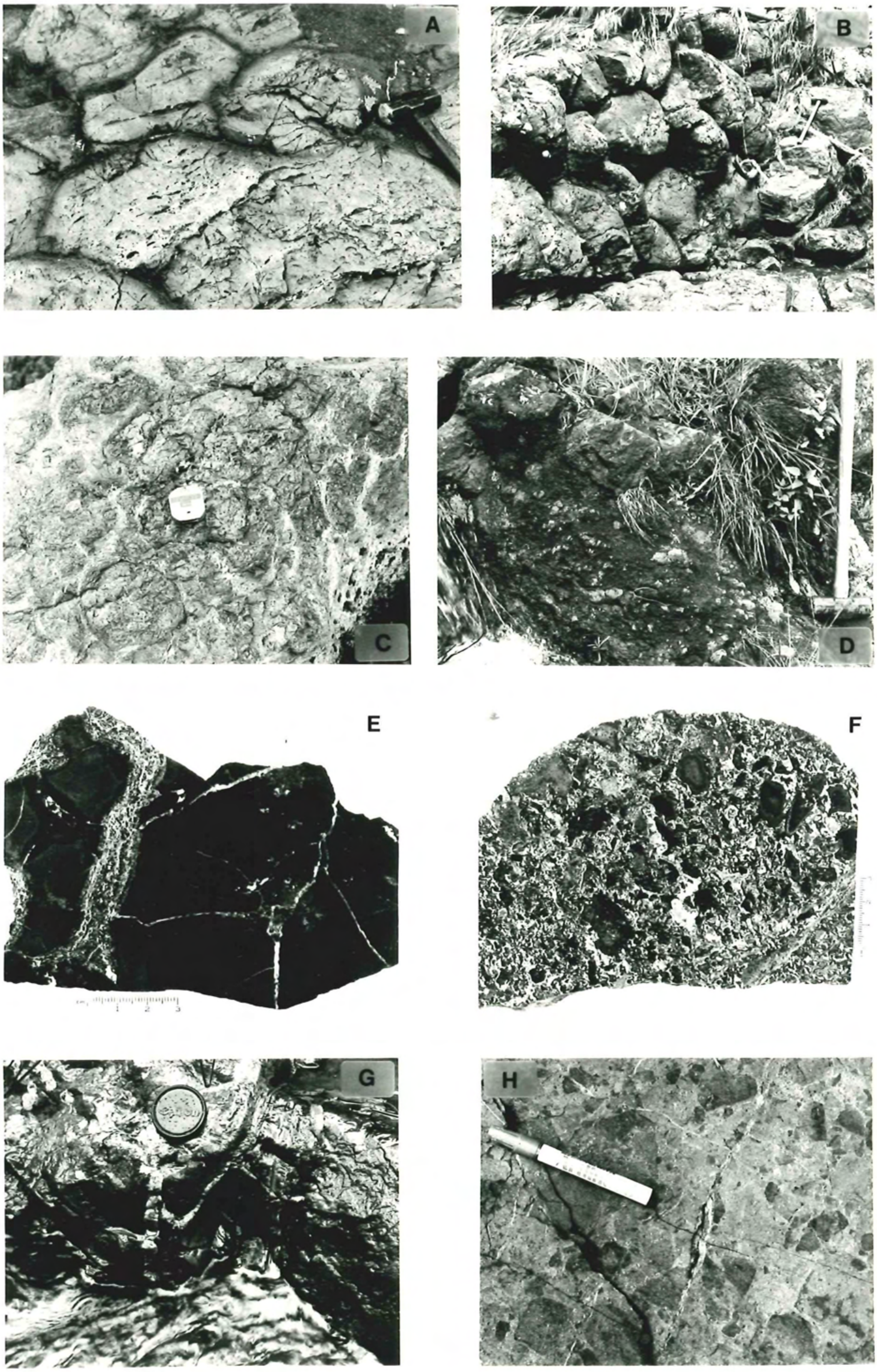
E. Slabbed specimen of Tamworth Group basaltic broken-pillow breccia from the Morrisons Gap area. Note: (i) the mottled appearance of some fragments due to alteration and primary textural variations; (ii) minor fine-grained hyaloclastite; and (iii) abundant carbonate + clay + chlorite veins and cavity-fillings. Although this specimen contains several carbonate amygdales (e.g. upper right of centre and extreme upper right) amygdales/vesicles are rarely found in the majority of Tamworth Belt basaltic rocks examined [sample 049, GR2854,0686].

F. Slabbed specimen of a closed-framework microlitic hyaloclastite from the Glen Ward beds. The basaltic fragments are almost wholly chloritized. The pale-coloured cement is largely pink stilbite + minor epidote and chlorite [sample 089, GR6167,7963].

G. Interpillow finely laminated siliceous argillite in Tamworth Group basaltic extrusives, Morrisons Gap area [GR2848,0695].

H. Subangular jasperoidal fragments in a Glen Ward basaltic breccia. Small white patches within the jasperoidal fragments are clear and milky chalcedony. Veins almost entirely consist of carbonate. Pen is 1.5 cm in diameter [GR5774,8405].

PLATE 3·2



soil) for approximately 150 metres and constitutes the only autochthonous jasper recorded from the Tamworth Belt. No microscopic radiolaria remains were detected in this jasper and, as it is closely associated with basaltic extrusives, it is probably of localized fumarolic origin. Jasper fragments and cavity fillings in basaltic rocks in the Glen Ward beds and PBOC may have had a similar origin. They might represent rare periods of high hydrothermal activity coupled with a low degree of terrigenous sedimentation.

(2) Basaltic Intrusives

Basaltic intrusives, although typically sill-like in broad outline, often have highly irregular and locally discordant contacts with siliceous argillites (Plate 3.3B). The latter are sometimes recrystallized with bedding obliterated, and they may display a hackly (Plate 3.3C), occasionally subconchoidal fracture for up to several metres from the contact. Such effects are rare where contacts are sharp and concordant. In most cases sediments in close proximity to doleritic sills show minimal recrystallization suggesting that they may have been poorly consolidated at the time of intrusion.

Einsele *et al.* (1980) and Lonsdale and Lawver (1980) describe basaltic and doleritic sills intruding shallow covers of poorly consolidated sediments in the Guaymas Basin, Gulf of California. Einsele *et al.* (1980) found that contact effects in the surrounding sediments were limited to the remobilization of silica and the recrystallization of clay minerals. They attributed these features to the rapid loss of heat from the sills through the boiling of pore water in the sediments. However, somewhat more intense hornfelsing of sediments has been reported from other DSDP sites where basaltic sills were intersected (e.g. Minami-Daito Basin; Dick, 1982).

This mechanism might also account for the very low grade contact metamorphic effects in Tamworth Belt sediments adjacent to dolerite intrusions (e.g. 161 to 165). Benson (1915) and Vallance (1969c) also noted that some basaltic rocks in the Nundle area appear to have been emplaced beneath shallow covers of unconsolidated sediment. In some cases unconsolidation of the sediments permitted the development of pillows in these intrusives.

Nevertheless, doleritic rocks have intruded lithified sediments and at several localities these intrusives contain angular xenoliths of argillite (GR 5755,8481) and volcaniclastic sandstone (166, Plate 3.3D). At GR 5725,8540 on the Pigna Barney River dolerite has engulfed blocks of limestone with dimensions of up to several metres (Plate 3.3E,G). The dolerite forms complexly shaped apophyses into the highly recrystallized limestone (which is a relatively pure marble with minor epidotization near the contacts) and contacts range from sharp (Plate 3.3E,F) to diffuse (Plate 3.3F,G). Much of the dolerite is riddled with carbonate veins, especially in the vicinity of the limestone blocks (Plate 3.3F).

Thin aphanitic basaltic dykes are common throughout the Tamworth Group and its correlatives from Nundle to the Pigna Barney - Curricabark area. They often follow joint planes through massive outcrops of dolerite or volcaniclastics (Plate 3.3H) and occasionally form step-like sill-dyke alternations through well-bedded argillites. Sheeted or nested dyke sequences such as those common in ophiolites (Moores and Vine, 1971; Williams and Malpas, 1972; Kidd and Cann, 1974; Stern *et al.*, 1976; Kidd, 1977; Coleman, 1977; Thayer, 1977; Abbotts, 1979,1981) have not been observed in any of the areas examined.

At least some of the deformation and stratigraphic disruption in the Tamworth Group and Glen Ward beds (see Chapter 1) can be attributed to the emplacement of the doleritic intrusives. In the Archaean of Ontario Raudsepp and Ayres (1982) describe localized updoming and complex folding and faulting resulting from successive emplacement of gabbroic sills (up to 240m thick) into relatively unlithified lacustrine sediments. Complex faulting is a common feature of the Tamworth Belt rocks (complex folding is rare). Although this deformation may largely reflect proximity to the Peel and Manning Fault Systems, such faulting might in part be related to the emplacement of some of the doleritic intrusions into progressively lithifying Tamworth Belt sediments.

Isolated outcrops of doleritic rocks closely resembling those in the Glen Ward beds are scattered throughout the area dominated by low-Ti basalts and gabbros of the PBOC (Map 1). Some of these are substantial in size (several tens to several hundreds of sq.m.), others are only on a scale of several sq.m. Contacts between these doleritic rocks and mafic rocks of the PBOC were not observed. Consequently it is not known whether

PLATE 3.3

Photographs A-H all depict relatively minor variants of the Glen Ward beds.

A. Large irregularly-shaped mass of jasperoidal material (dark grey, e.g. directly beneath hammer head) in a Glen Ward basaltic breccia [GR5774,8405].

B. Highly irregular contact between a doleritic intrusive (light grey) and slightly hornfelsed siliceous argillites (darker grey). Veins consist of carbonate ± prehnite [GR5843,8414].

C. Hackly fracture displayed by hornfelsed siliceous argillite (relatively rare) adjacent to a doleritic intrusive [GR5775,8400].

D. Xenolith (arrowed) of mafic volcaniclastic sandstone in an iron-stained doleritic intrusive [sample 166, GR5956,8400].

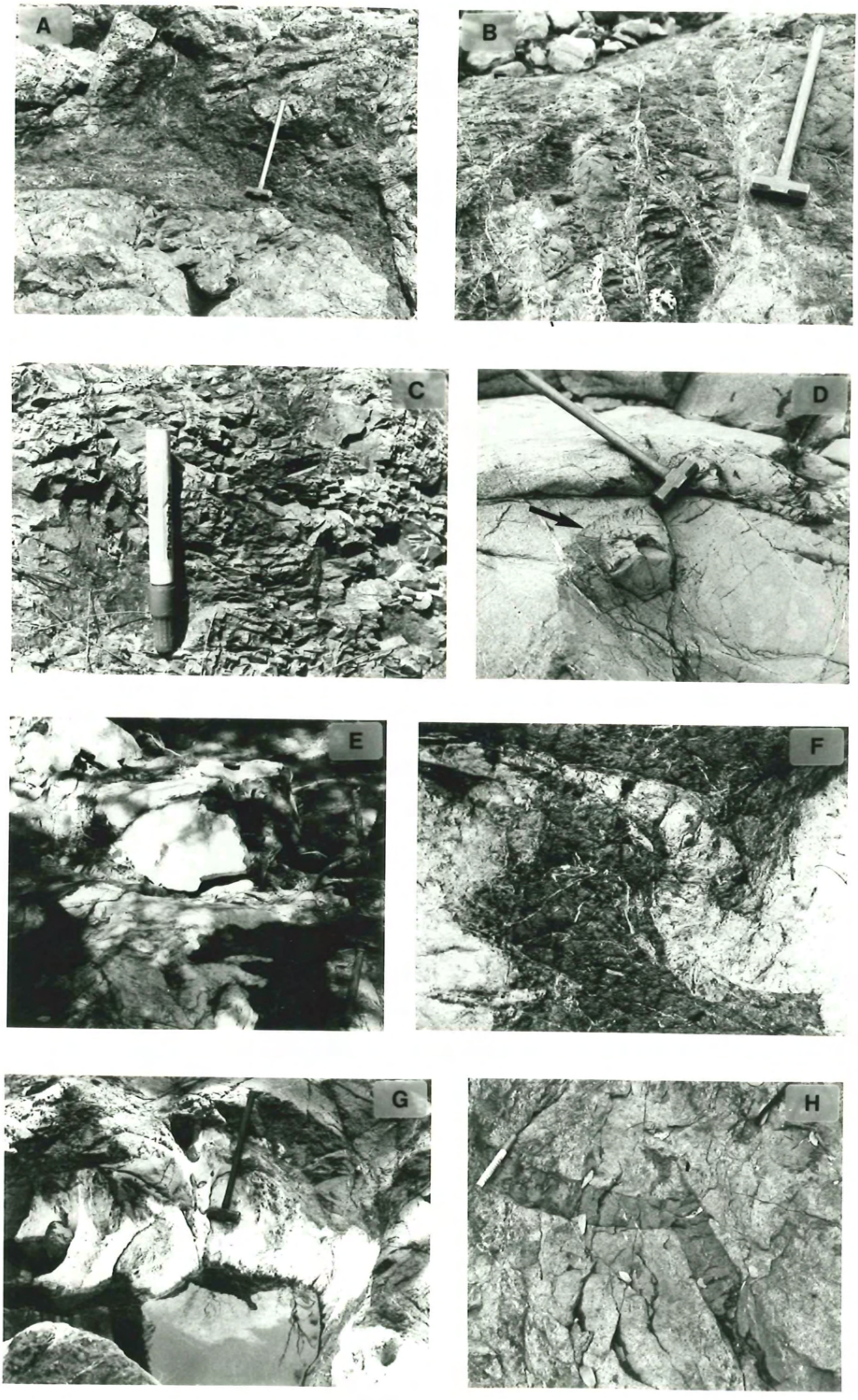
E. Blocks of relatively pure limestone (only moderately recrystallized) engulfed by a doleritic intrusive. Note apophysis of 'dolerite' lower right of centre [GR5725,8540].

F. As above (E). Note: (i) carbonate veining in the 'dolerite'; and (ii) both sharp and diffuse contacts. The area displayed is approximately 50 cm in width.

G. As above (E). Note sharp, irregular and diffuse contacts and the localized development of minor epidote-rich 'skarn' near some contacts (e.g. medium-grey, high relief assemblage to the right and upper right of the hammer head).

H. A fine-grained basaltic dyke intruding a massive doleritic unit. Note deflection of the dyke along a relatively minor joint plane [GR5823,8406].

PLATE 3·3



basaltic rocks of the Glen Ward beds have intruded the PBOC mafic rocks or have been faulted into them at this locality.

3.3 PETROGRAPHY

The textural characteristics of basaltic rocks in the Myra beds and the Tamworth Belt are described in some detail. These:

(i) Provide some information on the mode of emplacement of the rocks concerned.

(ii) Are important criteria whereby basaltic extrusives of the PBOC may be distinguished from those in the Myra beds and Tamworth Belt. Most comparisons of this type are made in Chapter 5.

3.3.1 Myra beds

All basaltic rocks in the Myra beds display some textural and mineralogical modifications as a result of cataclasis and low-grade metamorphic and hydrothermal processes. This alteration is typically more advanced than that in basaltic rocks of the Tamworth Belt.

Distinct metadomains (Smith, 1968; Smith and Smith, 1976) are common but these tend to reflect the degree of shearing and tectonic brecciation rather than reflecting primary features such as flow tops and bases, and intrusive margins (Smith, 1974). Pillow rims, however, are commonly preferentially epidotized. Even the more massive outcrops are riddled with chloritized microshears and veins composed of varying proportions of carbonate, prehnite, epidote, chlorite and quartz; with less common albite, pumpellyite and hematite.

The principal primary minerals found in these rocks are plagioclase, augite, titanomagnetite and/or ilmenite and, rarely, quartz (216). Relict olivine or Ca-poor pyroxene was not found, although carbonate pseudomorphs after skeletal and euhedral olivines were identified in one group of lavas (*Type 3*). Primary amphibole is rare and is confined to the doleritic rocks (e.g. 222).

On the basis of general textural features three main petrographic types may be recognized, namely:

Type 1:- a basalt-dolerite association where every gradation exists between quench-textured basaltic rocks and medium-grained doleritic rocks.

Type 2:- a markedly porphyritic group of intrusives and extrusives.

Type 3:- a highly vesicular quench-textured group of plagioclase-rich extrusive and flow breccias.

Types 1 and *2* were also recognized by Mayer (1972). Petrographic *Types 1, 2* and *3* generally correspond to field *Types* (i), (ii) and (iii) (see Section 3.2.1) respectively except that in some rare cases (e.g. samples 218, 246) *Type* (i) extrusives have *Type 2* textures (i.e. plagioclase-phyric) and some *Type* (ii) doleritic intrusives are non-porphyritic (e.g. 220). *Types 3* and (iii) are identical in the Myra beds but exceptions may exist elsewhere in the Woolomin Association.

The salient textural characteristics of each petrographic type are described below.

(1) *Type 1*

This is a basalt-dolerite association in which every gradation exists from subvariolitic and hyalopilitic textures in the aphanitic rocks (220, 228, 229) through intersertal (chloritized glass) to subophitic (207, 215) or intergranular (222, 230) textures in the doleritic rocks. The extrusives are sometimes pillowed, but are more usually massive. Amygdales are typically sub-macroscopic and are not abundant.

Type 1 basaltic rocks occur widespread throughout the Myra beds and are the most common basaltic type. Except for the greater degree of alteration displayed by *Type 1* basaltic rocks, they are texturally similar to the substantially more voluminous basaltic rocks of the Tamworth Group and Glen Ward beds (*cf.* Benson, 1915; Vallance, 1969a; Cross, 1974; Bayly, 1974; Offler, 1982; this thesis, Section 3.3.2) and many basaltic rocks described from other parts of the Woolomin Association (e.g. Heugh, 1971; Bayly, 1974; Fitzpatrick, 1975; Cuddy, 1978; Rose, 1978; Paull, 1978; Offler, 1979,1982; Herbert, 1982).

Some of the thicker flow units have aphanitic margins which grade into microdoleritic or doleritic interiors (e.g. 201). Doleritic intrusives, on the other hand, are generally quite even-grained and homogeneous. However, one doleritic intrusive (GR 6658,9054) displays a narrow chilled outer contact zone which is slightly finer-grained than the interior.

The aphanites usually contain microphenocrysts of clinopyroxene, plagioclase and sometimes titanomagnetite in a quench-textured or (originally) intersertal groundmass. The outer margins of pillows are usually highly epidotized (indicating that they were considerably palagonitized and therefore rich in Fe^{3+} prior to low grade metamorphism; Baragar *et al.*, 1979) or chloritized, and highly sheared resulting in the obliteration of primary textures. Subvariolitic (228) and hyalopilitic (229) textures are common in pillow interiors, but the latter are more typical of the massive flows (200).

Shearing at the margins of most *Type 1* basaltic units in the Myra beds has obliterated primary textures in the more rapidly quenched portions of these rocks. However, euhedral plagioclase microphenocrysts are ubiquitous in the more aphanitic rocks. These are often accompanied by microphenocrysts of clinopyroxene and, more rarely, titanomagnetite. No evidence of the former presence of olivine has been found. Olivine may have been present as a minor phase in the quenched outer margins of these rocks, but the only crystallization sequence now recognized is plagioclase-clinopyroxene-titanomagnetite (± ilmenite)-quartz (in some doleritic intrusives e.g. 216); with some intratelluric microphenocryst growth, especially of plagioclase.

(2) *Type 2*

This is a markedly porphyritic group of intrusives and extrusives which are commonly pillowed (Plate 3.1A,D). They are plagioclase-phyric and are particularly common at locality 3.5 where they form the majority of the basalt-dolerite pile. They are also exposed at GR 7305,9365, GR 6425,8200 and GR 6063,8010 (Map 1) where they are relatively limited in extent.

The plagioclase phenocrysts are often euhedral and vary up to 1 cm in length, although the majority range from 3 to 5mm. They are usually albitized (Ab_{95-98}) and are typically altered to fine-grained aggregates of sericite, carbonate and prehnite. Rare relicts of sodic labradorite (218, Michel-Lévy method) and labradorite (219) have been observed. Some phenocrysts contain fine filamentous veins of fracture-filling albite (221) and more contain rounded blebs of quench-textured groundmass (218). The latter provide evidence of partial resorption and suggest that the plagioclase phenocrysts were not in equilibrium with the melt at the time of eruption. The groundmass blebs are often replaced by chlorite or epidote.

The groundmass of the extrusive rocks typically shows a fine-grained quench-texture of chloritized glass containing subvariolitic clinopyroxene and plagioclase (now usually albite) and abundant microphenocrysts of plagioclase. It is sometimes riddled with fine equigranular Fe-Ti oxides (218), but often not noticeably so (221). Amygdales are usually carbonate-filled, but pyrite, chlorite and epidote also occur as amygdale fillings. Opaque oxides are often clustered around amygdales, but segregation vesicles/amygdales (Smith, 1967) are rare. Disseminated pyrite is locally conspicuous, especially at locality 3.5. The groundmass in the doleritic types has a relatively fine-grained subophitic texture or, especially in the coarser grained examples, an intergranular texture.

The entire cross section of a 25 cm diameter plagioclase-phyric pillow was sampled from locality 3.5 (GR 8025,9305). A segment of this pillow is shown in Plate 3.4A. It is slightly atypical of the outcrop in its relative paucity of amygdales, but appears to be representative in other respects. Thin epidote + carbonate ± prehnite ± chlorite veins are scattered throughout. The pillow contains approximately 10% euhedral to subhedral albitized, sericitized and prehnitized plagioclase phenocrysts, 1-4mm in size and somewhat heterogeneously distributed throughout, but not so as to suggest gravitational settling or "floating" (*cf.* Ui, 1981). Pumpellyite is an occasional alteration phase. Plagioclase phenocrysts show clear evidence of partial resorption, the groundmass blebs being largely replaced by epidote or chlorite.

Bulk samples of three macroscopically distinct zones of this pillow (Plate 3.5A) (inter-vein material) were analyzed (samples 203-205, analyses 6-8 Table 3.5a) to evaluate possible chemical heterogeneity (e.g. Hopgood, 1962; Vallance, 1969c; Baragar *et al.*, 1979; see Section 3.5.4, Part (1)). The textural characteristics of these analyzed samples are outlined below.

The groundmass in the core zone of the pillow (203, approximately

20 cm diameter) consists of a fine felted mass of semi-acicular and skeletal albite and pyroxene, the latter being almost invariably replaced to varying degrees by epidote. Opaques are now largely oxidized and hydrated (turbid brown and slightly translucent) and small patches of carbonate are scattered throughout. There is a broad transition zone (204) between the relatively homogeneous core and an outer, more rapidly quenched zone 3-4 cm in width. Plagioclase phenocrysts in this transition zone are, apart from albitization, generally less altered than those in the core zone. Carbonate amygdales increase in abundance towards the outer zone and commonly cluster in and around patches of more highly quenched opaque-charged groundmass. Overall, the groundmass is slightly finer-grained than that in the core zone and fine granular opaques appear less oxidized and more abundant.

The outer pillow zone (205) consists of three macroscopically distinct bands of highly variable thickness. All contain altered plagioclase phenocrysts. The innermost band is dark green-black, has a colloform-like contact with the lighter green (epidote green) transition zone (Plate 3.5A), and ranges up to 2 cm in thickness (5mm in the portion that was thin-sectioned, 204). It consists of a turbid opaque-rich groundmass of devitrified subvariolitic and dendritic structures of fine pyroxene and plagioclase (albite). This passes outwards into a pale grey-brown variolitic band with individual varioles being 0.1 to 0.2mm in diameter. These structures are common in pillow lavas and in this case appear to be the product of spherulite development (Cawthorn, 1977) rather than liquid immiscibility (*cf.* Furnes, 1973; Gelinas *et al.*, 1976,1977). This band varies from several mm to 2 cm in thickness with the spherulites increasing in abundance radially outwards (at the expense of interstitial chlorite and feldspar microlites) until they coalesce.

The outermost pillow selvage is highly epidotized and chloritized. It has been considerably sheared and mixed with creamy-green cryptocrystalline interpillow material and hematite.

The abundant epidote, which requires the availability of considerable Fe^{3+}, suggests that these glassy outer pillow selvages were extensively palagonitized prior to low-grade metamorphism (Baragar *et al.*, 1979; Holland and Norris, 1979). The presence of chlorite, however, suggests that some relatively unoxidized sideromelane may have been present at the onset of metamorphism (Baragar *et al.*, 1979). The hematite may represent remobilized ferric oxide crusts formed during hydration and oxidation of the basalt glass (Dimroth and Lichtblau, 1978). No crusts of liesegang rings of iron oxide were observed within these pillows but the dark outer zone of the pillow described above might reflect the incipient development of these features. Indeed, this outer zone is markedly enriched in Fe^{3+} (and ΣFe) relative to the remainder of the pillow (see Table 3.5a). Some hematite-rich veins also extend into the pillow interior along cooling fractures.

The outer highly altered selvage and the hematite-rich veins were removed from the sample (205) before analysis.

The crystallization sequence in the *Type 2* intrusives and extrusives was identical to that of the *Type 1* basaltic rocks (i.e. plagioclase-clinopyroxene-Fe-Ti oxide) except that intratelluric crystallization of plagioclase was more pronounced in the former. Evidence of olivine or Ca-poor pyroxene was not found in either basalt type. Except for pillow margins, *Type 2* basaltic rocks are typically more crystalline and the crystals are more equidimensional than in *Type 1*. This is in accord with their greater degree of intratelluric crystallization enabling more extensive nucleation in the melt prior to eruption or intrusion, and slower cooling rates of the generally more voluminous *Type 2* units.

(3) *Type 3*

This is a highly vesicular quench-textured group of plagioclase-rich pillow lavas, massive flows and flow breccias. They are the most abundant basaltic type at locality 3.3 and, to a lesser extent, at locality 3.4 (Map 3). They crop out poorly as a result of locally intense shearing and tectonic brecciation.

Vesicles or amygdales (usually carbonate-filled, or more rarely chlorite- or quartz-filled) may constitute up to 20% by volume of some pillows. The larger amygdales (up to 1.5 cm in longest dimension) and some small ones (1mm-5mm) are often wholly or partially rimmed by narrow zones of iron-charged quenched groundmass (232, 234, Plate 3.4B) and resemble the segregation vesicles described by Smith (1967). Smith (1967) suggests that the entry of residual melt into vesicles could be brought about by an increase in pressure, and consequent decrease in volume of the volatiles occupying the vesicles, during the latter stages of crystallization.

Baragar *et al.* (1977) propose a similar mechanism whereby high external pressure might force "residual magmatic fluids from the interstices of the rock into the vesicle cavity as the gas contracted on cooling". The segregation vesicles would thus be localized where the "degree of crystallization was sufficient to retain the form of the vesicle but insufficient to prohibit the movement of residual liquid". Bideau *et al.* (1977), for deep-water pillows at least, favour the escape of volatiles from the vesicles into the melt during cooling to enable segregated melt to enter the vesicles. They cite the occurrence of protrusion voids near vesicles as evidence for this hypothesis.

Protrusion voids are not evident in Myra *Type 3* basaltic rocks but some textural features suggest that an additional factor may be important in the formation of their segregation vesicles. Patches of quenched residual liquid in these rocks (and in basaltic rocks in the Tamworth Belt) are often riddled with small amygdales (236). These most probably represent vesicles formed by release of volatiles from the segregated melt fraction at the time of quenching, because if they were present prior to quenching, they would have coalesced into larger vesicles similar to those elsewhere in these rocks. The envelope of melt surrounding earlier-formed vesicles would have been similarly saturated with volatiles (with consequent depression of its solidus) and become more so as it evolved (especially with H_2O as the $NaAlSi_3O_8$ (*ab*) component in the melt increased; Hamilton *et al.*, 1964; Eggler and Burnham, 1973; Burnham, 1975,1979; Holloway, 1981) through fractionation of earlier phases. In this way some vesicles may have been loci for the segregation of evolving melt fractions which would be buffered against crystallization by local saturation with volatiles. This mechanism is not inconsistent with that proposed by Baragar *et al.* (1977) and also alleviates the need for events causing pressure increases during crystallization (Smith, 1967). It might also be a qualitative indicator of magmas with volatile components enriched in H_2O relative to CO_2.

The pillows with radiating vesicles (see Section 3.2.1, part (1); Plate 3.4C) have fine-grained quench textures with abundant acicular and skeletal plagioclase (apparently oligoclase, R.I. less than R.I. balsam, extinction sub-parallel to *a*) which is often arranged in fan and bow-tie spherulitic aggregates. The plagioclase in these aggregates usually forms discrete crystals (Plate 3.5G) rather than the fibrous sheaf-like or plumose forms indicative of large degrees of supercooling and consequent very rapid quenching (Bryan, 1972; Lofgren, 1974,1975; Schiffman and Lofgren, 1982). However, the latter are present in some pillows (Plate 3.4H). Turbid brown opaque-dusted devitrified glassy material is intergranular to the plagioclase and this is often segregated into darker plagioclase-poor, amygdale-rich patches. Tiny chlorite-filled amygdales are abundant throughout the groundmass although some irregularly-shaped chlorite patches may represent chloritized glass or pseudomorphs of anhedral ferromagnesian phases. The larger amygdales, and most of those in the melt segregation patches, are carbonate-filled.

Relict augite occurs as small intergranular crystals in one of the massive flows (sample 240, see Table E-6). Intergranular sheaf-like microlitic bundles in the more highly quenched rocks originally may have been intergrowths of pyroxene and plagioclase but they are difficult to resolve optically, and are often replaced by chlorite. These features are more readily observed in the slightly coarser-grained massive lavas (240) which have intersertal textures with tabular to skeletal plagioclase up to 0.5mm long, and contain some partially resorbed euhedral plagioclase phenocrysts up to 1.5mm long. Prismatic and acicular dendrites extend from the margins of some tabular plagioclase grains. Patches of quench-textured groundmass are common.

A distinctive feature of *Type 3* Myra basaltic rocks is the presence of *ca.* several percent or (usually) less of carbonate pseudomorphs after euhedral and skeletal olivine microphenocrysts and groundmass grains (Plate 3.5E,F). They are usually 0.1-0.2mm in size, but several range from 0.5mm to 1 mm. No relict olivine was found (10 thin sections) but pseudomorphs of characteristic skeletal forms (Bryan, 1972; Rhodes *et al.*, 1979) and euhedra (sections sub-parallel to [100] are common) enable the recognition of earlier olivines to be made with some confidence. Many olivine pseudomorphs contain one or more tiny (0.01-0.02mm) opaque or translucent brown spinel euhedra (Plate 3.4E,F; see Section 3.4.2). Acicular opaque oxide microlites are abundant throughout the groundmass in these rocks but their compositions are poorly known (some are ilmenite).

The pillows with concentrically aligned vesicles (Plate 3.4D) show preferred orientation of plagioclase laths (232) and are more crystalline than those with radiating vesicles. Phenocrysts were not observed but these might have been resorbed completely at the slower cooling rates suggested by the relatively high degree of crystallinity and coarser average grainsize of these pillows. Equidimensional intergranular opaques are common. Also, in these pillows highly acicular (often regularly spaced) Fe-Ti oxides often transect plagioclase crystals at a high angle to the *a* axis (Plate 3.4G). Consequently they appear to post-date the flow alignment of the plagioclase. These opaque needles do not simply fill fractures in the plagioclase but may cross-cut several grains. Where they occur wholly within plagioclase grains they are generally too voluminous to be the result of exsolution from typical iron-rich plagioclases (which almost invariably contain less than one percent total Fe as FeO; Bryan 1974,1979), a feature of some ocean floor gabbros (Davis, 1981). The origin of this texture in these Myra basaltic rocks is not understood.

Except for their vesicularity, the textures of *Type 3* basaltic rocks more closely resemble those of quenched MORB's than either of the other two types (and for that matter, basaltic rocks in the Tamworth Belt). Intratelluric olivine (pseudomorphed) and plagioclase microphenocrysts are scattered throughout all but the types with concentric vesicles, and commonly show a disequilibrium relationship with the liquid. (Note resorbed patches in olivine microphenocryst, Plate 3.4E). Smaller olivine microphenocrysts in the groundmass have skeletal textures similar to those considered typical of basalts in which olivine occurs alone on the liquidus (Rhodes *et al.*, 1979). The habits of the groundmass plagioclase, opaque oxides, and pyroxene indicate moderate degrees of supercooling (Bryan, 1972; Lofgren, 1974,1975).

Recent investigations of textures produced during controlled cooling experiments using basaltic melts (Donaldson, 1976; Corrigan, 1982; Schiffman and Lofgren, 1982) have established regular relationships between textural elements (olivine, plagioclase and pyroxene crystal dimensions and morphology) and cooling rate. However, these parameters are only directly applicable to magmas which were quenched at temperatures above their respective liquidi. All Myra basaltic rocks show evidence of significant intratelluric crystallization so only qualitative comparisons can be made.