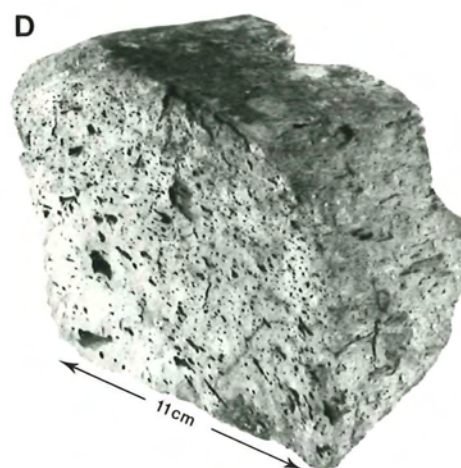
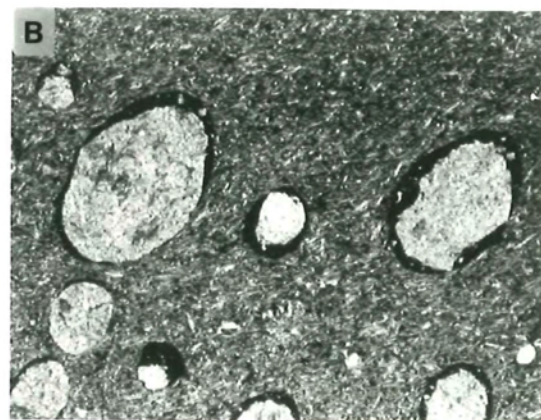
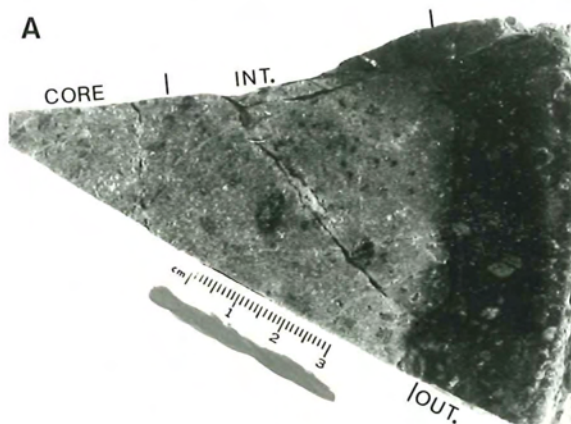


PLATE 3.4

Myra Basaltic Extrusives

- A. Concentric textural zonation in a segment of a Myra *Type* 2 pillow. Note: (i) plagioclase phenocrysts (pseudomorphed by chlorite + albite ± prehnite ± sericite) ; (ii) carbonate + epidote (white) and hematite ± chlorite (black) veins/fracture fillings; (iii) scattered small white carbonate amygdales; and (iv) colloform-like banding at the contact between the intermediate (INT) and outer (OUT) zones [GR8025,9305].
- B. Carbonate-filled segregation vesicles in a Myra *Type* 3 basaltic pillow. Note: (i) irregular distribution of late-stage melt segregations (black) around vesicle margins; and (ii) flow alignment of vesicles and groundmass plagioclase [sample 234, mag. = 9x, plane-polarized light; locality 3.3 (see Fig. B-1)].
- C. Radially-oriented carbonate-filled segregation vesicles near the outer margin of a Myra *Type* 3 basaltic pillow [sample 233, locality 3.3 (see Fig. B-1)].
- D. Concentrically-oriented ellipsoidal vesicles in a quadrant from a small Myra *Type* 3 basaltic pillow. Note: (i) outer pillow rind has spalled off exposing vesicles; and (ii) vesicles become relatively fewer and larger towards the pillow core [sample 238, locality 3.3 (see Fig. B-1)].
- E. Carbonate pseudomorph after an olivine microphenocryst in a Myra *Type* 3 basaltic pillow. Note: (i) tiny euhedral spinel inclusions; and (ii) partially resorbed patches near the 'olivine' core [sample 237, mag. = 35x, plane-polarized light; locality 3.3 (see Fig. B-1)].
- F. As above (E). Note carbonate pseudomorph after a small skeletal olivine grain, left centre.
- G. Acicular Fe-Ti oxides cross-cutting albitized plagioclase laths in a Myra *Type* 3 basaltic pillow [sample 232, mag. = 220x, plane-polarized light; locality 3.3 (see Fig. B-1)].
- H. Quench-textured (skeletal and spherulitic) albitized plagioclase in a Myra *Type* 3 basaltic pillow. Some spherulitic clinopyroxene also occurs in the dark Fe-Ti oxide-rich interstitial material. Pale grey blebs are carbonate amygdales [sample 234, mag. = 90x, plane-polarized light; locality 3.3 (see Fig. B-1)].

PLATE 3.4



The scarcity of dendritic crystals is a significant feature of all the Myra basaltic rocks (with the possible exception of the outermost pillow rims in which original textures are almost invariably obliterated by shearing and/or epidotization). In a study of the crystallization of Grane Ronde (Yakima Basalts, Columbia River Group) pillow basalts, Schiffman and Lofgren (1982) found that pyroxene dendritic habit disappears at cooling rates lower than $25^{\circ}\text{C}/\text{hour}$, when it is then replaced by coarse radiate-, or fan spherulitic pyroxene. In Myra basaltic rocks dendritic pyroxene is found only in the groundmass of some *Type 3* pillows where it occurs sparsely, and is difficult to resolve from turbid material. This, and the highly skeletal nature of coexisting plagioclases, suggests that these lavas cooled at greater rates (probably in the range $25^{\circ} - 50^{\circ}\text{C}/\text{hour}$) than the other Myra basaltic types, and also that the former were nearer their liquidus temperatures at the time of extrusion. As might be expected, grain morphologies of the massive *Type 3* basalts and those pillows showing flow-orientation of plagioclase laths suggest slower rates of cooling, possibly $5^{\circ} - 25^{\circ}\text{C}$ per hour.

To summarize, the majority of basaltic rocks in the Myra beds display textures indicative of quenching at comparatively moderate rates of cooling. In the absence of less equivocal information these rocks are interpreted as extrusives. Doleritic intrusives are also locally abundant. All three petrographic types described above show evidence of intratelluric crystallization of plagioclase >> clinopyroxene >> titanomagnetite, with phenocrysts being very much more abundant in *Type 2* than in the other types.

Field and petrographic evidence for the modes of emplacement of the various Myra basaltic types are broadly consistent. However, the actual timing of volcanic activity relative to the formation of the associated sediments is often conjectural.

3.3.2 Tamworth Belt

Tamworth Group and Glen Ward beds

Pillow lavas, thin massive flows and intrusives and the margins of their thicker equivalents, typically have an aphanitic, rarely plagioclase-phyric texture. Complete gradation exists between these rocks

and the intersertal, sub-ophitic or intergranular textures of the coarser-grained intrusives and interiors of thick extrusives.

The major primary phases in these basaltic rocks are plagioclase (largely albitized), augite and titanomagnetite (\pm ilmenite). The augite commonly displays weak concentric zoning and occasional sector zoning. Relict olivine and Ca-poor pyroxene were not identified in any of the thin sections examined (>300). Pseudomorphs of olivine are exceedingly rare (see part (1), this section). No pseudomorphs of Ca-poor pyroxene were recognized, although it must be admitted that recognition of the latter would be difficult. Accessory minerals include apatite, sphene and pyrite. Hornblende and quartz are minor phases in rare, usually more evolved doleritic rocks.

Plagioclase is usually completely albitized in the aphanitic rocks but calcic relicts are common (the majority fall in the range An_{65-45} by optical and microprobe determinations) in the more crystalline types. Albite in the latter is often more kaolinized and sericitized than in the aphanites. Clinopyroxene is typically unaltered, but on occasion may be partially or wholly replaced by chlorite, carbonate or uralitic amphibole. Other secondary alteration products include prehnite, epidote, quartz, leucoxene, hydrated opaque oxides (probably titanomaghemite), and rare clinozoisite and pumpellyite. Pumpellyite is almost invariably confined to amygdales or fragmental deposits. Most outcrops are riddled with carbonate veins (see, for example, Plate 3.3B).

(1) Basaltic Extrusives and Pyroclastics

In hand specimen the aphanitic rocks vary from black to deep green in colour. The chilled margins of most pillows are darker-coloured than the pillow interiors (Plate 3.2A) and are from 1 cm to 5 cm thick. Subvariolitic (110, 069) to vitrophyric (109) textures are typical of these chilled margins. Fan, bow-tie and plumose plagioclase and pyroxene spherulites are common, the plagioclase spherulites tending to be coarser-grained and more open than the pyroxene. Discrete acicular and skeletal plagioclase crystals are also common. Usually, isolated spherulites or spherulite clusters are scattered throughout a turbid, opaque-rich chloritized groundmass. Although spherulites are often abundant in the outer margins of Tamworth Belt basaltic pillows, the thin

bands of completely variolitic texture (coalesced spherulites) which are common in MORB pillows (e.g. Marshall and Cox, 1971; Bryan, 1972; Moore, 1975b; Ayuso *et al.*, 1976; Scott and Hajash, 1976; Baragar *et al.*, 1977, 1979) and basaltic pillows in some greenstone belts (Furnes, 1973; Gelinas and Brooks, 1974; Dimroth *et al.*, 1978) were not observed. In contrast, many low Ti basalt pillows of the PBOC are entirely variolitic (see Section 5.7.2).

The chilled margins of Tamworth Belt basaltic pillows almost invariably contain scattered, often abundant euhedral microphenocrysts of plagioclase. These are usually accompanied by microphenocrysts of clinopyroxene. The latter may occur as discrete crystals, glomerophyritic clusters or in subophitic relationships (072) with plagioclase. The plagioclase crystals rarely exceed 0.5mm in longest dimension and the clinopyroxenes rarely exceed 0.2mm. These provide evidence for at least a small degree of intratelluric crystallization prior to extrusion.

Most of the fragmental material associated with Tamworth Belt basaltic extrusives was derived from the disaggregation of chilled pillow margins, or the brecciation of pillows on a small scale. Basaltic fragments in hyaloclastites and fine-grained basaltic breccias typically have vitrophyric or microlitic textures* (088), although more crystalline fragments are common (072, 087, 112). The coarser breccias contain fragments exhibiting the full range of textures seen in the extrusives. Vesicles and amygdales are sometimes conspicuous in the fragmental deposits relative to the associated extrusives, but both are generally vesicle- and amygdale-poor.

Basaltic fragments in the hyaloclastites and breccias are almost invariably highly chloritized (with one conspicuous exception: specimen 072, see below) and the fragmental deposits as a whole abound in secondary alteration products and space-fillings. The latter are typically prehnite, quartz, Fe-stained quartz and carbonate with lesser epidote, chlorite and pumpellyite. Many basaltic fragments in some breccias, especially interpillow breccias and interpillow hyaloclastite, have been altered to a translucent creamy-green or brown clay aggregate (e.g. 049). Chlorite,

* Dimroth *et al.* (1978) extend the usage of the term hyaloclastite to include microlitic (in addition to sideromelane) shards.

however, is by far the most common alteration product and is usually accompanied by lesser amounts of carbonate, prehnite, epidote and rare pumpellyite.

The pillow interiors often have a slightly mottled appearance, primarily due to the patchy distribution of darker-coloured chloritized aphyric domains. These form small, highly irregular, and often amygdaloidal patches (071, 073) scattered throughout the intersertal or vitrophyric pillow interiors. Larger, more discrete patches or segregations are also common in some of the thinner massive flows (Plate 3.5A; 055, 077), in massive portions of partly pillowed flows (069) and in some fine-grained doleritic intrusives. These patches rarely constitute more than several percent of the rock. They rarely exceed 2 cm in longest dimension in the pillows but may be up to 50 cm in length in the massive basaltic rocks where they are usually elongate sub-parallel to the margins of the host.

The chloritized glass forming the bulk of the aphyric patches is relatively crystal-poor (Plate 3.5B,C), although much richer in sub-microscopic and minute acicular and dendritic Fe-Ti oxides. Microphenocrysts are rare. Acicular and highly skeletal plagioclase crystals occur in most patches and delicately plumose pyroxene in some (073). Both have forms indicative of more rapid quenching than those adjacent in the host basaltic rock.

Some patches contain dark sub-spheroidal or irregularly-shaped areas which are exceedingly rich in opaque oxides (069, 071). These features are quite distinct from those attributed to the formation of iron-rich and silica-rich immiscible liquids during late stage crystallization of tholeiitic melts (Philpotts, 1978a,b; 1979). Rather, they are largely the result of extensive micro-spherulitic crystallization of pyroxene and plagioclase which caused the concentration of opaque oxides in the intervening mesostases.

Many patches in the extrusives are highly amygdaloidal (Plate 3.5B,C), very much more so than the host basaltic units which are often free of amygdales. The amygdales range up to 5mm in diameter and are usually composed of carbonate (071), with less common chlorite and/or epidote (077) or rare quartz (e.g. 085) or pumpellyite (077).

These aphanitic patches are peculiar to the Tamworth Belt basaltic rocks, especially those in the Glen Ward beds, and were not observed

in basaltic rocks of the Myra beds or of the PBOC. They are by no means ubiquitous in Tamworth Belt basaltic rocks and may not be a common feature of other basaltic rocks of this type. They probably represent relatively evolved, iron- and volatile-enriched melt fractions segregated during quenching of the host basalt. In this regard they may be 'quenched' equivalents of the segregation veins described from basalt flows in Hawaii and Japan by Kuno (1965). They also resemble the vesicle cylinders and sheets described by Wright and Okamura (1977) from the Makaopuhi Lava Lake, Hawaii.

Unfortunately chemical and mineralogical data on the finer-grained patches in Tamworth Belt basaltic rocks are not available and these comparisons cannot be evaluated in any detail.

Recognizable pseudomorphs after olivine are extremely rare in Tamworth Belt basaltic rocks. They were identified with some confidence in only two samples (072, 087), both of which are chloritized glassy fragments from basaltic breccias. In sample 087 chlorite and pumpellyite pseudomorph euhedral and skeletal (hopper shapes, see Donaldson, 1976) olivines less than 0.1mm in longest dimension (Plate 3.5D). These are sparsely scattered throughout chloritized hyaline and cryptocrystalline basaltic fragments. Some such fragments contain minute skeletal plagioclase while others have plagioclase and/or clinopyroxene microphenocrysts. Most contain abundant small chlorite- and pumpellyite-filled amygdales (e.g. 055, 087) which range from 0.1mm to approximately 0.5mm in diameter.

Sample 072 is remarkably fresh, although groundmass glass is altered. It contains abundant unaltered euhedral plagioclase (An_{65-62}), augite (see Table E-2) and titanomagnetite microphenocrysts, and scattered chalcedony pseudomorphs after skeletal to euhedral olivine microphenocrysts (Plate 3.5E,F,G). The latter range from 0.2mm to 0.5mm in longest dimension, are often partially resorbed and occasionally contain (or are attached to) tiny opaque spinel (?) euhedra.

The groundmass is largely dark brown chloritized glass containing abundant delicate plumose, dendritic, variolitic and fluidal textures (Plate 3.5 H to O). Dendritic pyroxenes and opaque oxides are commonly inter-leaved and form overgrowths on the microphenocrysts (Plate 3.5L,M) (including the olivine pseudomorphs) and skeletal grains (Plate 3.5 H,I,O). Pyroxene also forms plumose spherulites in the groundmass (Plate 3.5 J,K).

and highly skeletal plagioclases are abundant (Plate 3.5 O).

The texture of sample 072 suggests that it experienced a period of intratelluric crystallization of olivine, plagioclase, augite and minor titanomagnetite (which sometimes forms inclusions in plagioclase and clinopyroxene microphenocrysts) at small degrees of undercooling; and this was followed by rapid ascent, eruption and quenching. Comparison of groundmass textures with those produced by controlled experimental quenching of natural basalt melts by Lofgren (1974) and Schiffman and Lofgren (1982) suggest cooling rates in excess of 25°C per hour,^{*} and supercooling in excess of 70°C (spherulitic plagioclase coexisting with dendritic and spherulitic pyroxene - Lofgren, 1974, Fig. 5).

Sample 072 provides a rare opportunity to contrast some pristine petrographic features of Tamworth Belt basaltic rocks with those of MORB's, especially the abundance of clinopyroxene microphenocrysts and the absence of sector-zoned plagioclase in the former. Sector-zoned plagioclase is characteristic of the variolitic and inner zones of MORB pillow basalts (Bryan, 1972) but has not been observed in any relict calcic plagioclase examined during this study. Also, the groundmasses and microphenocryst populations of all basaltic extrusives examined are considerably more clinopyroxene-rich than the majority of MORB's, although this may be largely a function of the more evolved nature of many of the former^{**} (see Section 3.5.5).

However, while evolved olivine-poor, clinopyroxene-rich basalts are not characteristic of MORB populations they have been described from many localities on the ocean floor (see Section 3.6; Table 3.11). It is

* Schiffman and Lofgren (1982) found that the pyroxene dendritic habit disappears at cooling rates slower than 25°C per hour. Experimental starting materials were: (i) Lofgren (1974): MORB from the Gorda Ridge; $mg = 55$, 1% normative ol , 19% normative hy ; (ii) Schiffman and Lofgren (1982): Grande Ronde Basalt (Columbia River Basalts); $mg = 40$, 6% normative qz . The compositions of most Tamworth Belt basaltic rocks fall within these limits (see Section 3.5.5).

** Bryan (1979), for example, found that clinopyroxene phenocrysts tend to occur in liquids from the FAMOUS area which have less than 8% normative olivine, $\Sigma\text{FeO/MgO} > 1.0$, $\text{TiO}_2 > 1.0\%$ and $\text{K}_2\text{O} > 0.15\%$.

more the geochemical characteristics of Tamworth Belt basaltic rocks which distinguish them from typical MORB (see Section 3.5.5).

(2) Basaltic Intrusives

Intersertal (chloritized glass), intergranular and sub-ophitic to ophitic textures are typical of Tamworth Belt intrusives. The majority are texturally homogeneous except for chilled margins and occasional finer-grained patches. Some of the thicker units contain rare plagioclase-rich pegmatitic schlieren (Plate 3.5Q, GR 5889,8419), and very rare diffuse mineralogical layering (Plate 3.5P, GR 5964,8408). Coarse-grained doleritic and gabbroic sills (051, 059, 091, 105) are not uncommon.

The most abundant primary phases in these rocks are plagioclase (40% to 90%^{*}), augite (20%-60%), titanomagnetite (<10%) with minor ilmenite. Amphibole and/or quartz are occasional minor phases. Chloritized interstitial groundmass may form up to 20% of some rocks but is relatively minor in comparison with the doleritic interiors of many massive extrusive units.

Plagioclase is usually albitized but calcic relicts are common (Table E-3). Some relicts show broad concentric zones. Plagioclase typically forms euhedral to subhedral laths with intergranular or sub-ophitic augite and intergranular Fe-Ti oxides. Large Fe-Ti oxide grains in the coarse doleritic and gabbroic types are often skeletal or dendritic (059, 104) and may poikilitically enclose small grains of plagioclase or augite. Fe-Ti oxide inclusions in plagioclase or augite are rare in all but the more evolved dolerites (068, 102).

Most of the doleritic rocks do not contain amphibole. However, deep green-brown primary amphibole is often present in sparse amounts in the more evolved (quartz-bearing, Fe-Ti oxide-rich) types (e.g. 099, 068). In these rocks the primary amphibole forms discrete prismatic intergranular crystals (commonly with equant Fe-Ti oxide inclusions) and optically homogeneous overgrowths on augite grains. The two most Mg-rich

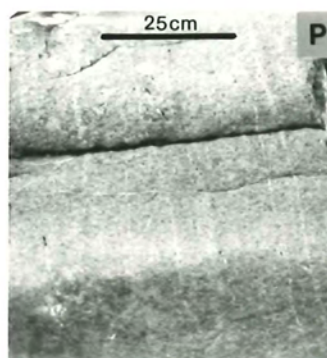
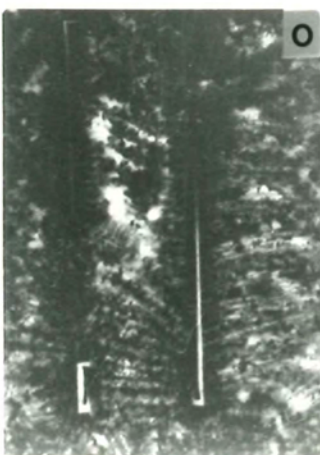
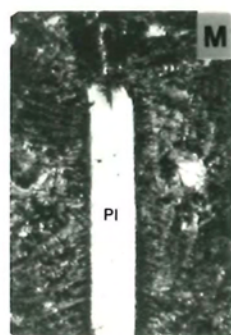
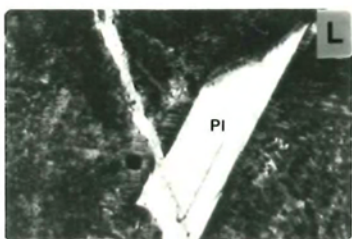
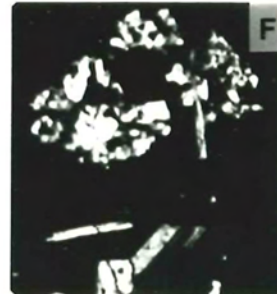
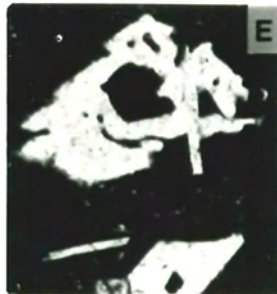
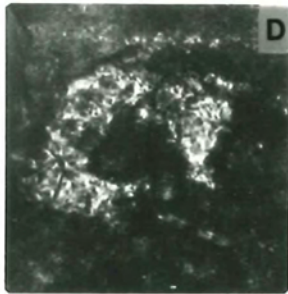
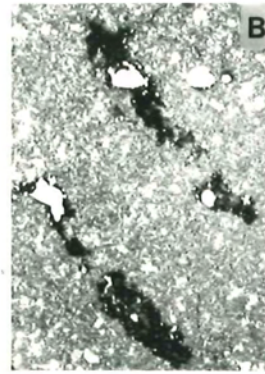
* In pegmatitic schlieren (Plate 3.5Q). Some minor plagioclase accumulates (093, 094, 095) contain approximately 70%-80% plagioclase, but most doleritic rocks contain approximately 50%-60% plagioclase.

PLATE 3.5

Glen Ward Basaltic Rocks

- A. Thin, elongate aphanitic patches in a massive basaltic extrusive. Pen is 1.5 cm in diameter [GR8410,5825].
- B. As above. Note: (i) carbonate amygdales in and near finer-grained patches (dark); and (ii) carbonate-filled segregation vesicle (rare) to the right of the uppermost fine-grained patch [sample 069, mag. = 2x, plane-polarized light].
- C. As above (B) [sample 071, mag. = 9x, plane-polarized light].
- D. Partially resorbed (? skeletal) pumpellyite pseudomorph after olivine in a fragment from a microlitic basaltic breccia [sample 087, mag. = 350x, crossed nicols].
- NOTE: Photomicrographs E-O are all from sample 072 [GR5785,8430]. Of these, H-O illustrate delicate quench textures preserved in the groundmass.
- E,F. Skeletal olivine grains now pseudomorphed by chalcedony [mag. = 35x, E = plane-polarized light, F = crossed nicols].
- G. Euhedral olivine microphenocrysts now pseudomorphed by chalcedony [mag. = 35x, crossed nicols].
- H,I. Dendritic growths of quench clinopyroxene on a plagioclase microphenocryst and its skeletal extremities. Clinopyroxene dendrites also constitute most of the groundmass [mag. = 220x, H = plane-polarized light, I = crossed nicols].
- J,K. Open (J) and fan (K) spherulites of quench clinopyroxene displaying small bleb-like dendritic clinopyroxene overgrowths [mag. 90x, crossed nicols].
- L,M. Dendritic and acicular growths of Fe-Ti oxides and clinopyroxene on plagioclase microphenocrysts. The former are displayed best in L, between the cross-cutting carbonate vein and the plagioclase microphenocryst [mag. = 90x, plane-polarized light].
- N. Delicate fluidal textures preserved in a patch of devitrified, originally vitrophyric groundmass [mag. = 90x, plane-polarized light].
- O. Curved clinopyroxene dendrites radiating from a highly skeletal plagioclase grain. The latter displays clear evidence of long-range ordering prior to quenching [mag. = 220x, plane-polarized light].
- P. Doleritic intrusive displaying diffuse mineralogical layering. Thin white carbonate veins lie sub-parallel and perpendicular to the layering [GR5964,8408].
- Q. Pegmatitic schlieren in a doleritic intrusive. Note that contacts with the host may be relatively sharp (upper right) or highly diffuse (upper left, bottom centre) [GR5889,8419].

PLATE 3·5



doleritic rocks analysed (060, 061; analyses 1 and 2, Table 3.6a also contain a small amount of primary intergranular brown pargasitic hornblende.* The most evolved doleritic rock analysed (068; Table 3.6a, analysis 7) contains both primary and secondary amphibole but those of intermediate composition (063, 064; Table 3.6a, analyses 5 and 6) are amphibole-free.

Evolved quartz-bearing doleritic rocks are quite common. Quartz usually occurs as ragged to subhedral grains in chloritized interstitial patches (068). It may also form interstitial myrmekitic intergrowths with plagioclase (102, 103, 120). Secondary uralitic amphibole is common in these evolved dolerites where it mantles or completely replaces augite grains, and may replace interstitial mesostasis (106). This uralitic amphibole may have formed as a deuteric alteration product during the latter stages of crystallization of these rocks or might be related to localized hydrothermal activity (see Section 3.5.3, Part (1)).

The erratic and patchy distribution of secondary amphibole in both the Tamworth Belt and Woolomin Association doleritic rocks suggests that it is largely deuteric or hydrothermal in origin and does not reflect regional metamorphic processes of any consequence.

Doleritic and gabbroic rocks in the Tamworth Belt typically lack convincing petrographic evidence of the former presence of olivine or Ca-poor pyroxene. These rocks otherwise have many textural and mineralogical characteristics comparable to tholeiitic doleritic rocks elsewhere (e.g. McDougall, 1964; Muir and Tilley, 1964; Wilkinson, 1968; Smith and Lindsley, 1971; Yamakawa, 1971; Hyndman, 1972; Macdonald *et al.*, 1981). Macdonald *et al.* (1981) identified serpentine-chlorite pseudomorphs after olivine in tholeiitic quartz dolerite dykes of Scotland and found that they occur only in samples with MgO > 6 wt.%. While several of the analysed Tamworth Belt doleritic rocks have MgO > 6 wt.% (Table 3.6a, analyses 1, 2 and 5), and most contain significant normative olivine**

* $(\text{Na}_{0.8}^{+K_{0.05}}) \text{Ca}_{1.6} (\text{Mg}_{2.9}\text{Fe}_{1.7}) (\text{Si}_{6.4}\text{Al}_{1.3}\text{Ti}_{0.3}) \text{O}_{22}(\text{OH})_2$.

** In these rocks this is at least partially the result of calcium loss during albitization of plagioclase and some mobility of Fe and Mg. Sample 068, for example, contains several percent modal quartz but 6% normative olivine (Table 3.6b). The Scottish dolerites are quartz normative.

(Tables 3.6b, 3.8b), all but samples 060 and 061 (Table 3.6a, analyses 1 and 2) have $\Sigma\text{FeO}/\text{MgO}$ ratios greater than 1.8 and contain less than 20 $\mu\text{g/g}$ nickel. It is unlikely that these high $\Sigma\text{FeO}/\text{MgO}$ rocks originally contained significant modal olivine, although their low nickel contents strongly suggest that their parent magmas may have experienced minor olivine fractionation. Similar arguments apply to the Tamworth Belt basaltic extrusives.

In doleritic rocks of this type some early formed olivine, unless efficiently fractionated, might be expected to form inclusions in early plagioclase or clinopyroxene. Indeed, some chlorite patches in plagioclase in sample 063 do have partially faceted outlines. While these might represent pseudomorphed olivine inclusions, the chlorite is rather more iron-rich ($mg = 46.3$ see Table E-14) than might be expected if its mg value reflects the mg value of an olivine precursor.*

Many evolved tholeiitic basaltic suites contain some Ca-poor pyroxene, (Kuno, 1959, 1966, 1968; Wilkinson, 1968; Deer *et al.* 1978). Offler (1979, 1982) reported rare orthopyroxene (composition unspecified) in Tamworth Belt doleritic rocks from the Glenrock Station area, but orthopyroxene and/or pigeonite have not been found in similar rocks in the Glen Ward beds or in the Nundle area. Similarly, pseudomorphs of Ca-poor pyroxenes have not been identified, although it must be stressed that in any case such identifications would be exceedingly difficult to validate (see discussion in Macdonald *et al.*, 1981).

The observed textural relationships in Tamworth Belt doleritic rocks indicate the following crystallization sequence: plagioclase-augite-Fe-Ti oxides-(amphibole)-quartz. Olivine may have been an early minor phase and Ca-poor pyroxene *might* have crystallized as an intergranular phase - subsequently chloritized. In the more evolved rocks (e.g., 068) Fe-Ti oxides co-precipitated with early-formed plagioclase and augite.

* An olivine of this composition would be in equilibrium with an iron-rich melt ($mg = 20.5$ i.e. $\Sigma\text{FeO}/\text{MgO} = 6.9$, assuming $K_D = 0.3$; Roeder and Emslie, 1970). Sample 063 (analysis 5, Table 3.6a) has a $\Sigma\text{FeO}/\text{MgO}$ ratio of 1.82 ($mg = 49.2$).

3.4 CHEMISTRY OF SOME PRIMARY MINERAL PHASES

Preamble

The most abundant primary phases in basaltic rocks of the Woolomin Association and Tamworth Belt are Ca-rich pyroxene, Fe-Ti oxides, and occasionally calcic plagioclase.

In this study only the Ca-rich pyroxenes have been examined in any detail, and this Section (3.4) is concerned almost entirely with the chemistry of these phases - especially as it might reflect the intrinsic magmatic affinities of the host basaltic rocks. Representative analyses of Ca-rich pyroxenes from some basaltic rocks of the Woolomin Association and Tamworth Belt are listed in Appendix E and are discussed in Section 3.4.1 below.

The chemistry of some magnesiochromite inclusions in pseudomorphs after olivine in Myra *Type 3* pillow lavas is discussed in Section 3.4.2. Sections 3.4.3 and 3.4.4 include some general comments on the chemistry of relict plagioclases and Fe-Ti oxides respectively in the Myra and Tamworth Belt basaltic rocks.

Analyses of detrital pyroxenes from some volcanoclastic sediments in the Myra beds and the Glen Ward beds are also listed in Appendix E (Tables E-4 and E-8). These pyroxenes were analysed for two reasons:

- (i) To evaluate their potential for determining the magmatic affinities of the very significant volcanogenic component in these sediments.
- (ii) To investigate the possibility that some volcanic detritus may have been derived from the basaltic extrusives in one or other of the Woolomin Association or Tamworth Belt.

These analyses are discussed in Chapter 2 but for comparative purposes and economy of space they are plotted on some of the diagrams in this Chapter.

3.4.1 Ca-rich Pyroxenes

3.4.1.1 Pyroxene-Host Rock Chemical Relations: A Brief Review

Early investigations of the chemistry of pyroxenes from basaltic rocks (e.g. Wilkinson, 1956, 1957; Brown, 1957; Kushiro, 1960; LeBas, 1962; Verhoogen, 1962; Coombs, 1963) showed that their compositions reflect, to a greater or lesser degree, some chemical characteristics of the respective host magmas. In particular, Ca-rich pyroxenes from alkaline and subalkaline basaltic rocks often can be distinguished largely on the basis of their differing iron-enrichment trends (Wilkinson, 1956, 1957; Brown, 1957; Aoki, 1964; and many subsequent workers, see Deer *et al.*, 1978), their Ca (+Na)-Mg-Fe, Si-Al and Ti-Al relationships (Kushiro, 1960; LeBas, 1962; Verhoogen, 1962) and their C.I.P.W. normative characters (Coombs, 1963). Also, unlike many subalkaline types (with the notable exception of MORB), alkaline basaltic rocks do not carry co-existing low-pressure Ca-rich and Ca-poor pyroxenes.

However, distinctions between alkaline and subalkaline basalts based solely on Ca-rich pyroxene chemistry should be made with caution:-

- (i) The Al contents (especially Al^{VI}), and to some extent the Ti contents of pyroxenes increase with increasing pressure of crystallization (Muir and Tilley, 1964a; Brown, 1967; Thompson, 1974; Mysen, 1976; Wass, 1979). Consequently, pyroxenes which have crystallized from tholeiitic magmas at elevated pressures may resemble, in their Al and Ti contents, those in alkaline hosts.
- (ii) Undersaturated (o $\bar{\text{L}}$ -normative) tholeiitic magmas may crystallize relatively Al- and Ti-rich pyroxenes similar in composition to those in alkaline rocks (Verhoogen, 1962; Brown, 1967). On the other hand, mildly alkaline magmas may precipitate relatively Si-rich, Al-poor pyroxenes similar in this respect to pyroxenes in tholeiitic hosts (Gibb, 1973).
- (iii) Mildly alkaline magmas crystallizing under conditions of low and possibly falling oxygen fugacity ($f\text{O}_2$)

may precipitate pyroxenes with low Ti and Al contents and iron-enrichment trends similar to those of pyroxenes in tholeiitic rocks (Barberi *et al.*, 1971; Gibb, 1973; Vieten, 1980).

- (iv) Quench pyroxenes in subalkaline hosts often have anomalously high Ti and Al contents and anomalous $Ca:Mg:Fe'$ relations (see discussions below), and may in fact have compositions resembling those from alkaline hosts.
- (v) Many petrologists view Fe-enrichment trends in the pyroxene quadrilateral as fundamental tools to discriminate between pyroxenes from different magma types (e.g. Aoki, 1964; Barberi *et al.*, 1971; Gibb, 1971, 1973; Garcia, 1978; Snoke and Whitney, 1979; Wilson *et al.*, 1981). Nevertheless, comparisons of this nature must be evaluated with caution as
 - (i) Many Ca-rich pyroxenes, especially those in alkaline hosts, contain significant proportions of chemical components which are not represented on the $Ca:Mg:Fe'$ projection (*cf.* Papike *et al.*, 1974; Cameron and Papike, 1981). Some of these may even substitute directly for quadrilateral components (e.g. Fe^{3+} -Al and Fe^{3+} -Na; *cf.* Cameron and Papike, 1981)
 - (ii) Commonly cited Fe-enrichment trends (especially those based on analyses of pyroxene separates) often involve some simplification of the actual compositional variation in the respective Ca-rich pyroxene populations (*c.f.* Buchanan, 1977, 1979, on pyroxenes from the Bushveld intrusion).
 - (iii) Ca-rich pyroxene crystallized from hydrous melts can exhibit higher Ca values than those from equivalent anhydrous melts (Helz, 1973).

Basaltic magmas erupted in specific tectonic settings often have geochemical characteristics considered peculiar to those settings (e.g. Chayes and Velde, 1965; Pearce and Cann, 1973; Pearce, 1976; Sugisaki, 1976; Winchester and Floyd, 1975, 1977; Pearce *et al.*, 1975, 1977;

Garcia, 1978). This has encouraged some workers to apply pyroxene compositions to discriminate between the various magma types (e.g. Nisbet and Pearce, 1977; Papike and White, 1979; Leterrier *et al.*, 1982). The possibility that the intrinsic magmatic affinities of a particular basaltic suite, and by implication its tectonic setting, could be identified via the chemistry of its pyroxenes is obviously important in interpreting the pristine character and eruptive regimes of ancient basaltic rocks.

Pyroxenes, especially the Ca-rich variants, commonly remain relatively unaltered following low-grade metamorphic and hydrothermal alteration of their hosts (e.g. Vallance, 1974a,b; Bass, 1975; Mevel and Velde, 1976), even though the original bulk chemistry of the host may be highly modified, and some petrologists argue that a study of elements considered immobile under such conditions (see Section 3.5.1) and of relict pyroxene compositions, may lead to recognition of the character of the original magma type. Unfortunately, many recent studies of this type, especially those attempting to discriminate between different subalkaline magmas, have produced equivocal results which often conflict with other evidence.* It will be argued below that the chemistry of pyroxenes from the Myra and Tamworth basaltic rocks, although not providing a unique solution of magmatic and tectonic affinities, nevertheless does impose some constraints in these areas.

3.4.1.2 Introductory Comments

Relict clinopyroxenes from eleven basaltic units in the Myra beds (5 extrusives, 6 intrusives) and twenty-two basaltic units in the Tamworth Belt (12 extrusives, 10 intrusives) were analysed by microprobe. Samples were collected from the more crystalline parts of the extrusives and remote from chilled margins in the intrusives. Representative core and rim compositions are listed in Appendix E. All are augites or (rarely)

* e.g. recent debates on the origin of many ophiolites - see Smith (1975), Cameron *et al.* (1979) and Upadhyay and Neale (1979) for reviews. Ophiolitic rocks and ancient volcanic provinces often show confusing pyroxene-host rock chemical relations, e.g. Barron (1976), Capedri and Venturelli (1979), Capedri *et al.* (1979), Jenner and Fryer (1980), Beddoe-Stephens and Lambert (1981) and Day *et al.* (1982). In addition, Hynes (1981) found that Ca-rich pyroxenes from some high-titania alkaline basalts of Japan plot within the fields of pyroxenes from subalkaline hosts on the F_1 vs. F_2 discriminant diagram of Nisbet and Pearce (1977).

endiopsides and those listed are average compositions of between three and ten grains from each sample (see Appendix E for more details). Throughout the text and tables these are generally referred to as Ca-rich pyroxenes or simply, pyroxenes. The term Ca-enriched is used in a relative sense only. No Ca-poor pyroxenes (orthopyroxene, pigeonite) were found in any of these rocks. Some quench-textured subcalcic augites in basaltic extrusives in the Glen Ward beds were analysed but the compositions of those pyroxenes are not discussed in this thesis.

Sector-zoned clinopyroxenes are common in the Myra and Tamworth extrusives and relatively less common in the intrusives. Reconnaissance analyses of these pyroxenes showed little chemical variation from sector to sector but, in view of the significant compositional heterogeneity of other sector-zoned pyroxenes (e.g. Strong, 1969; Nakamura and Coombs, 1973; Wass, 1973; Bence *et al.*, 1974a,b; Thompson and Humphris, 1980), few sector-zoned pyroxenes were analysed in the present study. Analyses of sector-zoned pyroxenes are not presented in Appendix E.

Extrusives: Clinopyroxenes analysed in the extrusive rocks are microphenocrysts (usually 0.1-1.0 mm in diameter) which are relatively homogeneous except for thin outer rims, the compositions of which often differ markedly from the cores. Optically, some show weak concentric zoning around broad relatively unzoned cores but many appear to be homogeneous throughout. Compositional differences between the broad cores and the narrow outer zones (see below) are rarely reflected by marked optical differences.

Reconnaissance microprobe analyses of groundmass pyroxenes having acicular, plumose and spherulitic habits indicative of rapid growth under quench conditions (e.g. Bryan, 1972; Lofgren, 1971; Fleet, 1975; Schiffman and Lofgren, 1982) were usually of poor quality. This was probably due to the presence of unresolvable intricate intergrowths of quench pyroxene, plagioclase and iron oxides, and enhanced by the effects of alteration which is often more advanced in groundmass phases. Nevertheless, metastable subcalcic compositions (Boyd and Schairer, 1964; Muir and Tilley, 1964a) with high and variable Al and Ti contents were identified. These chemical features are typical of quench pyroxenes from subalkaline hosts (Mével and Velde, 1976; Coish and Taylor, 1978;

Schiffman and Lofgren, 1982) but they convey little other information on the primary nature of the host magma. Consequently the chemistry of these phases has not been evaluated in any detail.

Intrusives: Optical zoning is typically less evident in pyroxenes of the doleritic intrusives. However, weak concentric and/or sector zoning is not uncommon. Twinning is rare. The analysed grains typically have broad homogeneous cores with a narrow outer zone progressively enriched in Fe towards the rims.

The chemistry of pyroxenes from some basaltic rocks in the Tamworth Belt has been studied previously by Vallance (1969c, 1974a) in the Nundle area, and Offler (1979) in the Glenrock Station area. Offler (1979) also examined the chemistry of pyroxenes from some Woolomin basaltic rocks in the Glenrock Station area. The results of these studies are reviewed in the light of pyroxene data presented here from similar rocks in the Morrisons Gap and Pigna Barney - Curricabark areas.

3.4.1.3 Some General Aspects of the Chemistry of Ca-rich Pyroxenes from Basaltic Rocks in the Myra Beds and Tamworth Belt

Some aspects of pyroxene chemistry which may be potentially important in studies of pyroxene-host rock relations are nonetheless of limited application to this study. Thus, the (1) compositional zoning, (2) Fe^{3+} abundances, and (3) $\text{Al}^{\text{IV}}\text{-Al}^{\text{VI}}$ relations in all of the pyroxenes analysed are discussed generally here prior to a more detailed discussion of their chemistry and its implications for the magmatic affinities of their respective hosts.

(1) Compositional Zoning

Compositional zoning in pyroxenes which crystallized under equilibrium conditions from evolving basaltic melts should reflect progressive changes in the chemistry of the host melts (e.g. Gibb, 1973). Normal zoning in such pyroxenes should therefore mimic the trends of cryptic variation displayed by pyroxenes successively removed from fractionating basaltic melts of similar composition. Consequently, in some instances valid comparisons may be made between the well-established iron-enrichment trends of pyroxenes from layered intrusions and those in

zoned pyroxenes from compositionally similar basaltic rocks. Indeed, extreme examples of zoned crystals mimicing the overall chemical evolution of the host magma may be seen in the orthocumulates of layered intrusions themselves (Wager *et al.*, 1960; Wager and Brown, 1968).

In view of their potential value in genetic studies, attention is drawn to some constraints in the interpretation of zoned pyroxenes in the Myra and Tamworth Belt basaltic rocks.

The great majority of pyroxene grains analysed from basaltic rocks in the Myra beds and Tamworth Belt (and all of those represented in Table E-2, E-3, E-5, E-6 and E-7) have broad, chemically-homogeneous cores and thin, usually Fe-enriched, outer rims. These rims typically account for less than 10% of the diameter of pyroxene microphenocrysts in the extrusives (i.e. less than ca 30 vol. %) and less than 30% of the diameter of pyroxene grains in the doleritic intrusives (i.e. less than ca vol. %).

The variations in chemistry between pyroxene cores and rims are consistent from grain to grain in each sample (with very few exceptions). However, pyroxenes from different basaltic units show a wide variety of compositional zoning trends. These trends are illustrated on many of the diagrams in this Section and are summarized in Table 3.1. Offler (1979) also found considerable variation in the compositional zoning of pyroxenes from a number of basaltic units in the Glenrock Station area (see Fig. 2 of Offler, 1979).

The compositional zoning in pyroxenes from the Myra and Tamworth Belt basaltic rocks conceivably reflects two distinct crystallization events. The broad homogeneous cores most probably represent intra-telluric or subvolcanic crystallization essentially under equilibrium conditions where either the proportion of pyroxene in the melt was relatively low, or only very limited fractionation occurred (i.e. melt compositions remained relatively constant). Unfortunately, only a single sample is available from most of the basaltic units examined (see General Introduction, Part (6)) and consequently the overall range of pyroxene core compositions displayed by each of these units is not entirely known.

The variety of core-rim compositional relations shown by pyroxenes of the different basaltic units (Table 3.1, Figs 3.1, 3.2, 3.3, 3.5, 3.6)

might suggest that many of the rims, especially those of microphenocrysts in the intrusives, crystallized as overgrowth cores either: (i) under a wide range of physical and chemical conditions, varying considerably from sample to sample; or (ii) under disequilibrium conditions involving slow diffusion in the melt relative to pyroxene growth rate during final cooling.

Given the relatively limited data available, the first of these possibilities is difficult to evaluate with any confidence. A thorough study of the textural, chemical and mineralogical variations within each basaltic unit conceivably might lead to correlations between pyroxene compositions and factors such as differing melt compositions, mineral parageneses, oxygen fugacities (*cf.* Barberi *et al.*, 1971; Vieten, 1980) and silica activities (*cf.* Kushiro, 1960; Verhoogen, 1962). However, those pyroxenes whose cores are enriched (relative to the rims) in Fe^{3+} (Fig. 3.2) or Na, or depleted in Cr (054, 070, 207, 209) or Al^{VI} (Fig. 3.3) would be difficult to explain solely in terms of pyroxene-melt equilibria as conventionally envisaged.

Most of the basaltic rocks from which pyroxenes have been analysed display some petrographic evidence of relatively rapid cooling (see Section 3.3), including (originally) intersertal textures and/or intergranular patches of fine-grained groundmass in the doleritic intrusives. In the intrusives evidence suggests rapid cooling only during the latter stages of crystallization, whereas the extrusives show evidence of quenching at almost any stage in their crystallization histories.

In their study of mineralogy as a function of depth in the Makaopuhi tholeiitic lava lake, Hawaii, Evans and Moore (1968) found that pyroxenes did not crystallize under equilibrium conditions until a depth of 50-60m below the cooling surface. At progressively shallower depths the pyroxenes displayed increasingly disequilibrated compositions to produce what Evans and Moore (1968) termed a "quench scatter". Coish and Taylor (1979) found a similar quench scatter in pyroxene compositions from throughout a 15.6m thick cooling unit in DSDP Leg 34 basalt, although Ti and Al were systematically higher in the pyroxenes from the flow margins. Most of the Myra and Tamworth basaltic cooling units from which pyroxenes were analysed are of the order of several tens of metres in thickness. Inasmuch as the results of the above studies may be applicable

to the Myra and Tamworth basaltic rocks, it is possible that epitelluric pyroxene crystallization in these rocks took place under disequilibrium conditions whether they show textural evidence of rapid crystallization or not.

Consequently, cooling rate is likely to have been a significant factor influencing the compositions of late stage overgrowths on intratelluric pyroxenes in the basaltic rocks examined. The extent to which cooling rate might have influenced pyroxene core-rim compositional trends in these rocks is discussed briefly below. This discussion also attempts to evaluate the extent to which some of these trends might also reflect the intrinsic magmatic affinities of the hosts.

Reconnaissance analyses suggest that the rims of pyroxene microphenocrysts in most of the extrusives closely match the compositions of the smaller coexisting subhedral groundmass pyroxenes. However, habits of the latter (i.e. largely stumpy prismatic) are quite distinct from the skeletal, plumose and spherulitic quench groundmass pyroxenes (see Section 3.3).

Quench pyroxenes in subalkaline basalts typically have anomalously high Cr, Ti and Al contents, and often have lower Ti/Al ratios than pyroxenes which crystallized from compositionally similar, more slowly cooled melts (Mevel and Velde, 1976; Coish and Taylor, 1979; Gamble and Taylor, 1980; Schiffman and Lofgren, 1982). Also, the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio in pyroxenes usually decreases as a function of increased cooling rate (Coish and Taylor, 1979), as does the Si content and the Ca value ($Ca = 100 \text{ Ca}/(\text{Ca}+\text{Mg}+\Sigma\text{Fe}+\text{Mn})$) (Boyd and Schairer, 1964; Muir and Tilley, 1964; Smith and Lindsley, 1971; Yamakawa, 1971; Evans and Moore, 1968; Baragar *et al.*, 1977; Schiffman and Lofgren, 1982).

Although the morphologies of late stage overgrowths forming the outer rims of pyroxenes in the Myra and Tamworth basaltic rocks are not typical of quench pyroxenes, the great variety of core-rim compositional trends displayed by pyroxenes from the various basaltic units (Table 3.1, Fig. 3.1) does suggest that the rims may have compositions which were dictated, to some extent, by slow diffusion in the liquid relative to the pyroxene growth rate (*cf.* Smith and Lindsley, 1971; Ewart, 1976).

The rims of pyroxenes in the Myra and Tamworth basaltic rocks are often depleted in Ca and Mg relative to their cores (Table 3.1, Fig. 3.1).

TABLE 3.1

Summary of core-rim compositional trends in Ca-rich pyroxenes from basaltic rocks of the Myra beds and Tamworth Belt.

	MYRA BEDS						TAMWORTH BELT					
	EXTRUSIVES (4)			INTRUSIVES (6)			EXTRUSIVES (13)			INTRUSIVES (10)		
	C > R	0	R > C	C > R	0	R > C	C > R	0	R > C	C > R	0	R > C
Si	75	-	25	50	17	33	38.5	-	61.5	50	10	40
Ti	0	-	100	17	-	83	23.1	30.8	46.1	40	10	50
Σ Al	25	25	50	50	-	50	61.5	-	38.5	70	-	30
Al ^{IV}	25	-	75	50	-	50	61.5	-	38.5	50	-	50
Al ^{VI}	75	-	25	50	17	33	61.5	-	38.5	30	30	40
Cr [*]	2/3			3/3			7/8			4/5		
Fe ³⁺	50	-	50	50	-	50	46.2	-	53.8	50	-	50
Σ Fe	0	-	100	0	-	100	30.8	7.7	61.5	10	-	90
Mn	25	-	75	17	-	83	30.8	15.4	53.8	10	10	80
Mg	100	-	0	100	-	0	69.2	-	30.8	80	10	10
Ca	100	-	0	67	-	33	53.8	-	46.2	70	10	20
Na	0	-	100	17	17	66	30.8	7.7	61.5	40	-	60

C > R Percentage of samples in which Ca-rich pyroxene cores are enriched in the element indicated relative to their rims.

0 Percentage of samples in which Ca-rich pyroxene cores have essentially the same content of the element indicated relative to their rims.

R > C Percentage of samples in which Ca-rich pyroxene cores are depleted in the element indicated relative to their rims.

Cr^{*} Proportion of samples with Ca-rich pyroxenes containing detectable Cr where Cr in the core exceeds that in the rim.

Fe³⁺ Calculated according to the charge balance method of Papike *et al.* (1974).

Although these trends might be interpreted to reflect tholeiitic affinities, numerous exceptions occur, especially among the basaltic extrusives of the Glen Ward beds. Thus some rims are enriched in Ca, some in Mg, and others in Ca and Mg relative to their respective cores.

Pyroxenes from two extrusives (070, 077) and a doleritic intrusive (068), all from the Glen Ward beds, display core-rim compositional trends of some magnitude which are sub-parallel to the Ca-Fe join in the pyroxene quadrilateral (Fig. 3.1). Substitution of Fe^{2+} for Ca at relatively constant Mg is a common feature of subalkaline pyroxenes which have crystallized under disequilibrium conditions induced by rapid cooling (Kuno, 1955; Muir and Tilley, 1964; Smith and Lindsley, 1971; Yamakawa, 1971; Mevel and Velde, 1976). Similarly, the increases in Ti and Al in the rims of pyroxenes from 068 and 070 are in accord with more rapid crystallization than the cores. Also, pyroxenes displaying Ca-Mg substitution at relatively constant Fe (e.g. Ui, 1981) have been interpreted as metastable phases resulting from rapid crystallization (e.g. Offler, 1979).

As outlined below, a wide variety of Ca-Mg-Fe-Ti-Al relations may in fact be produced in pyroxenes in response to disequilibrium crystallization and it is important that these constraints be taken into account when evaluating the magmatic affinities of their respective hosts.

Disequilibrium Crystallization Trends

Quench and metastable pyroxenes from MORB commonly show a broad scatter in $\text{Ca:Mg:Fe}'$ relations ranging from salite to Ca-poor augite (Bence *et al.*, 1974a,b; Kempe, 1974; Ayuso *et al.*, 1976; Mazzullo and Bence, 1976; Papike and White, 1979; Schweitzer *et al.*, 1979; Sigurdsson, 1981), even from within a single cooling unit (Coish and Taylor, 1979). Many of these compositions considerably overlap those of Ca-rich pyroxenes from alkaline rocks and, because orthopyroxene and/or pigeonite are exceedingly rare in MORB (e.g. Shibata, 1979) and ocean-floor doleritic rocks (e.g. le Roex and Dick, 1981), the true subalkaline character of these hosts might not be immediately apparent if magmatic affinities are based solely on pyroxene compositions.

Augites from the chilled margin of a thick (~90m) tholeiitic flow of Picture Gorge Basalt in Oregon are zoned from Fe-poor, Ca- and Al-rich

cores to Fe-rich rims with lower Ca and Al contents (Smith and Lindsley, 1971). Evans and Moore (1968) found a similar trend in augites from the Makaopuhi tholeiitic lava lake whose Cr, Al, Na and Fe contents decrease with decreasing Ca, Ti remaining constant. In contradistinction, Coish and Taylor (1979) found that Al and Ti are higher in augites from the chilled margin relative to the centre of a 15.6m thick cooling unit of MORB from DSDP Leg 34. The Ti and Al contents of pyroxenes in zones intermediate between the centre and margins overlap those of the latter zones and, overall, Ti decreases and Al increases with increasing $m\bar{x}$. There is almost complete overlap in $Ca:Mg:Fe'$ relations in the augites from both the interior and the margins of the flow, some of which are in fact salites (the characteristic pyroxenes in alkali basalts and related types).

Epitelluric rims of augite microphenocrysts from the chilled margin of the Tawhiroko tholeiitic dolerite in New Zealand have lower Al contents and higher Ti/Al ratios than the coexisting cores (Nakamura and Coombs, 1973). There is also a decrease in Fe in the rims of these augites leading to a trend of decreasing Al with decreasing Fe, the opposite to that observed by Ewart (1976) in quenched augites from Tongan basaltic andesites. On the other hand, there is no correlation between Al and Fe or Ca in quench pyroxenes from spilites of the French Alps (Mével and Velde, 1976). The trends of decreasing Al and increasing Ti/Al ratios in the epitelluric pyroxenes of the Tawhiroko dolerite, and of decreasing Al in the metastable augites of the Picture Gorge Basalt flow studied by Smith and Lindsley (1971) contrast with those in many rapidly quenched subalkaline basaltic melts (where Ti/Al ratios decrease and Al contents increase as a function of increasing cooling rate (e.g. Ewart, 1976; Mével and Velde, 1976; Coish and Taylor, 1979; Schiffman and Lofgren, 1982)).

These examples of diverse pyroxene compositional trends clearly indicate that care is necessary when comparing the Ca-Mg-Fe-Al-Ti relations of pyroxenes which have crystallized from rapidly cooled melts with those in rocks of similar bulk composition, but which might have experienced significant equilibrium crystallization prior to final quenching or rapid cooling. Most of the Myra and Tamworth Doleritic intrusives appear to be of this latter type, although many of the extrusives also show unusual pyroxene core-rim compositional relations. While it is possible, in most cases,

to develop feasible parageneses to explain most core-rim compositional variations in pyroxenes from each individual basaltic unit, the data available are too limited to evaluate in any detail the significance of possible compositional controls. Nevertheless petrographic and chemical (see Sections 3.3.2 and 3.5.5) similarities of the basaltic units in at least the Tamworth Belt are such that it is unlikely that the pyroxene core-rim compositional trends truly reflect a great diversity of crystallization conditions.

For the above reasons the following discussion of the compositional variations in pyroxenes from the Myra and Tamworth Belt basaltic rocks will be confined largely to the chemistry of the presumably intratelluric pyroxene cores. These are likely to have crystallized under conditions more closely approaching equilibrium than the rims, and consequently they should be more reliable indicators of the intrinsic magmatic affinities of their hosts. However, some other characteristics of these pyroxenes such as their calculated Fe^{3+} contents and $\text{Al}^{\text{IV}}\text{-Al}^{\text{VI}}$ relationships must be interpreted with caution. These are discussed in general terms below.

(2) Fe^{3+} Abundances

All analyses of pyroxenes reported in this study were determined by microprobe and hence analysed Fe^{3+} is unknown.

Most pyroxenes from basaltic rocks in the Myra beds, and all those from basaltic rocks in the Tamworth Belt, contain insufficient Al^{VI} , Ti^{4+} and Cr^{3+} in octahedral sites to maintain charge balance with $\text{Na}(\text{M2})$ and Al^{IV} (Fig. 3.2). It is likely that much of this apparent charge deficiency is eliminated by the presence of octahedral Fe^{3+} in these pyroxenes (*cf.* Campbell and Borley, 1974; Papike *et al.* 1974; Papike and White, 1979; Schweitzer *et al.* 1978, 1979; Cameron and Papike, 1981) but the charge balance may also be influenced by other species such as $(\text{OH})^-$ (Vieta, 1980).

The Fe^{3+} contents of all pyroxenes listed in Appendix E have been estimated following the charge balance method of Papike *et al.* (1974). This may be subject to significant errors (Schweitzer *et al.* 1978), especially at low levels of Fe^{3+} (Vieta and Hamm, 1978). However, it is preferable to recast microprobe analyses to incorporate estimates of Fe^{3+}

because the calculated $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios of pyroxenes are sensitive to their $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratios (i.e. $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ increases as $\text{Fe}^{3+}/\text{Fe}^{2+}$ increases).

Augite separates from Tamworth Group basaltic rocks in the Nundle area (Fe^{3+} determined by analysis; Vallance, 1969c, 1974a) are plotted in Fig. 3.2C. Those with low Al contents are markedly deficient in Fe^{3+} (analysed) to maintain charge balance, while those with high Al contain excess Fe^{3+} . Some of the charge deficiency in the former pyroxenes might be reduced if Cr^{3+} was known (not determined by Vallance 1969c, 1974). Because augites of comparable *mg* from similar rocks in this study are relatively Cr-poor (Fig. 3.11), the effect of Cr on charge balance would be negligible.

Discrepancies in charge balance are commonly seen when other pyroxenes (from the literature) for which Fe^{3+} has been determined are plotted on a basis of $(\text{Na} + \text{Al}^{\text{IV}})$ vs. $(\text{Al}^{\text{VI}} + 2\text{Ti} + \text{Cr} + \text{Fe}^{3+})$. While, in gross terms, charge balance is approximated in natural pyroxenes (see Fig. 28 of Cameron and Papike, 1981), the potential errors in Fe^{3+} estimation enable only the most qualitative observations of Fe^{3+} relations to be made. Also, the extent to which non-equilibrium crystallization might produce charge imbalances and pyroxene non-stoichiometry is as yet poorly known.

For these reasons the calculated Fe^{3+} contents of pyroxenes analysed in this study have not been unduly emphasized. Some general observations are nevertheless valid.

- (i) On a charge-balance diagram (Fig. 3.2) all pyroxenes from the Myra and Tamworth basaltic rocks plot within the field of MORB pyroxenes analysed by Schweitzer *et al.* (1978, 1979), see Fig. 3.2D. From this diagram it is also evident that some pyroxenes from other Tamworth Belt basaltic rocks are depleted in Al and Ti relative to those in MORBs (e.g. some from Tamworth Group doleritic intrusives; Offler, 1979) and others are enriched in Al and Ti (e.g. some from Tamworth Group extrusives Vallance 1969c, 1974a).
- (ii) Pyroxenes from basaltic rocks in the Woolomin beds (Offler, 1979) appear to be more Fe^{3+} -rich than those from basaltic rocks in the Myra beds. Augites in Myra *Type 3* basaltic extrusives appear to have

higher Fe^{3+} and $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratios (0.31) than the other types.

(iii) Pyroxenes from Tamworth Group basaltic extrusives in the Glenrock Station area (Offler, 1979) appear to be more Fe^{3+} -rich than those with comparable *mg* from basaltic rocks elsewhere in the Tamworth Belt.

(iv) There is little consistency in the apparent Fe^{3+} core-rim compositional trends in the pyroxenes analysed (see Table 3.1, Fig. 3.2).

(3) $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ Relations

Pyroxenes which have crystallized from basaltic melts at elevated pressures commonly have lower $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios than those crystallizing from similar melts at lower pressures (Wass, 1979). To some extent the $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios are also dependent on host melt compositions. Of potential importance in this regard are:

- (i) $\text{Al}-\text{Fe}^{3+}$ substitution, which is largely influenced by oxygen fugacity (Cameron and Papike, 1981).
- (ii) $\text{Ti}-\text{Al}^{\text{IV}}$ substitution, which is influenced by the silica activity of the melt (Verhoogen, 1962), the order of crystallization of plagioclase and pyroxene (Barberi *et al.* 1971), the degree of fractionation of the melt (Wass, 1979) and the rate at which the pyroxene crystallized (e.g. Mevel and Velde, 1976; Schiffman and Lofgren, 1982).
- (iii) The proportions of minor components (e.g. Na, Cr, Ti) in the host melt (Wass, 1979).

Few experimental data are available on which to base quantitative assessments of the influence of factors other than pressure on the $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratio in pyroxenes. On the basis of empirical observations Wass (1979) suggests that, at the present level of understanding, evaluations of the relative pressures of crystallization of different pyroxenes on the basis of their $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios should be restricted to those occurring within a given basaltic host. However, this assertion implies that, within

given basaltic host, pyroxenes with differing $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios may well reflect a polybaric pyroxene crystallization history for that host. In view of other possible (but largely unquantified) influences on pyroxene $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios outlined above, such interpretations must be made with extreme caution, especially for pyroxenes which might have crystallized at pressures less than ~8-10 kb. This is illustrated by the diversity of $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios displayed by Ca-rich pyroxenes from some layered intrusions (Table 3.2).

Crystallization of Ca-rich pyroxene in many (if not most) of the ultramafic-mafic intrusions listed in Table 3.2 typically began following emplacement and proceeded at relatively constant load pressures. Apparently, pressure was not the most important factor influencing the $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios in these pyroxenes, nor is there a significant correlation between pyroxene Fe-enrichment and $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios. Indeed, many Ca-rich pyroxenes in some low-pressure intrusives have comparable or lower $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios than some in the higher-pressure examples. These preliminary data (Table 3.2) suggest that the relative pressures of crystallization of intrusives with chemically similar parental magmas and crystallization histories might be indicated by the maximum $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios attained by their respective Ca-rich pyroxenes. The validity of this proposal depends on the acquisition of more experimental and other data.

Hence, the following evaluation of the $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios in Ca-rich pyroxenes from basaltic rocks in the Myra beds and Tamworth Belt, and in members of the PBOC (Chapters 7-9) has been restricted to qualitative observations only.

$\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ Relations in Myra and Tamworth Ca-rich Pyroxenes

Endiopside phenocrysts in one basaltic extrusive in the Glen Ward beds (077) have relatively low $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios (1.88) which, when compared with the experimental data of Thompson (1974) for transitional and subalkaline basaltic compositions, might suggest crystallization at pressures of the order of 10 kb. As might be expected (*cf.* Wass, 1979), augite microphenocrysts coexisting with these endiopsides have significantly lower $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios. However, many pyroxene rims in the basaltic rocks studied have $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios similar to, or greater than,

TABLE 3.2

Ranges of $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios displayed by Ca-rich pyroxenes from some ultramafic-mafic and mafic intrusions.

P (load)	INTRUSION	$\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ (cpx)	SOURCE
<1-2 kb	Palisades Sill	>3*	Walker <i>et al.</i> (1973)
	Kap Edvard Holm	3-10	Elsdon (1971) Deer and Abbot (1965)
	Rhum	~2.8-3.3	Dunham and Wadsworth (1978)
	Skaergaard	2.5-7.8	Brown (1957)
	Eulogie Park	2.2-3.2	Wilson and Mathison (1968)
	Beaver Bay	2-19	Konda (1970)
	Bushveld	1.9-3.5*	Atkins (1969)
	Salt Lick Creek	1.2-1.6	Wilkinson <i>et al.</i> (1975)
	Jimberlana	1-10.6*	Campbell and Borley (1974)
	Dufek	1-7*	Himmelberg and Ford (1976)
5-6 kb	Fongen-Hyllingen	~5	Wilson <i>et al.</i> (1981)
?	Canyon Mountain (ophiolitic gabbro)	1.8-2.7	Himmelberg and Loney (1980)
10-12 kb	Giles Complex	Ewarra ~2	Moore (1971) Goode and Moore (1975)
		Kalka 2-4	
		Gosse Pile 0.5-2.8	
		Mt. Davies 0.5-1.2	
16 kb	Feragen Ultramafic Cumulates	1.0-1.4	Moore and Hultin (1980)

* Some relatively Fe-rich pyroxenes contain no Al^{VI} .

P (load) = pressure at which intrusion crystallized.

those of the coexisting cores (Fig. 3.3). It is most unlikely that these rims crystallized at higher pressures than the cores and their higher $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios most probably reflect disequilibrium partitioning of Al into the pyroxene during relatively rapid crystallization.

If the $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios of the cores of pyroxenes in the Myra and Tamworth basaltic rocks approximate equilibrium values, then they provide some evidence for intratelluric pyroxene crystallization at various pressures during the ascent of these magmas. There is also a rapid decrease in Al^{VI} with decreasing mg in pyroxenes from basaltic extrusives in the Myra beds and Glen Ward beds (Fig. 3.10). This might suggest that rather limited fractionation of pyroxene took place in these rocks at elevated pressures, although the possible influence of changing melt composition on the Al^{VI} content of these pyroxenes should not be overlooked. Inasmuch as the experimental data of Thompson (1974) is applicable, it would appear that pyroxenes in most of these rocks began to crystallize at pressures considerably lower than 10 kb.

Pyroxenes from Woolomin Association and Tamworth Group basaltic rocks in the Glenrock Station area contain little or no Al^{VI} (Offler, 1979), especially if their analyses are recast to include an estimate of Fe^{3+} . This is also true of some pyroxenes in basaltic rocks of the Woolomin Association and Tamworth Belt elsewhere (Fig. 3.3). Presumably these pyroxenes crystallized largely at shallow depths of emplacement. It is not known why basaltic rocks from the Glenrock Station are apparently devoid of pyroxenes containing significant Al^{VI} (i.e. intratelluric pyroxenes?) while pyroxenes in similar basaltic rocks elsewhere in the Woolomin Association contain moderate Al^{VI} . Pyroxenes from Tamworth Group basaltic rocks in the Nundle area (Vallance, 1969c, 1974a) have higher $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios than those from the Morrisons Gap area (Fig. 3.3C), although the Nundle bulk pyroxene separates with high ΣAl (and highest $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios) may include some pyroxene of quench composition (see Section 3.2.1.4).

3.4.1.4 Woolomin Association

(1) Previous Work

Only limited information is currently available on the chemistry of pyroxenes from basaltic rocks in the Woolomin Association. Offler

(1979) published chemical data for Ca-rich pyroxenes from five basaltic extrusives and one doleritic intrusive in the Woolomin beds in the Glenrock Station area. Pyroxenes from the extrusives range in composition from endiopside ($\sim Ca_{40}Mg_{52}Fe'_{8}$) to augite ($\sim Ca_{37}Mg_{35}Fe'_{28}$). Overall, the chemistry of these pyroxenes suggests that their hosts have tholeiitic or at least subalkaline affinities. Ca-rich pyroxenes from the doleritic intrusive, however, are aluminous titansalites ($\sim Ca_{48}Mg_{37}Fe'_{15}$, 4.23% TiO_2 , 6.52% Al_2O_3) and provide strong evidence for the alkaline affinities of their host.

On the basis of whole-rock and relict pyroxene chemistry Cawood (1980) recognized two groups of basaltic rocks in the Woolomin beds in the Nundle-Attunga area. One group is distinctly tholeiitic in character; the other is distinctly alkaline. Data available on pyroxenes in these rocks are limited to an average analysis for eight samples, all evidently from the tholeiitic group (Cawood, 1982b). Cawood (1982b) recorded relatively low standard deviations for ΣFeO and MgO (2.51% and 0.89% respectively) in these Woolomin pyroxenes, suggesting that they are largely endiopsides and magnesian augites (refer Table E-6).

Throughout the Woolomin beds generally, Herbert (1978, 1981, 1982) recognized two tholeiitic groups of basaltic rocks and also a high-alumina basaltic suite with transitional-to alkaline affinities. He found that "relict clinopyroxenes have recorded in their chemistry the parentage and evolutionary history of the host rocks" (Herbert, 1982). However, these pyroxene compositional data are as yet unavailable for detailed comparison with those presented here.

(2) Myra beds

The following constitutes the first investigation of the chemistry of pyroxenes from basaltic rocks in the Myra beds. Throughout this discussion the reader should bear in mind that the Woolomin beds and Myra beds constitute parts of the same tectonostratigraphic unit, the Woolomin Association, and that basaltic rocks in this association might have many diverse origins (see Sections 1.2.1 and 3.1.1).

Representative analyses of Ca-rich pyroxenes from five basaltic extrusives and six basaltic intrusives from the Myra beds in the Pigna

Barney - Curricabark area are listed in Table E-6 and E-7 respectively (Appendix E). Pyroxenes from all three petrographic types (see Section 3.3.1) are represented although, as previously mentioned, no *Type 3* doleritic intrusives have been found.

Samples of the extrusives are from massive flows or, where field relations are equivocal, inferred massive flows (e.g. 209). The intrusives sampled appear to be sill-like, although outcrop is generally poor and contact relations are often equivocal (see Section 3.2.1). Sample 215 was collected from the central portion of a 30m thick sill(?) with sheared contacts. All *Type 2* samples are from locality 3.5 (Map 3). Grid references for these sample localities are listed in Appendix K.

Pyroxenes from *Type 1*, *Type 2* and *Type 3* basaltic rocks are referred to as *Type 1*, *Type 2* and *Type 3* pyroxenes respectively. Within the constraints imposed by the number of samples available for study the following discussion attempts (in part, and with limited success) to discriminate between the three basaltic types on the basis of their pyroxene compositions.

Ca-rich pyroxenes in *Type 1* doleritic intrusives have considerably lower *mg* values than those analysed from *Type 2* doleritic intrusives. Consequently, until it can be established that this difference between the two basaltic types is not simply the result of non-representative sampling, it is possible that other differences in the chemistry of the pyroxenes might simply reflect different evolutionary stages of the respective melts.

Almost all pyroxenes from basaltic rocks in the Myra beds are *hy*-normative (the only exceptions being several spurious rim analyses which are not presented in Tables E-6 and E-7) and plot within, or close to, the field for Ca-rich pyroxenes from tholeiitic hosts on the diopside-olivine-silica diagram (Fig. 3.4) of Coombs (1963). Some other features of their chemistry suggest that most of these pyroxenes crystallized from basaltic magmas which were not notably saturated (i.e. approach compositions where $ol = 0$ and $qz = 0$).

(i) Ca:Mg:Fe' Relations

Extrusives

All pyroxene microphenocrysts from basaltic extrusives in the

Myra beds are augites. These have Fe-enriched rims^{*} (Fig. 3.1A) which, with the exception of those from sample 207, are also depleted in Ca. *Type 1* and *Type 3* pyroxenes are depleted in Ca. In this respect the latter resemble some of the least calcic augites from basaltic extrusives in the Glen Ward beds (Fig. 3.1C), those from samples 1856 and 7003 in the Woolomin beds in the Glenrock Station area (Offler, 1979), and those analysed by Cawood (1980, 1982b) from basaltic rocks in the Woolomin beds north of Nundle. They are, however, somewhat more calcic than the representative MORB pyroxenes selected by Schweitzer *et al.* (1978, 1979) and the field for quench pyroxenes in the Makaopuhi lava lake (Evans and Moore, 1968).

Type 1 and *Type 3* pyroxenes have lower *Ca* values than the most calcic pyroxenes from the Tamworth Belt basaltic rocks but fall within the field for pyroxenes from mildly alkaline intrusives in the Crescent Formation, Washington (Glassley, 1974) (Fig. 3.1). This field also resembles that for pyroxenes from the central portion of the Picture Gorge basalt (Smith and Lindsley, 1971) although the latter pyroxenes do not display compositions as Fe-poor as the *Type 1* augites. *Type 1* augites do not have counterparts among those from the Woolomin beds analysed by Offler (1979). *Type 1* and *Type 2* augites have $\text{Ca}+\text{Na}+\text{K}:\text{Mg}:\text{Fe}'$ ratios typical of Ca-rich pyroxenes from subalkaline hosts (LeBas, 1962; see Fig. 3.5A) and fall within the range of compositions of augites from the Tawhiroko tholeiitic dolerite, New Zealand (Nakamura and Coombs, 1973). *Type 3* are more calcic than the latter and have $\text{Ca}+\text{Na}+\text{K}:\text{Mg}:\text{Fe}'$ ratios intermediate between those characteristic of alkaline hosts and those with subalkaline hosts (LeBas, 1962; see Fig. 3.5).

Intrusives

Pyroxenes from *Type 1* doleritic intrusives cluster near the diopside corner of the pyroxene quadrilateral and range in composition from endiopside ($\sim\text{Ca}_{44.5}\text{Mg}_{47}\text{Fe}'_{8.5}$) to calcic augite ($\sim\text{Ca}_{43.5}\text{Mg}_{43}\text{Fe}'_{13.5}$). With the exception of sample 211, they are zoned to more Fe-rich rim compositions which generally have slightly lower *Ca* values (Fig. 3.1B). *Type 2* pyroxenes are significantly enriched in Fe relative to *Type 1*

* The rims of pyroxene microphenocrysts in sample 240 were not analysed.

and they are also more Fe- and Ca-rich than *Type 2* pyroxenes in the extrusives.

Overall, the pyroxenes in the Myra doleritic intrusives display a general trend of gradually decreasing Ca with Fe-enrichment. This trend resembles that of *Type 1* and *Type 3* augites from the basaltic extrusives, although pyroxenes in the doleritic intrusives display a greater range in Fe' . Consequently, the latter are also comparable with augites from the Picture Gorge Basalt (Smith and Lindsley, 1971) and mildly alkaline intrusives in the Crescent Formation, Washington (Glassley, 1974). In addition, the slightly more Ca-rich trend of most pyroxenes from *Type 1* doleritic intrusives is similar to that of augites from an alkali basalt - trachyte association on Gough Island (Le Maitre, 1962) (see Fig. 3.1B). The latter differ, however, in that they become markedly richer in alkalis, TiO_2 and Al_2O_3 with increasing Fe' than those from the *Type 1* doleritic intrusives.

Despite their relatively high Ca, all pyroxenes from *Type 1* doleritic intrusives plot within the field for Ca-rich pyroxenes from subalkaline hosts on the Ca+Na+K:Mg:Fe' diagram (Fig. 3.5A) of LeBas (1962). Augites from *Type 2* doleritic intrusives have $Fe' > 18$ and consequently their magmatic affinities are not reliably inferred from their Ca+Na+K:Mg:Fe' ratios.

The relatively high volatile content of *Type 3* extrusives (see Sections 3.2.1, 3.3.1) is reflected in the high Fe^{3+}/Fe^{2+} ratio (0.31) of the *Type 3* pyroxenes compared with the other types (see Table E-6). However this, and other differences in chemistry between *Type 3* pyroxenes and the other types might reflect the significantly lower *mg* of the former rather than fundamental chemical differences in the host basaltic types.

(ii) Si-Al-Ti Relations

Extrusives

Cores of Ca-rich pyroxene microphenocrysts from basaltic extrusives in the Myra beds contain 50-51.5% SiO_2 , 0.5-1.3% TiO_2 and 3-6% Al_2O_3 . Inasmuch as the few analyses available reflect the true compositional variations in pyroxenes from the various basaltic types; *Type 2* pyroxenes

have higher average SiO_2 , and *Type 1* have higher average Al_2O_3 , than the other types. All except sample 201 plot within the field of LeBas (1962) for Ca-rich pyroxenes from subalkaline hosts on a SiO_2 vs. Al_2O_3 diagram, as do most of the Woolomin pyroxenes analysed by Offler (1979) and (presumably) those analysed by Cawood (1982b) (see Fig. 3.6A). In general, pyroxenes from Woolomin basaltic extrusives in the Glenrock Station area (Offler, 1979) contain less Al_2O_3 (Fig. 3.6A) and TiO_2 (Figs. 3.7A, 3.8) than those from the Nundle-Attunga area (Cawood, 1982b) and from the Myra beds. These pyroxenes from the Glenrock area also contain little or no Al^{VI} , in contrast to the majority of those from basaltic extrusives in the other two areas in the Woolomin Association.

The Ti/Al ratios of pyroxenes from basaltic extrusives in the Myra beds range from 0.11-0.15 in *Type 1* and *Type 2* rocks, to 0.24 in *Type 3*. Those from Woolomin basaltic rocks in the Glenrock Station area display a much wider range of Ti/Al ratios (0-0.5, see Fig. 3.7A). All the rims of *Type 1* and *Type 2* pyroxenes have higher Ti contents and higher Ti/Al ratios and most have higher $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios than their respective cores (Fig. 3.7A). The overall core-rim compositional trends (Table 3.1) and (especially) the Ti-Al relationships of *Type 1* and *Type 2* pyroxene microphenocrysts (Fig. 3.7A) suggest that these might have crystallized under conditions more closely approaching equilibrium* than those in basaltic extrusives in the Glen Ward beds (see Section 3.4.1.3, Part (1)). If this was so, then it would appear that the Ti and Fe contents of residual liquids were increasing during the latter stages of pyroxene crystallization. This is in accord with petrographic evidence for the late-stage crystallization of Fe-Ti oxides (see Section 3.3.1). There is also a well-developed trend of decreasing Al with decreasing *mg* in the *Type 1* and *Type 2* pyroxene rims (Table E-6) which might suggest that residual liquids were depleted in Al following crystallization of plagioclase.

Intrusives

Ca-rich pyroxenes analysed from *Type 1* doleritic intrusives generally contain less SiO_2 (49.5-50.0%), less Al_2O_3 (2.9-3.4%) and more

* This is significant in that it suggests that the lower *Ca* of *Type 2* pyroxene microphenocrysts relative to *Types 1* and *3* is not simply a reflection of metastable crystallization of the former.

TiO₂ (1.30-1.45) than those from *Type 2* doleritic intrusives (*viz.* SiO₂, 50-53%; Al₂O₃, 3-5%; TiO₂, 0.4-1.4%). The *Type 2* pyroxenes with the lowest SiO₂/Al₂O₃ ratios (212, 213) plot marginally within the field for Ca-rich pyroxenes from alkaline hosts on a SiO₂ vs. Al₂O₃ diagram (Fig. 3.6A, see LeBas, 1962). The remaining two *Type 2* pyroxenes plot well within the field for Ca-rich pyroxenes from subalkaline hosts. *Type 1* pyroxenes have $Fe' > 18$ and are not reliably characterized by this plot (LeBas, 1962).

The rims of *Type 1* pyroxenes are enriched in SiO₂ and depleted in Al₂O₃ relative to the cores. The rims of *Type 2* pyroxenes are depleted in SiO₂ or have similar SiO₂ content to their cores, but the behaviour of Al₂O₃ is variable (Fig. 3.6A). On the other hand, TiO₂ is enriched in the rims of all *Type 2* pyroxenes but shows both enrichment and depletion in the rims of *Type 1* pyroxenes. The Ti/Al ratios of the cores of *Type 1* pyroxenes (0.27-0.29) are significantly higher than those of *Type 2* pyroxene cores (0.1-0.18). Overall then, the pyroxenes in the Myra doleritic intrusives display a greater range in Ti/Al ratios than the associated extrusives (Fig. 3.7A). With a few exceptions (212 and 209) they also contain less Al^{VI} and have higher Al^{IV}/Al^{VI} ratios than pyroxenes in the *Type 1* and *Type 2* extrusives (Fig. 3.3A). This might suggest that intratelluric pyroxenes in the extrusives preserved their initial Al^{IV}/Al^{VI} ratios during rapid cooling while those in the more slowly cooled doleritic intrusives experienced partial re-equilibration at the relatively low pressures of emplacement.

(iii) Minor Components

Extrusives

Ca-rich pyroxene microphenocrysts from the three basaltic types in the Myra beds and those analysed from basaltic rocks in the Woolomin beds by Cawood (1982b) have broadly similar MnO (<0.32%), Na₂O (<0.5%) and Cr₂O₃ (<0.4%) contents (Table E-6). However, Na₂O was below the microprobe detection limit in those from the Glenrock Station area (Offler, 1979). Because low levels of Na are difficult to analyse by microprobe, and Offler (1979) did not detect Na in salites (which might be expected to have relatively high Na₂O) from the alkaline doleritic unit in the Glenrock Station area (sample 1857 of Offler, 1979) the

apparent lack of Na_2O in Glenrock pyroxenes might simply reflect analytical constraints.

Some of the Glenrock pyroxene microphenocrysts contain significantly more Cr_2O_3 (up to an unusually high value of 1.17%; Offler, 1979) than those of similar *mg* from basaltic extrusives in the Myra beds (Fig. 3.13).

Intrusives

On average, Ca-rich pyroxenes from *Type 1* intrusives contain less Cr_2O_3 and more Na_2O and MnO than those from *Type 2* intrusives (see Table E-7). This might simply reflect the lower *mg* values of the former because Cr_2O_3 typically decreases and Na_2O and MnO typically increase with Fe-enrichment in pyroxenes (e.g. Deer *et al.*, 1978; see also Fig. 3.13). Indeed, the Fe-rich rim of the *Type 2* pyroxene (213) contains more MnO and comparable Na_2O to the *Type 1* pyroxenes. With the exception of the relatively high Cr_2O_3 in sample 210 (0.84%) and relatively high Na_2O in the rim of sample 201 (0.56%) the minor element contents of all pyroxenes from basaltic extrusives and intrusives in the Myra beds are within the following limits: $\text{Cr}_2\text{O}_3 < 0.5\%$, $\text{MnO} < 0.4\%$, $\text{Na}_2\text{O} < 0.45\%$.

(iv) Magmatic Affinities

As noted in the preceding discussion, the $\text{Ca:Mg:Fe}'$, $\text{Ca+Na+K:Mg:Fe}'$, $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios and *hy*-normative chemistry of Ca-rich pyroxenes from basaltic extrusives and intrusives in the Myra beds suggest that these rocks are largely subalkaline or transitional to mildly alkaline in character. Of these, pyroxenes in the *Type 2* extrusives display the more convincing subalkaline characteristics and might not be closely related to *Type 2* intrusives.

The overall Fe-enrichment trend of Myra pyroxenes (other than those from *Type 2* extrusives; Fig. 3.1A,B), is comparable to those of pyroxenes: (i) from the upper-central part of a thick flow unit of the Picture Gorge Basalt (Smith and Lindsley, 1971); (ii) from minor mildly alkaline intrusives in the Crescent Formation; (iii) from transitional to mildly alkaline extrusives in the Hawaiian islands (Beeson, 1976), Washington (Glassley, 1974); (iv) and from a strongly alkaline basalt-

trachyte series from Gough Island (Le Maitre, 1962). These rocks originated in diverse tectonic environments (as outlined below) and illustrate some inherent shortcomings in the use of Fe-enrichment trends in Ca-rich pyroxenes to evaluate the magmatic affinities of basaltic rocks (see Bevins, 1982; and Section 3.4.1.1).

The Picture Gorge Basalt is one of the oldest members of the Columbia River Province of continental flood basalts in Oregon and Washington (U.S.A.) (Swanson *et al.*, 1979). These basalts display a limited range in composition from slightly undersaturated to just-saturated tholeiites (Waters, 1961; Hyndman, 1972; Wright *et al.*, 1973; Nathan and Fruchter, 1974; McDougall, 1976).

Basaltic rocks of the Crescent Formation have been assigned to a variety of tectonic environments. These include:

- (i) Combined MORB and Hawaiian-type hot-spot volcanism (Glassley, 1974; Cady, 1975).
- (ii) Combined non-hot-spot intraplate seamount and Hawaiian-type hot-spot volcanism (Glassley, 1976).
- (iii) Iceland ridge-island volcanism (Muller, 1980).

The Hawaiian and Gough Island basaltic rocks are products of within-plate oceanic, and Mid-Ocean Ridge-crest hot-spot volcanism respectively.

Clearly, the Fe-enrichment trends of Myra Ca-rich pyroxenes are not diagnostic of a particular tectonic environment, although transitional basaltic rocks with comparable pyroxene Fe-enrichment trends appear to be more common in intraplate settings. Indeed, with the exception of those in *Type 2* extrusives, the Myra pyroxenes are more Ca-rich than those in most MORB's (with some exceptions, e.g. Ayuso *et al.*, 1976; Dick *et al.*, 1980).

Nevertheless, most of the Myra pyroxenes plot within the joint field for Ca-rich pyroxenes from VAB (Volcanic-Arc Basalts) and MORB on the $F_1:F_2$ discriminant plot (Fig. 3.14A) of Nisbet and Pearce (1977), while pyroxenes from two *Type 1* basaltic units plot slightly within the MORB + WPT (Within-Plate Tholeiite) field. By comparison, pyroxenes from Woolomin basaltic extrusives (Offler, 1979) plot more towards the VAB field than most Myra pyroxenes, and the average Woolomin Ca-rich pyroxene

of Cawood (1982b; see Table E-6) plots more towards the MORB + WPT field (Fig. 3.14A). As might be expected, titansalites from one Woolomin doleritic intrusive in the Glenrock Station area (Offler, 1979) plot well within the WPA (Within-Plate Alkaline) field on this diagram (Fig. 3.14A).

From a data base of 706 Ca-rich pyroxene analyses Leterrier *et al.* (1982) devised a series of empirical chemical variation diagrams (Ti:Ca+Na, Ti+Cr:Ca, Ti:Al) which, to some extent, may be used to discriminate between Ca-rich pyroxene phenocrysts from basalts (and basaltic andesites) of different magmatic affinities. When examined in sequence, these diagrams may discriminate between Ca-rich pyroxenes from: (i) Alkaline (WPA) and subalkaline hosts (Ti:Ca+Na); (ii) Non-orogenic (MORB, WPT) and orogenic (IAT, SHO (shoshonites), CAB) basalts (Ti+Cr:Ca); and (iii) IAT and CAB (Ti:Al). Of these, only the Ti:Ca+Na and the Ti+Cr:Ca diagrams are relevant to the Myra pyroxenes (see below).

(i) Ti:Ca+Na Diagram (Fig. 3.8)

Pyroxenes from all Myra basaltic rocks, and almost all those from basaltic rocks in the Woolomin beds, plot within the designated field for Ca-rich pyroxenes from subalkaline hosts. However, except for those in one *Type 2* extrusive (207), all Myra pyroxenes plot within the area of compositional overlap between pyroxenes from subalkaline and alkaline hosts. This suggests that most Myra pyroxenes crystallized from tholeiitic to transitional basaltic hosts, thus reinforcing conclusions based on other previously cited chemical characteristics. By virtue of their comparatively low Ti contents, most Ca-rich pyroxenes from Woolomin basaltic rocks in the Glenrock Station area (Offler, 1979) plot well within the subalkaline field on this diagram; while those from at least two basaltic units (samples 9262 and 1857 of Offler, 1979) plot within the alkaline field. Cawood's (1982b) average Ca-rich pyroxene from Woolomin basaltic rocks plots in a position more or less intermediate between the Myra and Glenrock pyroxenes.

(ii) Ti+Cr:Na Diagram (Fig. 3.9)

Most Ca-rich pyroxenes from Myra basaltic rocks plot well within the designated field for Ca-rich pyroxenes from non-orogenic basaltic hosts, and all fall within, or very close to, the total range of chemical variation in pyroxenes from non-orogenic basaltic hosts. The Ti:Ca

relations of Cawood's (1982b) average Woolomin Ca-rich pyroxene also suggest that Woolomin basaltic rocks in the Nundle-Attunga area have non-orogenic affinities, especially as these Woolomin pyroxenes are likely to contain significant Cr (since their chemistry is otherwise comparable to some Cr-bearing pyroxenes from basaltic units elsewhere in the Woolomin Association; *cf.* Table E-6, and Offler, 1979).

In this diagram the Glenrock pyroxenes plot largely within the field for Ca-rich pyroxenes from orogenic basaltic hosts. The Ti:Al diagram (Fig. 3.7) suggests that the Woolomin basaltic rocks examined by Offler (1979) might have affinities with IAT. Indeed, it is largely because of their low Ti contents that pyroxenes from these rocks also plot within or close to the field for Ca-rich pyroxenes from VAB in the $F_1:F_2$ discriminatory plot (Fig. 3.14A) of Nisbet and Pearce (1977). They also contain very little Na_2O (this may only be apparent due to analytical constraints, R. Offler pers. comm. 1982), and have $\text{TiO}_2:\text{MnO}$ ratios typical of pyroxenes from MORB but approaching those of Na-poor Ca-rich pyroxenes from VAP ($\text{TiO}_2:\text{MnO} < 1$, see Fig. 3.15). The possibility that these Woolomin basaltic rocks are in fact IAT is discussed further in Section 3.6.1 and Chapter 7.

The Na_2O and MnO contents of the Ca-rich pyroxenes in several Myra basaltic rocks (207, 210, 211) are below the detection limit ($\sim 0.1\%$) of the microprobe. Also, the low Na_2O and MnO values listed for pyroxenes from sample 213 (Table E-7) are probably unreliable (Na, mean = 0.11, standard deviation = 0.19; MnO, mean = 0.13, standard deviation = 0.15). When plotted in the $\text{Na}_2\text{O}:\text{TiO}_2:\text{MnO}$ discriminant diagram (Fig. 3.15A) of Nisbet and Pearce (1977), the remainder cluster in and adjacent to the MORB field (*Type 1* and *Type 3*) and along the $\text{TiO}_2\text{-Na}_2\text{O}$ join in the WPA field (*Type 1* and *Type 2*). This suggestion that the latter pyroxenes (from samples 201, 208, 212) have WPA affinities (largely a function of their low MnO contents ($< 0.1\%$)) is at variance with their other, potentially more diagnostic, chemical characteristics (see Figs. 3.4, 3.5, 3.6A, 3.8, 3.14A). Consequently, it would appear that the $\text{Na}_2\text{O}:\text{TiO}_2:\text{MnO}$ diagram may not always rigorously distinguish pyroxenes in alkaline hosts from those in subalkaline or transitional hosts. Indeed, the use of this diagram often leads to ambiguous diagnoses of the tectonic setting and magmatic affinities of ancient basaltic rocks (for example, see Capedri and

Venturelli, 1979; Capedri *et al.*, 1979; Pallister and Hopson, 1981), and it is commonly ignored by workers utilizing relict pyroxene chemistry to evaluate the magmatic affinities and palaeotectonic setting of ancient basaltic rocks (e.g. Searle *et al.*, 1980; Wark and Clarke, 1980; Beddoe-Stephens and Lambert, 1981; Pe-Piper, 1982).

3.4.1.5 Tamworth Belt

(1) Previous Work

Vallance (1969c, 1974a) analysed clinopyroxenes separated from six non-pillowed basaltic units from the Tamworth Group near Nundle. These are all augites with restricted variation in bulk *mg* (71.4 to 62.9) and Ti (0.86-1.30 wt.% TiO₂), and relatively high but variable Al (9.32-3.19 wt.% Al₂O₃).

Offler (1979) analysed clinopyroxenes by microprobe from basaltic rocks of the Tamworth Group in the Glenrock Station area. These pyroxenes, typically augites, exhibit a wider range in *mg* (approx. 80-60) and extend to more magnesian compositions than those reported from Nundle (Vallance, 1969c, 1974). However, as Vallance's analyses represent bulk compositions, these differences between the Nundle and Glenrock augites may be more apparent than real. Augites from the Glenrock Station area also display a broad range in *Ca* values (approx. 45-35 in the basaltic extrusives and 45-38 in the basaltic intrusives). On the basis of relict pyroxene compositions and some unpublished whole-rock chemistry, Vallance (1969c, 1974a) and Offler (1979) concluded that the Tamworth Group basaltic rocks are predominantly tholeiitic, with some transitional to slightly alkaline types. These conclusions are largely reinforced by this study, although basaltic rocks with demonstrably alkaline affinities appear to be confined to the Glenrock Station area (e.g. sample 9248B of Offler, 1979).

Practically all the Ca-rich pyroxenes analysed from the Tamworth Belt basaltic rocks are significantly *hy*-normative and hence plot within, or close to, the field for Ca-rich pyroxenes from tholeiitic hosts in the *di-ol-qz* projection (Fig. 3.4; Coombs, 1963). Some other chemical characteristics of these pyroxenes and their implications for the magmatic affinities of their hosts, are discussed below.

(2) Glen Ward Beds

Representative analyses of Ca-rich pyroxenes from nine basaltic extrusives and seven doleritic intrusives from the Glen Ward beds are listed in Tables E-2 and E-3 respectively (Appendix E). Samples of extrusives are from massive flows (066, 077, 084), pillowed flows (067, 069, 071, 073) and flow breccias (070, 072). The intrusives sampled are all sill-like units which range in thickness from approximately 5 metres (063) to several hundred metres (068). Grid references for these sample localities are listed in Appendix K.

(i) Ca:Mg:Fe' Relations

Extrusives

All pyroxene microphenocrysts from basaltic extrusives in the Glen Ward beds are augites which display a lesser degree of Fe-enrichment (Fe' 10.6-20.5) than those from Tamworth Group extrusives in the Glenrock Station area. Ca displays a similar broad range (Fig. 3.1C) in pyroxenes from both areas. As argued earlier, the diverse compositional zoning trends in especially the Glen Ward augites suggests that most of their rims are metastable products of rapid cooling. Consequently, the following discussion is largely restricted to core compositions.

In addition to possessing the most magnesian augite microphenocrysts found in the Tamworth Belt extrusives, sample 077 also contains phenocrysts (1-2 mm euhedra) of endiopside ($Ca_{44}Mg_{47}Fe'_9$). These exhibit weak normal zoning and are sometimes slightly resorbed. Some display subophitic relationships with similarly-sized albitized plagioclase. Similar endiopside characterizes one of the doleritic intrusives (074) in the Glen Ward beds suggesting a possible genetic relationship between these two units.

Augite microphenocryst cores from the Glen Ward basaltic extrusives display an overall ill-defined trend of Ca-depletion with Fe' -enrichment. Sample 072 contains relatively calcic augites compared to those with similar Fe' values in other samples (Fig. 3.1C), and lies close to the subalkaline-alkaline boundary of LeBas (1962) (Fig. 3.5B). On the other hand, augite from sample 071 is considerably less calcic than others from Glen Ward basaltic extrusives and plots close to the generalized quench trend for augites from the Makaopuhi Lava Lake (Evans and Moore, 1968).

This might suggest that the augite microphenocrysts in sample 071 crystallized metastably during rapid cooling of the host. However, it is noteworthy that the outer rims of these microphenocrysts, which presumably crystallized under conditions of greater undercooling than the cores, are considerably more calcic than the latter (Fig. 3.1C). Augites from other samples plotted in Figure 3.1 show similar core-rim compositional relations and reinforce earlier comments (Section 3.4.1.3, Part (1)) on the limitations of Ca depletion as a reliable indicator of rapid crystallization. In other respects, the augite microphenocrysts in sample 071 are not atypical of those in the majority of Glen Ward basaltic extrusives.

With the exception of sample 071, all representative augite microphenocrysts from basaltic extrusives in the Glen Ward beds plot close to, or at more Ca -rich compositions than the iron-enrichment trend of augites from the Skaergaard intrusion (Brown, 1957) and the trend of representative augites from MORBs (Schweitzer *et al.*, 1979; Fig. 3.1C). As such, they plot at compositions intermediate between those of typical tholeiites and those of transitional or slightly alkaline rocks such as the Picture Gorge Basalt (Smith and Lindsley, 1971); mildly alkaline basaltic intrusives in the Crescent Formation, Washington, U.S.A. (Glassley, 1974); and other mildly alkaline basaltic rocks (Aoki, 1964; Gibb, 1971, 1973). However, comparisons based solely on $Ca:Mg:Fe'$ relations may be somewhat limited in significance (see Section 3.4.1). Of more fundamental significance to the present discussion is the fact that all augite microphenocrysts with $Fe' < 18$ (see LeBas, 1962) from Glen Ward basaltic extrusives have $Ca+Na+Mg:Fe'$ ratios typical of Ca -rich pyroxenes from subalkaline hosts (Fig. 3.5).

Intrusives

Pyroxenes from doleritic intrusives in the Glen Ward beds are all Ca -rich and range in composition from endiopside ($\sim Ca_{44}Mg_{47}Fe'_{9}$) to augite ($\sim Ca_{39}Mg_{44}Fe'_{17}$). They display a relatively consistent trend of Ca -depletion with Fe' enrichment which, except for sample 068, is also reflected in the compositional zoning (Fig. 3.1D). This trend is similar to that of augite microphenocrysts from the extrusives but the latter augites extend to more Ca -poor and Fe' -rich compositions. Ca -rich pyroxenes from doleritic intrusives in the Glenrock Station area display

a much greater range in Ca values with increasing Fe' (Fig. 3.1D, and Offler, 1979).

Pyroxenes from basaltic extrusives and intrusives in the Glen Ward beds are broadly comparable in most other aspects of their chemistry and are discussed together for the remainder of this Section.

(ii) Si-Al-Ti Relations

Cores of Ca-rich pyroxenes from basaltic extrusives and intrusives in the Glen Ward beds typically contain more than 50% SiO_2 and less than 4% Al_2O_3 . They display a similar range in SiO_2/Al_2O_3 ratios and on a $SiO_2:Al_2O_3$ diagram (Fig. 3.6B) most plot well within the subalkaline field of LeBas (1962), while several plot along the subalkaline-alkaline boundary. All plot well within the field for MORB pyroxenes (Nisbet and Pearce, 1977).

Pyroxenes from all basaltic rocks in the Glen Ward beds contain less than 1.1% TiO_2 and average 0.6-0.7%. The rims are often slightly enriched in TiO_2 relative to the cores (Fig. 3.7B) and in the latter there is a general overall decrease in Ti with increasing mg (Fig. 3.10). Increasing Ti with Fe-enrichment is more characteristic of pyroxenes from tholeiitic basalts than those from alkaline basalts (Schweitzer *et al.*, 1979), although exceptions do occur (see Wass, 1979). The Al contents of the pyroxene cores relative to their respective rims are highly variable (Fig. 3.7B), and in the cores neither ΣAl nor Al^{VI} vary regularly as a function of mg (Figs. 3.11, 3.12).

The Ti/Al ratios of pyroxene cores in the intrusives range from 0.2 to 0.05; while those in the extrusives display a similar, slightly more restricted range (Fig. 3.7B). Offler (1979) found that pyroxenes in Tamworth Group doleritic intrusives in the Glenrock Station area generally have higher Ti/Al ratios, lower total Al, and often have lower Ti contents than those in the Tamworth Group extrusives from that area (see Table 3.3, Fig. 3.7B). Pyroxenes from basaltic extrusives and intrusives in the Glen Ward beds have Ti and Al contents more or less intermediate between the two extremes of their counterparts in the Glenrock Station area (Figs. 3.7B, 3.8), and are not readily distinguished by this means. As a group, however, they are distinguishable from pyroxenes in

TABLE 3.3

Mean Ti/Al ratios of Ca-rich pyroxenes and of some of their host and associated basaltic rocks from four areas in the Tamworth Belt.

AREA		DATA SOURCE	Ti/Al cpx (cores)			DATA SOURCE	Ti/Al rock			TiO ₂ rock [†]	
			n	\bar{x}	s		n	\bar{x}	s	\bar{x}	s
Glen Ward beds	ex.	a	9	0.12	0.03	g	11	0.05	0.01	1.2	0.2
	in.	b	7	0.14	0.05	h	5	0.06	0.01	1.5	0.3
<u>Tamworth Group:</u>											
Glenrock Station	ex.	c	4	0.15	0.03	i	6	0.07	0.01	1.6	0.2
	in.	d	4	0.26	0.04	i	3	0.08	0.04	2.0	0.7
Nundle	ex.	e [*]	4	0.16	0.04	e & j	6	0.09	0.01	2.2	0.1
	in.	e	1	0.12	-	e	1	0.08	-	1.9	-
Morrison's Gap	ex.	f	3	0.20	0.02	k	8	0.10	0.01	2.2 [†]	0.1
	in.	f	3	0.22	0.03	k	10	0.11	0.02	2.4 [†]	0.5

n = number of samples.

\bar{x} = mean Ti/Al.

s = standard deviation.

Data Sources: a Table E-2

f Table E-5

b Table E-3

g Tables 3.5, 3.6

c Table I of Offler (1979)

h Table 3.5

d Table III of Offler (1979)

i Table 1 of Offler (1982)

e Table 1 of Vallance (1974)

j Table II of Vallance (1969c)

k Tables 3.7, I-1

Tables indicated by the letters a, b, f, g, h and k are in this thesis.

* The pyroxenes with anomalously high Al₂O₃ from the Nundle area (sample 13237 of Vallance, 1969c; and sample 13236 of Vallance, 1974) are not considered representative of pyroxene microphenocrysts from Tamworth Belt basaltic rocks (see discussion in text) and are not included in this table.

[†] With the exception of 5 basaltic extrusives and 9 basaltic intrusives in the Morrison's Gap area (Table I-1, see Appendix I), all TiO₂ values are from analyses which have been recalculated volatile-free. The mean TiO₂ values for basaltic rocks from the Morrison's Gap area are likely to be several percent higher if determined on a volatile-free basis.

NB: Some pyroxene analyses are from basaltic hosts which have not been analysed, and pyroxenes have not been analysed from some of the basaltic rocks included in this table.

ex. = extrusives.

in. = intrusives.

the Glenrock Station area in that they have lower average Ti/Al ratios (Table 3.3).

(iii) Minor Components

Most of the more magnesian pyroxenes from basaltic rocks in the Glen Ward beds contain small amounts (<0.6%) of Cr_2O_3 (Tables E-2, E-3) which decrease with decreasing *mg* (Fig. 3.13). All have relatively low Mn and Na ($\text{Na}_2\text{O} < 0.4\%$) and these generally increase with increasing *mg*, although Na_2O has a somewhat erratic distribution.

(iv) Magmatic Affinities

Pyroxenes from basaltic rocks in the Glen Ward beds typically have SiO_2 and TiO_2 contents in the ranges 50-52% and 0.5-1% respectively (Tables E-2, E-3). These characteristics are generally more typical of pyroxenes from MORBs and volcanic arc basalts (VAB) than those from within-plate tholeiitic (WPT) or alkaline (WPA) basaltic rocks (*cf.* Nisbet and Pearce, 1977). Indeed, all the Glen Ward pyroxenes plot within the fields for Ca-rich pyroxenes from:

- (i) MORB + VAB on the $F_1:F_2$ discriminant diagram (Fig. 3.14B) of Nisbet and Pearce (1977).
- (ii) MORB on the $\text{SiO}_2:\text{Al}_2\text{O}_3$ diagram of Nisbet and Pearce (1977) and the $\text{Na}+\text{Al}^{\text{IV}}:2\text{Ti}+\text{Cr}$ diagram (Fig. 3.2D) of Schweitzer *et al.* (1978).
- (iii) Tholeiitic basalts on the *di-ol-qz* diagram (Fig. 3.4) of Coombs (1963).
- (iv) Subalkaline basaltic hosts on the $\text{Ca}+\text{Na}+\text{K}:\text{Mg}:\text{Fe}'$ diagram (Fig. 3.5) of LeBas (1962) and the $\text{Ti}:\text{Ca}+\text{Na}$ diagram (Fig. 3.8) of Leterrier *et al.* (1982).

On the $\text{Ti}+\text{Cr}:\text{Ca}$ diagram (Fig. 3.9) of Leterrier *et al.* (1982) the Glen Ward pyroxenes plot largely within the area of overlap between the fields for Ca-rich pyroxenes from non-orogenic basaltic rocks and those from orogenic basaltic rocks. Pyroxenes from sample 084 clearly have $\text{Ti}+\text{Cr}:\text{Ca}$ relations characteristic of Ca-rich pyroxenes from orogenic basalts, and Figure 3.7B suggests that they have affinities with IAT. The low $\text{Ti}+\text{Cr}$ in these pyroxenes might indicate that this rock unit (084)

is an evolved member of the PBOC (*cf.* Table E-1). Unfortunately, whole-rock chemical data are not available to further evaluate this possibility and sample 084 has been assigned to the Glen Ward beds on field relations and textural criteria (compare Sections 3.3.2 and 5.7.2). The Ti+Cr:Ca relations of pyroxenes from the other Glen Ward basaltic units are such that these cannot be confidently affiliated with one or other of the orogenic or non-orogenic basalt groupings solely on the basis of Figure 3.9.

Leterrier *et al.* (1982) have shown that orogenic basaltic rocks often can be subdivided into IAT and CAB on the basis of the Ti:Al relations of their Ca-rich pyroxenes. If the majority of the Glen Ward basaltic rocks are of orogenic affinity, then the Ti:Al relations of their pyroxenes would suggest that they are CAB (Fig. 3.7B). This suggestion is at variance with their mineralogy (primary hydrous phases are rare, even in the evolved types; see Section 3.3.2) and some aspects of their chemistry (with the possible exception of sample 066 which might be related to the Pitch Creek volcanics; see Section 3.5.3). Thus, as Figure 3.7B misclassifies these rocks, according to the scheme of Leterrier *et al.* (1982) it follows that the Ti+Cr:Ca relations of their pyroxenes (Fig. 3.9) favour non-orogenic or at least transitional (non-orogenic-orogenic) magmatic affinities.

The majority of Glen Ward pyroxenes have $\text{Na}_2\text{O}:\text{TiO}_2:\text{MnO}$ ratios similar to those of MORB pyroxenes. However, some are depleted in MnO and consequently have $\text{Na}_2\text{O}:\text{TiO}_2:\text{MnO}$ ratios resembling those of pyroxenes from WPA basalts (Fig. 3.15B). This result is most probably spurious as most other aspects of the chemistry of the Glen Ward pyroxenes (summarized above) suggest that they have affinities with non-alkaline hosts (see discussion at the end of Section 3.4.1.4).

Pyroxenes from Tamworth Belt basaltic rocks in the Glenrock Station area (Offler, 1979) generally have subalkaline characteristics similar to those in the Glen Ward beds, although some pyroxenes from Glenrock doleritic intrusives have $\text{Ca}+\text{Na}+\text{K}:\text{Mg}:\text{Fe}'$ relations similar to those from alkaline hosts (see Fig. 4 of Offler, 1979). However, the Glenrock pyroxenes are strongly depleted in Na_2O relative to those from most WPA basaltic rocks (*cf.* Deer *et al.*, 1978) and on the $F_1:F_2$ discriminant diagram (Fig. 3.14B) of Nisbet and Pearce (1977) they are displaced

slightly further from the field of pyroxenes from WPA basaltic hosts than those from the Glen Ward basaltic rocks.

The Ti+Cr:Ca and Ti:Al diagrams (Figs. 3.7B, 3.9) of Leterrier *et al.* (1982) ambiguously assign pyroxenes in the Glenrock basaltic extrusives to either orogenic or non-orogenic basalt types. These Glenrock pyroxenes display trends of increasing Ti and Ti+Cr with increasing Ca and Ca+Na similar to those for pyroxenes from most basaltic extrusives and intrusives in the Glen Ward beds (see Figs. 3.8, 3.9). Pyroxenes from the Glenrock dolerites, however, display trends of decreasing Ti and Ti+Cr with increasing Ca and Ca+Na and consequently they plot largely within the field for Ca-rich pyroxenes from orogenic basalts on Figure 3.9. To some extent this reinforces Offler's (1979) suggestion that some of the Glenrock Tamworth Group basaltic extrusives and the doleritic intrusives might not be consanguineous. Indeed, the Ti:Al relations of the pyroxenes from these doleritic intrusives are comparable to those of Ca-rich pyroxenes from CAB (Fig. 3.7B). In view of the limited data available, it is not possible to establish whether or not the above pyroxene criteria are a true indication of the magmatic affinities of these intrusives.

(3) Tamworth Group

Representative analyses of Ca-rich pyroxenes from three fine-grained basaltic extrusives and three doleritic-gabbroic intrusives from the Tamworth Group in the Morrisons Gap area are listed in Table E-5 (Appendix E). Samples 056 and 057 are from the central portions of massive flow units and sample 055 is from the core of a large (2m x 1m) pillow. Samples 054 and 058 are from doleritic intrusives (20-30m thick) and sample 059 is from a coarse gabbroic intrusive (160m thick, but possibly consists of three separate cooling units). Grid reference for these sample localities are listed in Appendix K.

(i) Ca:Mg:Fe' Relations

Pyroxenes from the extrusives and intrusives are all augites and cluster in the range $Ca_{43-39}Mg_{43-38}Fe'_{15-20}$ (Fig. 3.1E). Augite from sample 057, however, is significantly more magnesian and more calcic ($\sim Ca_{44}Mg_{44}Fe'_{12}$) than other augites from the Morrisons Gap area (Fig. 3.1E). In comparison, augites from the Nundle area (Vallance, 1969c, 1974a) are

generally more Fe-rich and display a slightly greater range in Ca . The augites with lower Ca values display a diffuse general trend of decreasing Ca with Fe enrichment, especially if those from the Morrisons Gap and Nundle areas are considered as a whole. However there is a subsidiary trend of Ca-enrichment at $Fe' \sim 20$ in most of the Nundle augites, the most Ca-rich also being the most Al-rich.

Although a trend of Ca-depletion with Fe' enrichment is characteristic of augites from tholeiitic hosts, most of the Morrisons Gap and Nundle augites have higher Ca values for a given Fe' value than typical tholeiitic augites. They have compositions intermediate between the Skaergaard or Bushveld trends and those of transitional or slightly alkaline rocks. Those with Fe' values ≤ 18 display a range of $Ca:Mg:Fe'$ compositions almost identical to those of pyroxenes from doleritic intrusives in the Glen Ward beds (Fig. 3.1E). Within this range, augites from the Morrisons Gap area are generally more calcic than those from the Nundle area (Fig. 3.1E), but all fall within the subalkaline field on the $Ca+Na+K:Mg:Fe'$ diagram (Fig. 3.5B) of LeBas (1962).

(ii) Si-Al-Ti Relations

Augite cores from basaltic rocks in the Morrisons Gap area contain 47.0-51.5% SiO_2 , 0.7-1.7% TiO_2 and 1.9-5.5% Al_2O_3 (Table E-5). Those with higher SiO_2 have less TiO_2 and Al_2O_3 and examples of both high and low SiO_2 types occur in the extrusives and intrusives. In comparison, augites from Tamworth Group basaltic rocks in the Nundle area (Vallance, 1969c, 1974a) have lower SiO_2 (47-50%), comparable TiO_2 (0.9-1.3%) and generally higher Al_2O_3 (3-9%). Overall, Ti and Al contents of these pyroxenes increase rapidly with decreasing mg (Figs. 3.10, 3.11) suggesting that the host melts were not significantly depleted in Ti and Al by possible early fractionation of plagioclase and, to a lesser extent, Fe-Ti oxides.

Augites with Fe' values < 18 from basaltic rocks in the Morrisons Gap area all fall within the field for pyroxenes from subalkaline hosts on the $SiO_2:Al_2O_3$ diagram (Fig. 3.6C) of LeBas (1962). In comparison, the least-evolved augites from the Nundle area ($Fe' = 17$) plot slightly within the field for pyroxenes from alkaline hosts (Fig. 3.6C). The magmatic affinities of pyroxenes with Fe' greater than 18 are not reliably

indicated by their SiO_2 Al_2O_3 relations (LeBas, 1962). However, the relative enrichment in Al of the more evolved augites from the Morrisons Gap and Nundle areas is well illustrated by this diagram (Fig. 3.6C).

The high Al_2O_3 content of some Nundle augites (Fig. 3.6C) might suggest that they could have crystallized:

- (i) From an alkaline host. The present major element chemistry of the (spilitized) host rocks indicates that they are tholeiites with either *ol+hy* or *hy+qz* in their norms (Vallance, 1974a). Similarly, the TiO_2 and Na_2O contents of the highly aluminous augites are lower than might be expected of augites from alkaline hosts (*cf.* LeBas, 1962; Le Maitre, 1962; Deer *et al.* 1978; Schweitzer *et al.* 1979; Wass, 1979; De Fino *et al.* 1982).
- (ii) Early relative to plagioclase. The crystallization of plagioclase relative to augite in relatively evolved basaltic melts is suppressed at pressures greater than ~7 kbar (Kushiro and Thompson, 1972; Fuji and Kushiro, 1977) or under conditions of high $P_{\text{H}_2\text{O}}$ (Nesbitt and Hamilton, 1970; Eggler and Burnham, 1973; Nicholls and Ringwood, 1973). Also, as the Al_2O_3 contents of MORB melts generally decrease with decreasing *mg* (e.g. Papike and Bence, 1973; Bence *et al.*, 1980), the lower Al_2O_3 in relatively evolved MORB-like melts might favour the early crystallization of augite relative to plagioclase. Nevertheless, some Group II (E-type) MORB (*cf.* Bryan *et al.* 1976) with relatively primitive major element compositions include Ca-rich pyroxene at low degrees of crystallization (Bryan and Grove, 1982).

There is no evidence of high pressure tschermakitic pyroxene phenocrysts in the Nundle basaltic rocks, nor is there evidence that high $f_{\text{H}_2\text{O}}$ was a characteristic of the magmas (they are generally poor in vesicles and primary hydrous mineral phases are rare; see Section 3.2.2). The Nundle basaltic extrusives typically have intermediate Al_2O_3 contents (~14-15 wt.%; see Tables 3.8a, I-1; and Vallance 1969c, 1974a) and have

closer affinities with Group II rather than Group I (N-type) MORB (see Section 3.5.3). Consequently, while it is feasible that at low pressures augite might have crystallized from the Nundle melts prior to plagioclase, it is very likely to have been quickly joined by the latter at low degrees of crystallization.

A probable alternative explanation for the high Al_2O_3 in some of the Nundle augites is that these mineral separates might have contained a significant proportion of quench pyroxene. Vallance (1974a) noted that the Nundle augites with the highest Al_2O_3 content came from "generally fine-grained flow rocks near the top of the volcanic pile". Mevel and Velde (1976) and Schiffman and Lofgren (1982), in particular, have demonstrated that the Al content of quench pyroxenes may increase considerably as a function of increased cooling rate. However, these Nundle augites also have anomalously high *Ca* values, high Al contents, and low Ti/Al ratios (see below) compared to most natural and experimental quench pyroxenes reported in the literature. This might reflect an increase in the CaAlAlO_6 component in these pyroxenes in response to rapid cooling.

Without further textural and analytical investigations the significance of these high Al pyroxenes cannot be properly evaluated. The fact that they have similar CaO and Na_2O contents to less aluminous augites from other Nundle basaltic rocks precludes (at least) the possibility of significant plagioclase contamination in the analysed pyroxene separates.

Augites from basaltic rocks in the Morrisons Gap area display a narrow range of Ti/Al ratios (0.26-0.20) which, except for sample 055, vary little from core to rim (Fig. 3.7C). In contrast, augites from the Nundle area display a general trend of decreasing Ti/Al at relatively constant Ti. This most probably reflects increased incorporation of Al into some of these augites during rapid crystallization (see discussion above). The least aluminous Nundle augites, however, have similar Ti/Al ratios to augites from the Morrisons Gap area; and together these reflect the higher average bulk-rock Ti/Al ratios of basaltic rocks in the Morrisons Gap and Nundle areas relative to those in the Glen Ward beds (Table 3.2).

Augite cores from the Morrisons Gap and Nundle areas display trends of rapidly increasing Ti and Al with decreasing *mg*, although the

Ti-enrichment in Nundle augites is less pronounced (Figs. 3.10,3.11).

(iii) Minor Components

All augites from basaltic rocks in the Morrisons Gap area are impoverished in Cr_2O_3 and have relatively low MnO (<0.3%) and Na_2O (<0.45%) contents. The Cr_2O_3 and MnO abundances are closely related to the Fe content of these pyroxenes, and generally increase with decreasing *mg*. The variation in Na_2O is less regular.

Augites from the Nundle area (Vallance 1969c,1974a) have similar MnO contents to the Morrisons Gap augites, but are considerably more enriched in Na_2O (*av.* $0.56 \pm 0.1\%$). Indeed, Vallance (1969c) has recorded pyroxene with $\sim 1.5\%$ Na_2O from a Tamworth Group basaltic rock in the Nundle area. Unfortunately, a description of the host rock and a complete analysis of this pyroxene has not been published.

Magmatic Affinities

Augites from Tamworth Group basaltic rocks in the Morrisons Gap area typically have SiO_2 and TiO_2 contents in the range *ca.* 47-51% and *ca.* 0.7-1.7% respectively. In comparison, those augites without anomalously high Al_2O_3 from similar rocks in the Nundle area display a more restricted range of SiO_2 (*ca.* 48.5-50.5%) and TiO_2 (*ca.* 0.85-1.3%) contents. These characteristics of the Morrisons Gap and Nundle augites, combined with their moderate *Ca* values (Fig. 3.1E), *Ca*+*Na*(+*K*) values (Figs 3.5B,3.3), and significantly *hy*-normative chemistry (Fig. 3.4), suggest that their host basaltic rocks have subalkaline or, on occasion, transitional magmatic affinities.

Augites from the Morrisons Gap area display a similar range of $\text{Na}_2\text{O}:\text{TiO}_2:\text{MnO}$ ratios to the majority of Ca-rich pyroxenes from basaltic rocks in the Glen Ward beds (Fig. 3.15). Together, these pyroxenes display a general trend of gradually increasing $\text{Na}_2\text{O}/\text{TiO}_2$ with decreasing MnO/TiO_2 , and traverse the fields for pyroxenes from MORB and WPA basaltic rocks on the $\text{Na}_2\text{O}:\text{TiO}_2:\text{MnO}$ diagram (Fig. 3.15) of Nisbet and Pearce (1977). Augites from the Nundle area have significantly larger $\text{Na}_2\text{O}/(\text{Na}_2\text{O}+\text{TiO}_2+\text{MnO})$ ratios than most other Ca-rich pyroxenes from basaltic rocks of the Tamworth Belt, and plot within fields which include Ca-rich pyroxenes from

VAB, WPT and WPA basaltic rocks (Fig. 3.15B).

In terms of their overall chemistry as evaluated by the discriminant functions of Nisbet and Pearce (1977), the Morrisons Gap and Nundle augites are similar to Ca-rich pyroxenes from MORB and VAB (Fig. 3.14B). However, they have lower F_1 values than pyroxenes from most other basaltic rocks in the Tamworth Belt, and consequently plot closer to the field for pyroxenes from WPA basaltic rocks on the $F_1:F_2$ diagram (Fig. 3.14B). This might suggest that their hosts more closely resemble transitional basalt types than do other Tamworth Belt basaltic rocks, a suggestion supported by their whole-rock chemistries (Section 3.5.3). The Ti:Ca+Na relations of at least some Morrisons Gap and Nundle augites (Fig. 3.8) reinforce this conclusion. Overall, the Ti:Ca+Na and Ti+Cr:Ca relations (Figs. 3.8, 3.9), and most other chemical characteristics of these augites suggest that their hosts have affinities with subalkaline to transitional non-orogenic basaltic hosts (i.e. MORB, BAB and WPT).

3.4.2 Spinels

Translucent brown Cr-Al spinels are common accessory phases in low Ti basaltic extrusives of the PBOC (see Section 5.7.3(3)). Of the other basaltic rocks examined they are found only in the Myra *Type 3* extrusives (see Section 3.3.1, Part (3)) where they occur as inclusions in carbonate pseudomorphs after olivine (Plate 3.4E,F). Some of these inclusions are also opaque. Similar opaque inclusions in olivine pseudomorphs in sample 072 (Glen Ward beds) have not been analysed.

The translucent and opaque spinel inclusions in one Myra *Type 3* basaltic extrusive (sample 232) were analysed by microprobe. Both types are titaniferous magnesiochromites, the opaque grains being slightly more Fe-rich than the translucent types (Table E-10). They have lower M values and lower 100 Cr/(Cr+Al) ratios than most spinels reported from MORBs, and have lower 100 Cr/(Cr+Al) ratios than all MORB spinels with similar M values (Fig. 5.3). They also have higher $\text{Fe}^{3+}/(\text{Cr}+\text{Fe}^{3+}+\text{Al})$ ratios than MORB spinels (Fig. 5.3). However, the most significant difference between the spinels in Myra *Type 3* basaltic extrusives and those typical of MORBs is the high TiO_2 and CaO contents of the former (Table E-10).

Most MORB magnesiochromites contain less than 0.6% TiO_2 , and almost all contain less than 0.9% TiO_2 (Frey *et al.*, 1974; Ridley *et al.*,

1974; Ayuso *et al.*, 1976; Sigurdsson and Schilling, 1976; Donaldson and Brown, 1977; Sigurdsson, 1977; Dick and Bryan, 1978; Shibata *et al.*, 1979; Fisk and Bence, 1980; O'Donnell and Presnall, 1980). The Myra magnesiochromites contain 1.5-1.6% TiO_2 and in this respect they resemble those from highly vesicular TiO_2 -rich (~2%) transitional olivine basalts dredged from the Mid-Atlantic Ridge (MAR) near the Oceanographer Fracture Zone (sample J of Sigurdsson and Schilling, 1976; see analyses 4,5; Table E-10). The Myra titaniferous magnesiochromites also have similar M values and $\text{Fe}^{3+}/(\text{Cr}+\text{Fe}^{3+}+\text{Al})$ ratios to those in sample J from the MAR, but the latter have substantially higher 100 $\text{Cr}/(\text{Cr}+\text{Al})$ ratios, in common with spinels with similar M values from tholeiitic MORB.

O'Donnell and Presnall (1980) found a single highly resorbed titaniferous magnesiochromite grain (Table E-10, analysis 3) in a TiO_2 -poor (0.86% TiO_2) tholeiitic MORB dredged from the MAR at 26°44.5' north. This grain has higher TiO_2 (2.14%) than any other magnesiochromite reported from MORBs so far. It has a similar M value and 100 $\text{Cr}/(\text{Cr}+\text{Al})$ ratio to the titaniferous magnesiochromites in the transitional olivine basalts from station J (Sigurdsson and Schilling, 1976) but has a higher TiO_2 content and $\text{Fe}^{3+}/(\text{Cr}+\text{Fe}^{3+}+\text{Al})$ ratio than the latter - features more characteristic of liquidus spinels in some Hawaiian tholeiites (Evans and Wright, 1972; see analyses 6,7, Table E-10) and in some alkali olivine basalts (*cf.* Ridley, 1977). The precise relationship between this spinel and its host is enigmatic.

Evans and Wright (1972) suggest that the titaniferous magnesiochromites in the Hawaiian tholeiites might owe their richness in TiO_2 to the relatively high TiO_2 content (~2.6%) of their host magmas. Indeed early-formed spinels in TiO_2 -enriched mare basalts contain ~4-7% TiO_2 (El Goresy *et al.*, 1971; Misra and Taylor, 1977) but some spinels which have crystallized from TiO_2 -poor magmas also have anomalously high TiO_2 contents. Thus spinels from the Rhum intrusion (parent magma ~0.8% TiO_2 ; Brown, 1956) contain up to 1.8% TiO_2 , and early formed spinels in some Karoo tholeiitic picrites (parent magma ~1% TiO_2 ; Eales and Snowdon, 1979) contain up to 2% TiO_2 (Eales and Snowdon, 1979; Eales *et al.*, 1980).

Nevertheless, the TiO_2 content of the Myra spinels is comparable to those in the station J olivine basalts which in turn have comparable

TiO₂ to the Myra *Type 3* basalts (~2.1%, see Table 3.5a). Also, the TiO₂ content of the Myra spinels is intermediate between that of MORB spinels and Hawaiian spinels; as is the TiO₂ content of the Myra *Type 3* extrusives (~2.1%) intermediate between that of spinel-bearing MORB (~<1.5%) and Hawaiian tholeiites (~2.5-3%). Therefore, the TiO₂ content of the Myra spinels and the morphology of their host olivines (see Section 3.3.1, Part (3)) is not inconsistent with the crystallization of these phases from their host *Type 3* extrusives, despite the presently low MgO content and low *mg* value (1.51 wt.% and 30.0 respectively) of the latter. Hence it is exceedingly likely that considerable Mg has been lost during alteration and incipient weathering of these rocks (see Section 3.5.2.1).

The significance of the high CaO contents of the Myra spinels is not understood. Few published analyses of spinels include CaO determinations - possibly because CaO contents are usually below the detection limit of the microprobe. However, O'Donnell and Presnall (1980) have analysed MAR magnesiochromites with 0.08-0.36% CaO.

3.4.3 Relict Plagioclase

Unaltered relicts of calcic plagioclase are common in many of the basaltic rocks examined; in others the plagioclase appears to have been completely albitized. In very rare instances (072) completely unaltered plagioclase may be abundant, but most relict grains are partially albitized. Analysed relict and secondary plagioclases from basaltic rocks in both the Myra beds and the Tamworth Belt almost invariably contain very little K₂O (< 0.2%). Rare exceptions include some microphenocryst rims and groundmass grains in some of the more evolved, relatively K₂O-rich extrusives (e.g. 066, Table E-12) and intrusives (e.g. 064, Table E-12). Unfortunately, Fe and Mg were not determined for most of the plagioclases analysed. Therefore, in the light of their low K₂O, the known chemistry of these plagioclases is adequately expressed by their 100 An/(Ab+An) (i.e. mol.% An) ratios.

Tables E-2 to E-8 list the maximum observed ranges of 100 An/(Ab+An) ratios of plagioclases in each of the samples investigated by microprobe. Calcic plagioclase relicts were identified optically in numerous other samples. With the possible exception of sample 072, all of these samples contain some albite (An₀₋₄), and in many (samples 054,

055, 059, 063, 067, 071, 073, 077, 209, 240) albite was the only feldspar found. In those samples where there is a distinct compositional gap between the most sodic plagioclase relict analysed and the almost ubiquitous albite, only the compositional range of relict grains is listed. In some cases (e.g. 058, 069, 216) the only relict calcic plagioclases detected were portions of the outer rims of albitized primary grains. These might be expected to have had more calcic cores.

The presence of relict calcic plagioclase in many of the basaltic rocks examined provides compelling evidence that these rocks were not derived from so-called 'spilitic' magmas (see Section 3.1).

(1) Myra beds

With the exception of those samples which have been completely albitized (e.g. 109, 240), basaltic rocks in the Myra beds commonly contain relicts of labradorite and/or andesine (Tables E-6, E-7; plus optical determinations on numerous other samples). Although the data are limited, there does not appear to be any fundamental chemical difference between plagioclases from *Type 1* and *Type 2* basaltic rocks. No relict calcic plagioclase was found in *Type 3* extrusives.

(2) Tamworth Belt

Relicts of calcic plagioclase are common in most doleritic intrusives in the Glen Ward beds. These usually range in composition from labradorite to andesine, but some bytownite (An_{77} , sample 060) and oligoclase ($\sim An_{20-30}$) have been found (Table E-3). Calcic plagioclase is less common in the basaltic extrusives in the Glen Ward beds, but occasional relicts (see Table E-2) are of similar composition to those in the doleritic intrusives. Relicts of andesine and labradorite were also found in basaltic extrusives in the Morrisons Gap area, but tend to be relatively rare in the doleritic intrusives (Table E-5).

Labradorite microphenocrysts in sample 072 contain 0.6-1.1% ΣFeO and 0.1-0.35% MgO (see representative analysis, Table E-12). The rims are typically enriched in Fe and depleted in Mg relative to the cores, the Fe-enrichment possibly being the result of increased incorporation of Fe into the plagioclase during rapid quenching (Schiffman and Lofgren, 1982). The rims are either slightly enriched or slightly depleted in

Na and K relative to the cores.

It is not known whether the above features are characteristic of primary plagioclase in other Tamworth Belt basaltic rocks. Bryan (1974), Ayuso (1976) and Mazzullo and Bence (1976) have shown that, for relatively low degrees of crystallization, ΣFeO and MgO generally increase in MORB plagioclases as they become more sodic and the liquid becomes more evolved. However, with the onset of pyroxene crystallization the ΣFeO and MgO contents of co-crystallizing plagioclases generally decrease as they become more sodic, although ΣFeO may stabilize at a relatively constant value (e.g. 0.8-0.9 wt %; Mazzullo and Bence, 1976).

As the Tamworth Belt basaltic rocks are generally relatively evolved (Fe-rich, usually with $mg < 50$; see Section 3.5.3), pyroxene probably crystallized relatively early in these rocks compared with most MORB. Hence, compared with those in MORB, primary plagioclases in the Tamworth Belt basaltic rocks might be expected to have low MgO and moderate to low ΣFeO , especially since many also crystallized Fe-Ti oxides at a relatively early stage (see Section 3.3.2).

3.4.4 Fe-Ti Oxides

Titanomagnetite is the predominant Fe-Ti oxide phase in basaltic rocks of the Myra beds and Tamworth Belt. Most titanomagnetite grains, especially microphenocrysts, contain abundant exsolved acicular ilmenite and/or ulvospinel. Ilmenite is a common accessory phase in the majority of these rocks and rarely may be the most abundant Fe-Ti oxide (e.g. 060).

Coexisting Ti-poor and Ti-rich oxides in a number of basaltic rocks from the Myra beds, Glen Ward beds and Tamworth Group were analysed by microprobe in an attempt to ascertain the temperatures and oxygen fugacities at which they equilibrated (*cf.* Buddington and Lindsley, 1964; Spencer and Lindsley, 1981). These analyses are almost invariably of poor quality. Many have low totals (< 98%, even after calculation of Fe^{3+}) and/or unacceptably high "minor element" contents i.e. SiO_2 , Al_2O_3 , MgO and CaO (each may exceed several wt.% and total up to 15 wt.%!). Successive analyses of optically homogeneous grains often yielded widely varying results, especially in SiO_2 values and analysis totals.

Analyses of Fe-Ti oxides and chrome spinels from other rock-types

were satisfactory. These were often interspersed with the basaltic samples during microprobe runs, and effectively eliminate the possibility of significant instrumental errors for the analyses in question. Presumably, many of the Fe-Ti oxides in the basaltic rocks examined are variably oxidized to titanomaghemite or titaniferous maghemomagnetite (*cf.* Marshall and Cox, 1971; Finke and Harrison, 1974; Bass, 1975; Ryall and Hall, 1979), or have partially recrystallized to submicroscopic sphene or leucoxene. Many might also contain submicroscopic silicate inclusions which could account for their high and variable SiO_2 , Al_2O_3 , MgO and CaO analyses.

For these reasons the chemistry of the Fe-Ti oxides in basaltic rocks of the Myra beds and Tamworth Belt has not been examined in any detail. Some of the better quality analyses obtained are listed in Table E-13.

Titanomagnetites in Myra basaltic rocks commonly have a greater ulvospinel component (~30-90 mol.%) than those in Tamworth Belt basaltic rocks (~10-60 mol % Fe_2TiO_4) but few reliable conclusions can be drawn from the results available. The predominance of titanomagnetite over ilmenite in the great majority of these rocks simply suggests that $f\text{O}_2$ was relatively high during the latter stages (at least; see Section 3.3.2) of their crystallization.

TABLE 3.0

Key to symbols used on diagrams throughout Chapter 3.

Woolomin Association

- ▼ Myra *Type* 1 basaltic extrusives
- ▲ " " 2 " "
- ◆ " " 3 " "
- ▽ Myra *Type* 1 doleritic intrusives
- △ " " 2 " "
- ⊕ Myra vesicular volcanic breccia (samples 406 and 407)
- x Woolomin basaltic extrusives (Offler, 1979,1982)
- ⊗ " doleritic intrusives (")
- * Average clinopyroxene analysis from 8 Woolomin basaltic rocks (Cawood, 1982a)
- * Detrital clinopyroxenes from Myra volcaniclastics

Tamworth Belt

- Glen Ward basaltic extrusives
- " " doleritic intrusives
- Morrisons Gap basaltic extrusives
- " " doleritic intrusives
- + Tamworth Group basaltic extrusives, Nundle (Vallance 1969c,1974a)
- ⊕ " " doleritic intrusives " (")
- ⊙ " " basaltic extrusives, Glenrock Station (Offler, 1979,1982)
- ⊗ " " doleritic intrusives, " " (")
- ⊞ Tamworth Group basaltic rocks (Benson, 1915)
- * Detrital clinopyroxenes from Glen Ward volcaniclastics

NOTE: Symbols vary in size on different diagrams. Capped symbols (e.g. ▼) indicate maximum values. Symbols enclosed by a large diamond have been plotted half-scale on the axes indicated by the attached arrows (e.g. sample 066 contains 821 µg/g Sr but to conserve space it has been plotted at 410 µg/g Sr in Figs. 3.16 and 3.17).

A loose copy of this table is included in the map pocket.

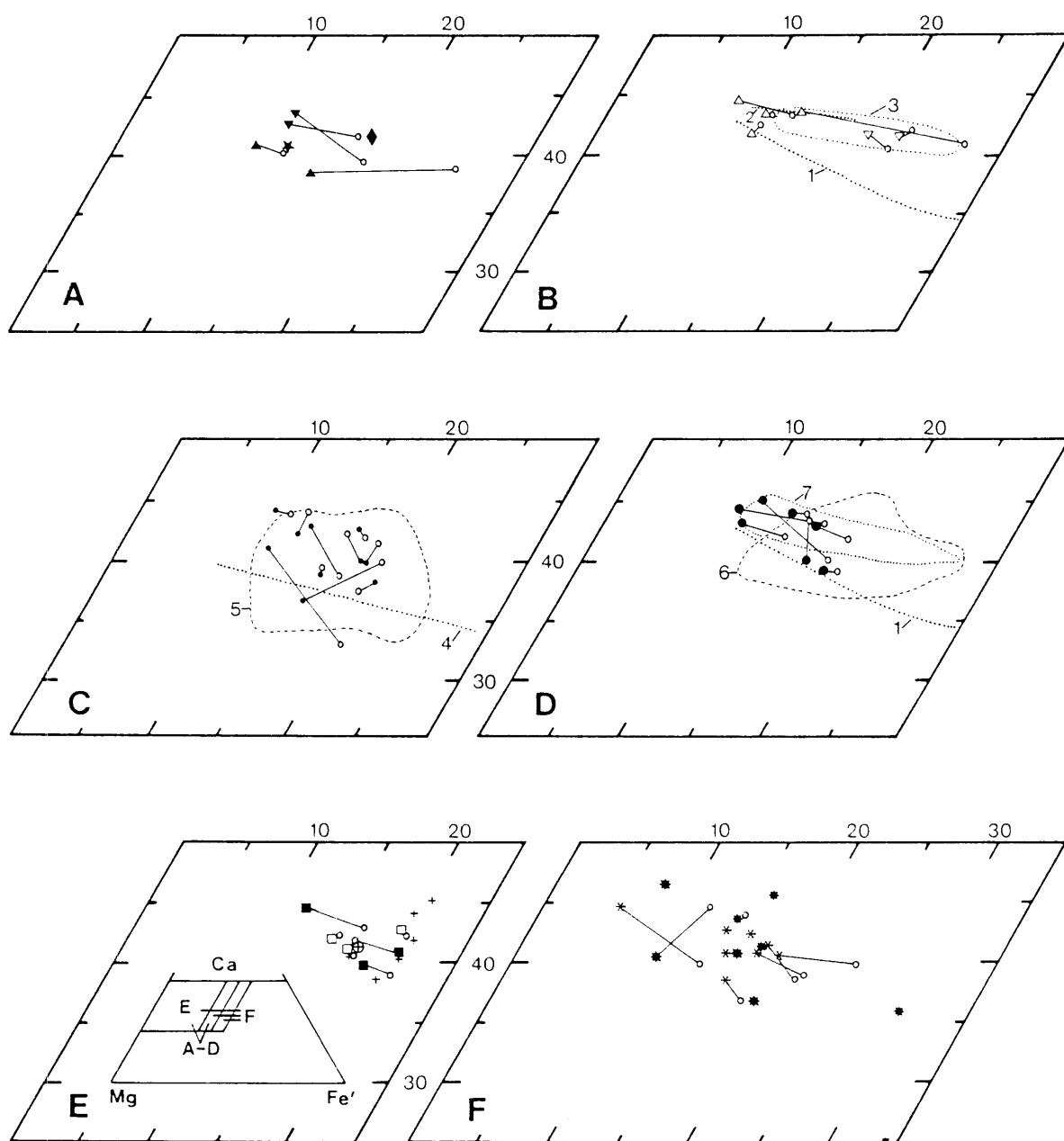


Fig. 3.1: Ca:Mg:Fe' relations (cf. inset) in Ca-rich pyroxenes from basaltic rocks in the Myra beds (A,B), Glen Ward beds (C,D), Tamworth Group in the Nundle and Morrisons Gap areas (E) and in detrital Ca-rich pyroxenes from volcaniclastics in the Myra beds and Glen Ward beds (F, see Chapter 2). Symbols as in Table 3.0. Open circles = rim compositions. $Fe' = \Sigma Fe + Mn$. Composition fields and Fe-enrichment trends: 1. Skaergaard (Brown, 1957); 2. Gough Island (Le Maitre, 1962); 3. Picture Gorge Basalt, central portion of flow unit (Smith and Lindsley, 1971); 4. Generalized MORB trend from analyses in Schweitzer *et al.* (1978,1979); 5,6. Tamworth Group basaltic extrusives and doleritic intrusives respectively, Glenrock Station Area (Offler, 1979); 7. Mildly alkaline intrusives, Crescent Complex, Olympic Peninsula, Washington (Glassley, 1974).

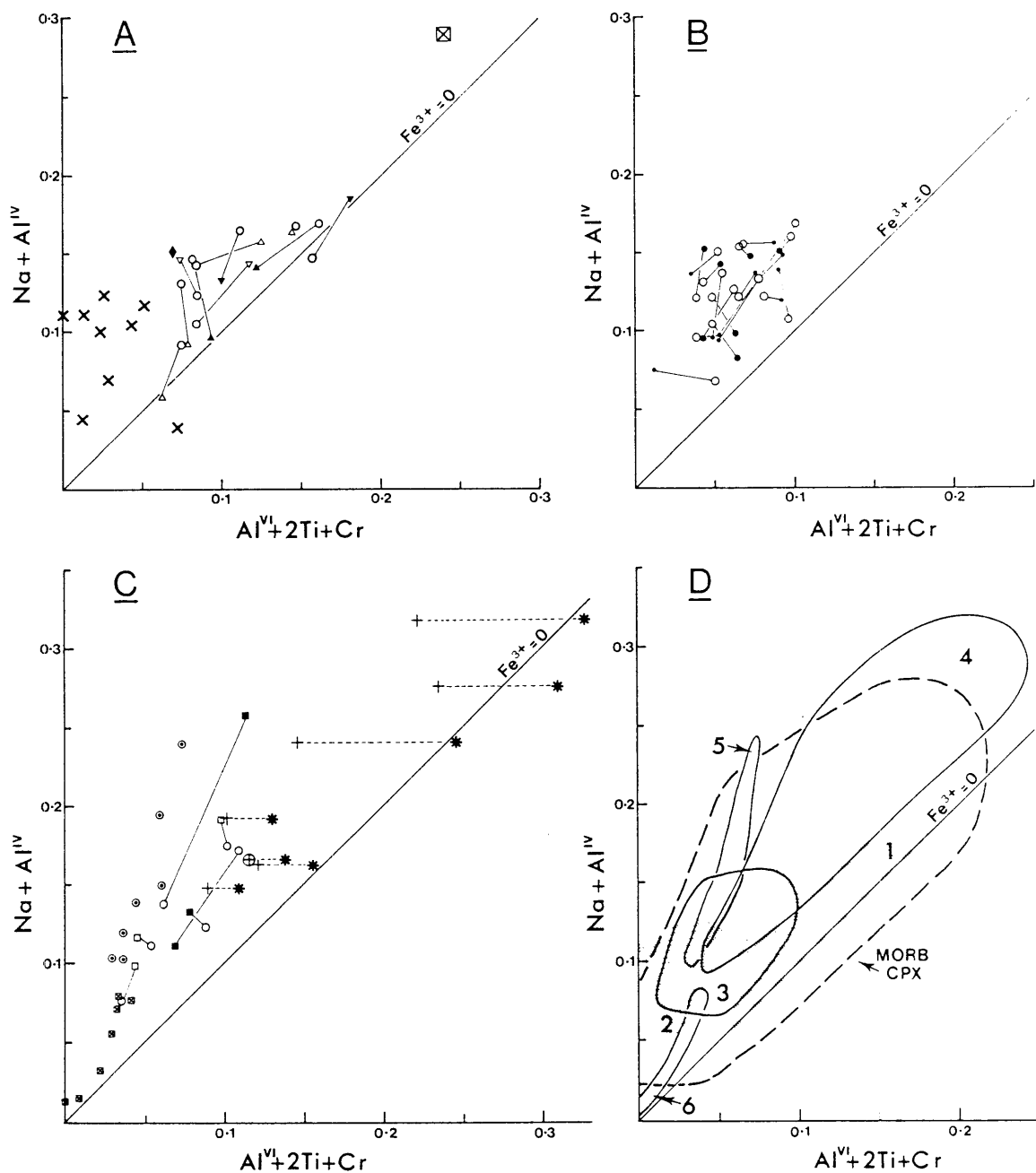


Fig. 3.2: Charge deficiencies (Y axis) *vs* charge excesses in Ca-rich pyroxenes from the Myra beds (A), Glen Ward beds (B) and Tamworth Belt (C). Symbols as in Table 3.0. Open circles = rim compositions. * = see text.

Diagram D = synoptic plot for all pyroxenes in diagrams A,B,C. Field for MORB pyroxenes from Schweitzer *et al.* (1979). Fields: 1 (shaded) = Myra beds; 2 (shaded) = Woolomin beds (Offler, 1979); 3 = Glen Ward beds; 4 = Tamworth Group, Nundle + Morrisons Gap; 5 = Tamworth Group extrusives, Glenrock Station (Offler, 1979); 6 = Tamworth Group intrusives, Glenrock Station (Offler, 1979).

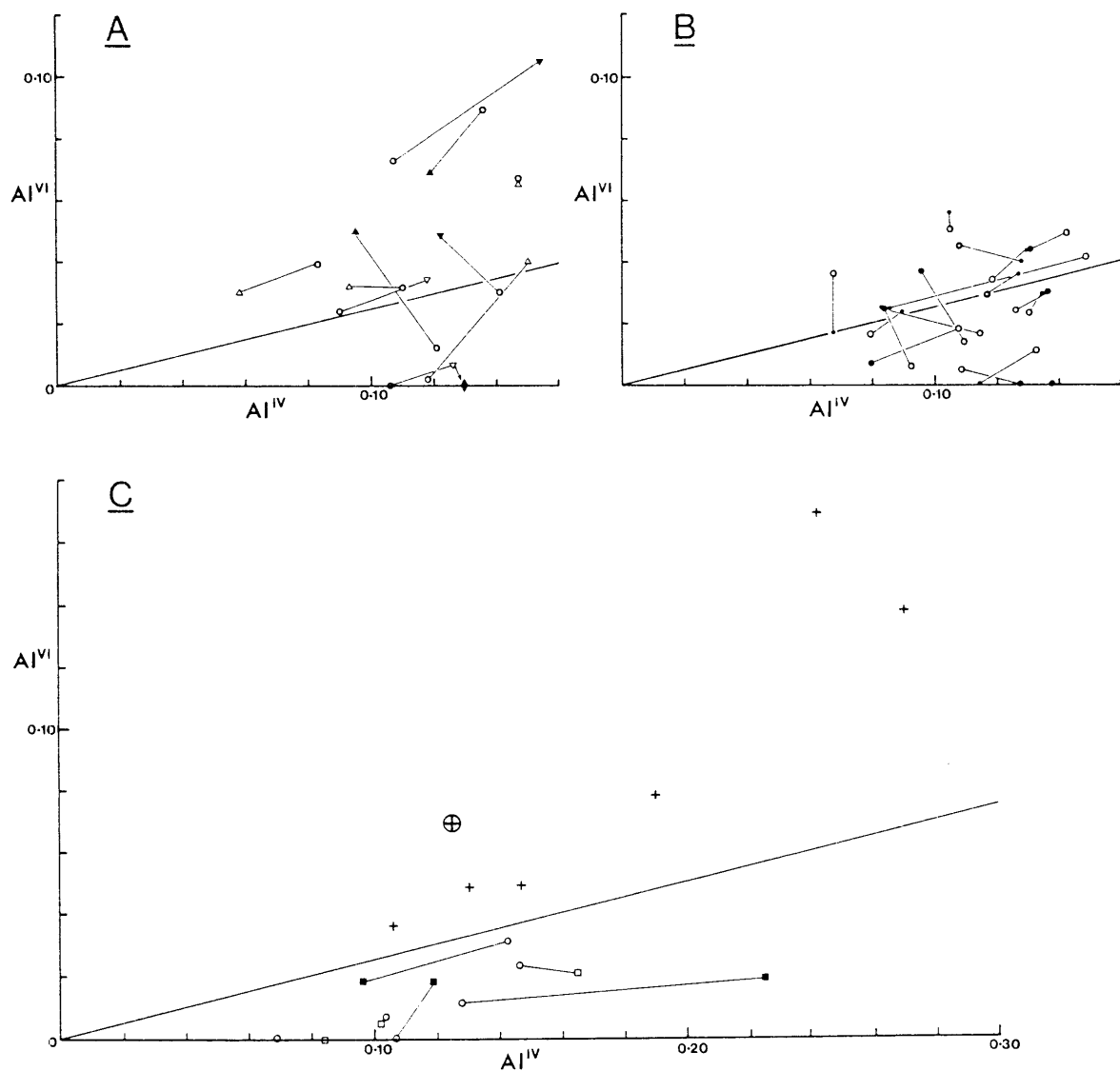


Fig. 3.3: $Al^{VI}:Al^{IV}$ relations in Ca-rich pyroxenes from basaltic rocks in the Myra beds (A), Glen Ward beds (B) and Tamworth Belt in the Nundle and Morrisons Gap areas (C). Symbols as in Table 3.0. Open circles = rim compositions.

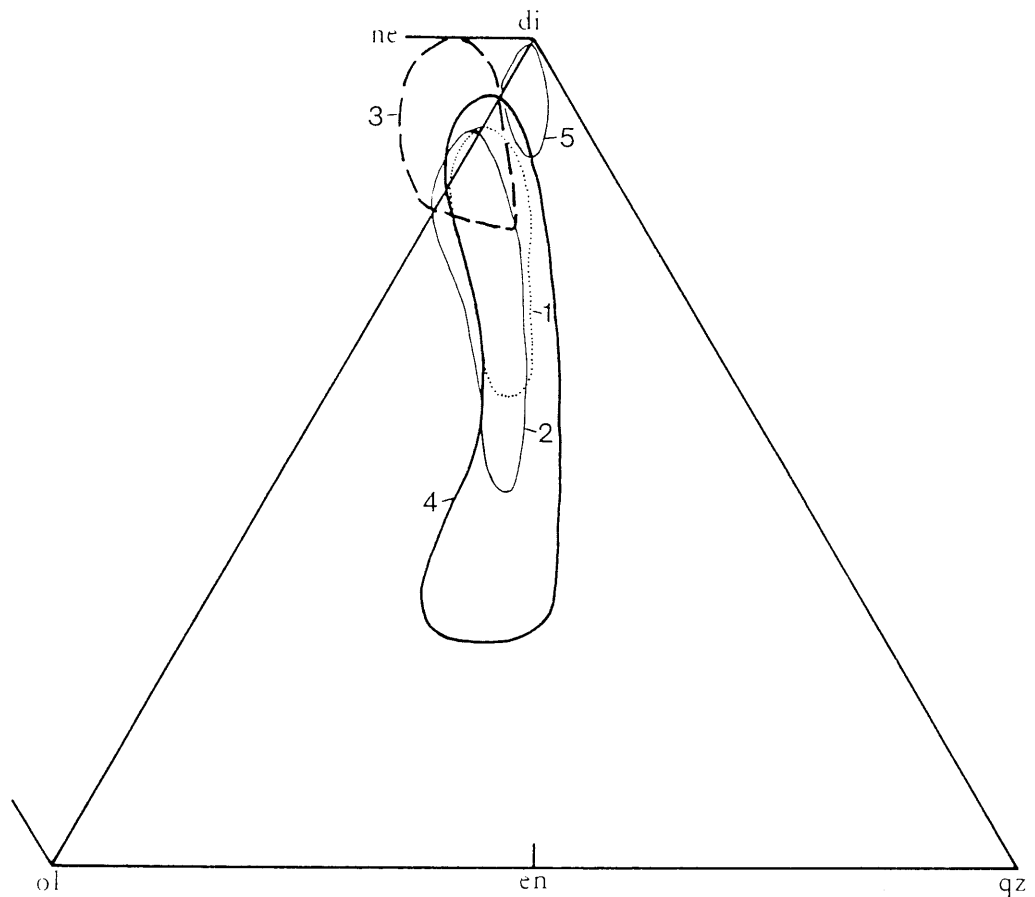


Fig. 3.4: C.I.P.W. normative relations of all analysed Ca-rich pyroxenes from basaltic rocks in the Myra beds (field 1) and Glen Ward beds (field 2). Fields 3 and 4 for Ca-rich pyroxenes from alkaline and tholeiitic basaltic hosts respectively (Coombs, 1963). Pyroxenes from the Pigna Barney Hornblendite-Tonalite Suite plot in field 5 (see Chapter 4).

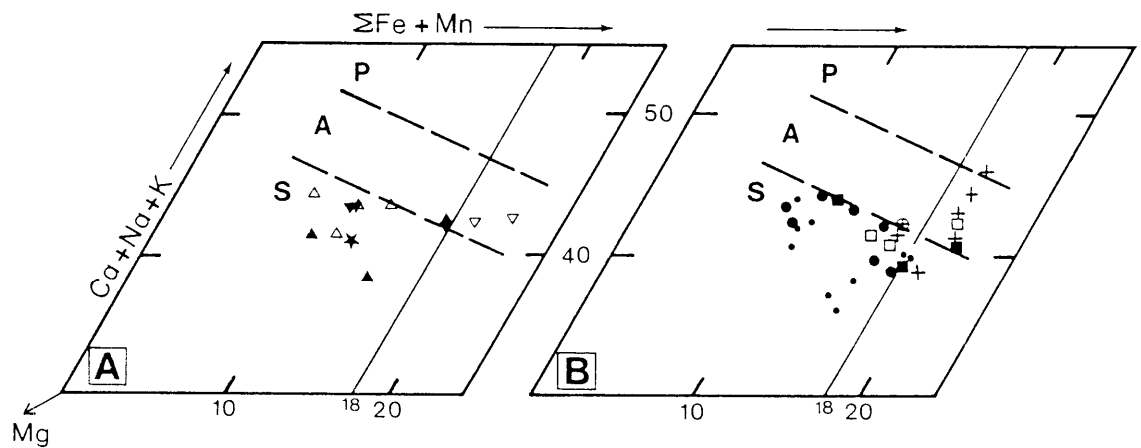


Fig. 3.5: Ca+Na+K:Mg:ΣFe+Mn relations in Ca-rich pyroxenes from basaltic rocks in the Myra beds (A) and the Tamworth Belt (B). Fields for Ca-rich pyroxenes from subalkaline (S), alkaline (A) and peralkaline (P) basalts after LeBas (1962). Symbols as in Table 3.0

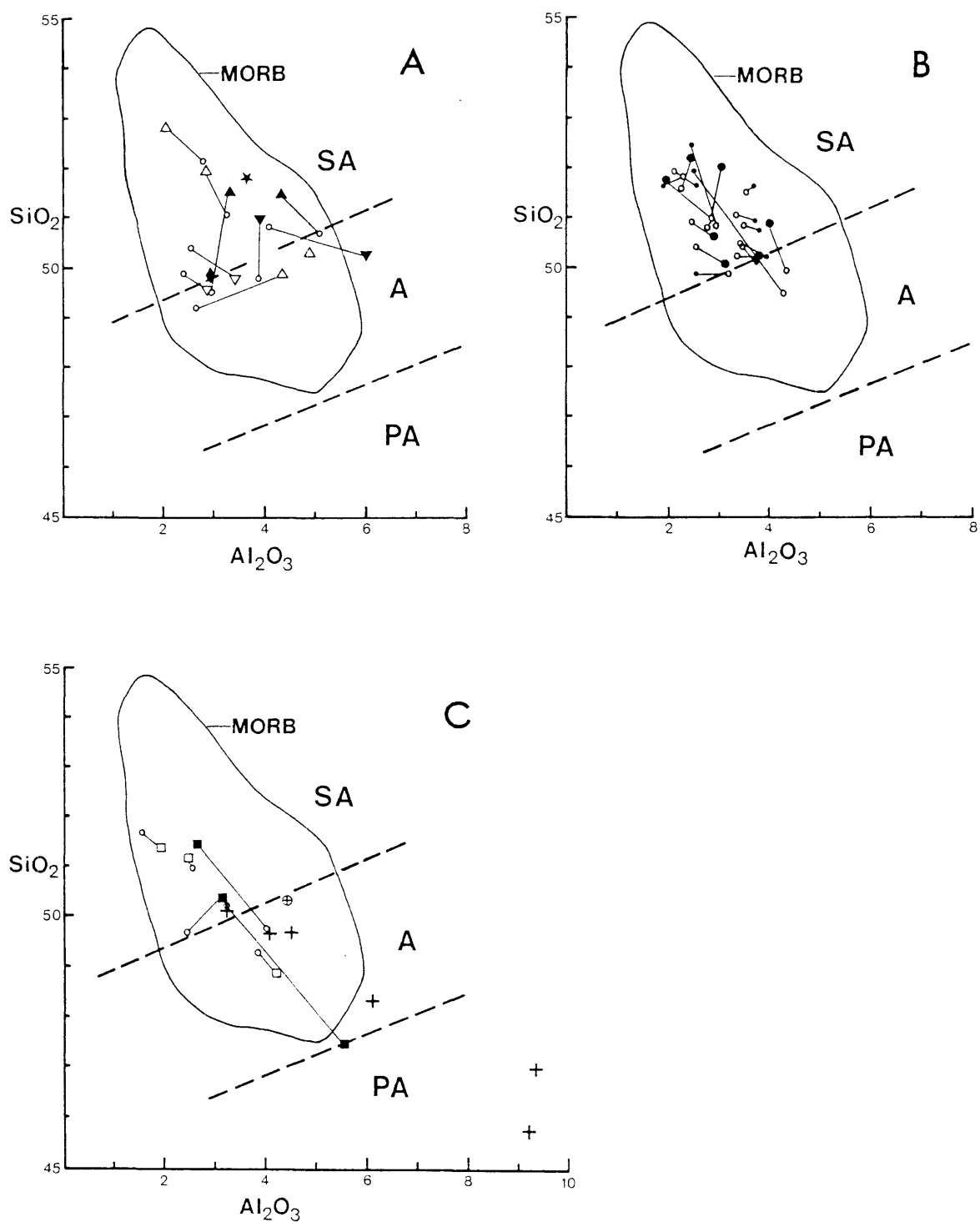


Fig. 3.6: SiO_2 : Al_2O_3 variations in Ca-rich pyroxenes from basaltic rocks in: A, Myra beds; B, Glen Ward beds; C, Tamworth Group in the Nundle and Morrisons Gap areas. Field for MORB pyroxenes from Nisbet and Pearce (1977). Dashed lines separate the fields of LeBas (1962) for Ca-rich pyroxenes from subalkaline (SA), alkaline (A) and peralkaline (PA) basalts. Symbols as in Table 3.0. Open circles = rim compositions.

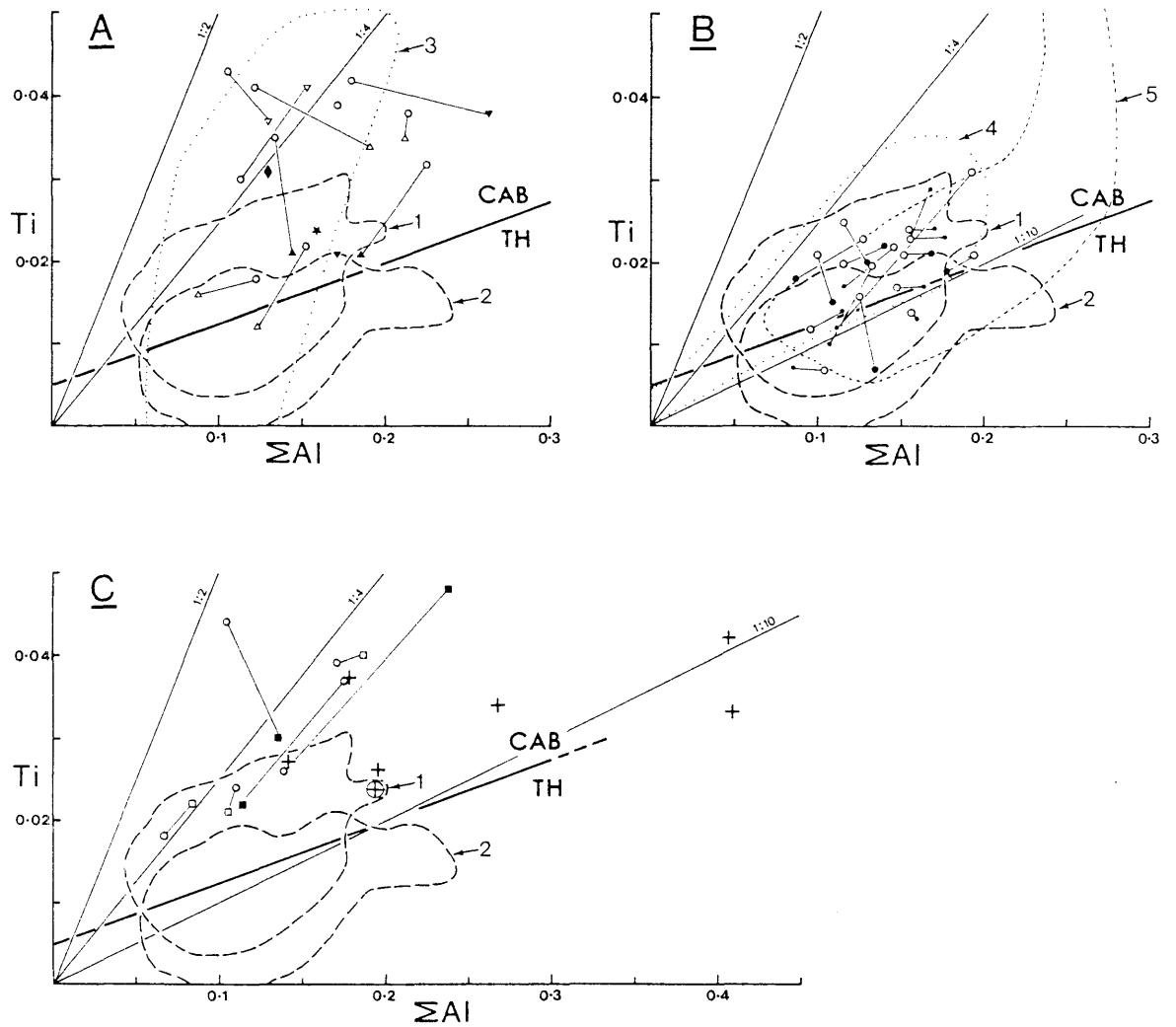


Fig. 3.7: Ti:ΣAl relations of Ca-rich pyroxenes from basaltic rocks in the Woolomin Association (A) and the Tamworth Belt (B and C). Symbols as in Table 3.0. Open circles = rim compositions. Heavy broken line separates Ca-rich pyroxenes from CAB and IAT (TH) with ~80% confidence (Leterrier *et al.*, 1982). Fields for all Ca-rich pyroxenes from: CAB = 1 and IAT = 2 (from Leterrier *et al.*, 1982); Woolomin basaltic rocks in the Glenrock Station area (Offler, 1979) = 3; Tamworth Group basaltic rocks in the Glenrock Station area (Offler, 1979), doleritic intrusives = 4, extrusives = 5.

NOTE: In this figure the fields of Leterrier *et al.* (1982) are not relevant to many of the samples plotted. See text.

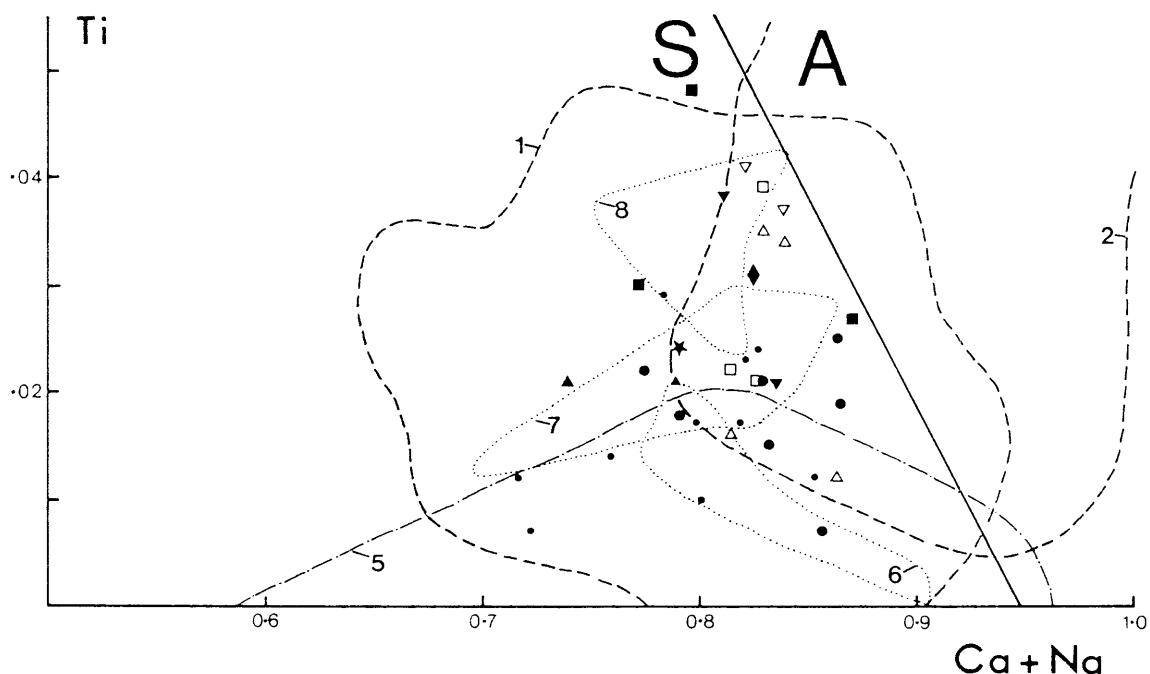


Fig. 3.8: Ti:Ca+Na relations of Ca-rich pyroxenes from basaltic rocks in the Woolomin Association and Tamworth Belt. Leterrier *et al.* (1982) found that 92% of Ca-rich pyroxenes from subalkaline basalts plot to the left of the unbroken line (field S) and 86% of Ca-rich pyroxenes from alkaline basalts plot to the right (field A). Other fields see Fig. 3.9. Symbols as in Table 3.0.

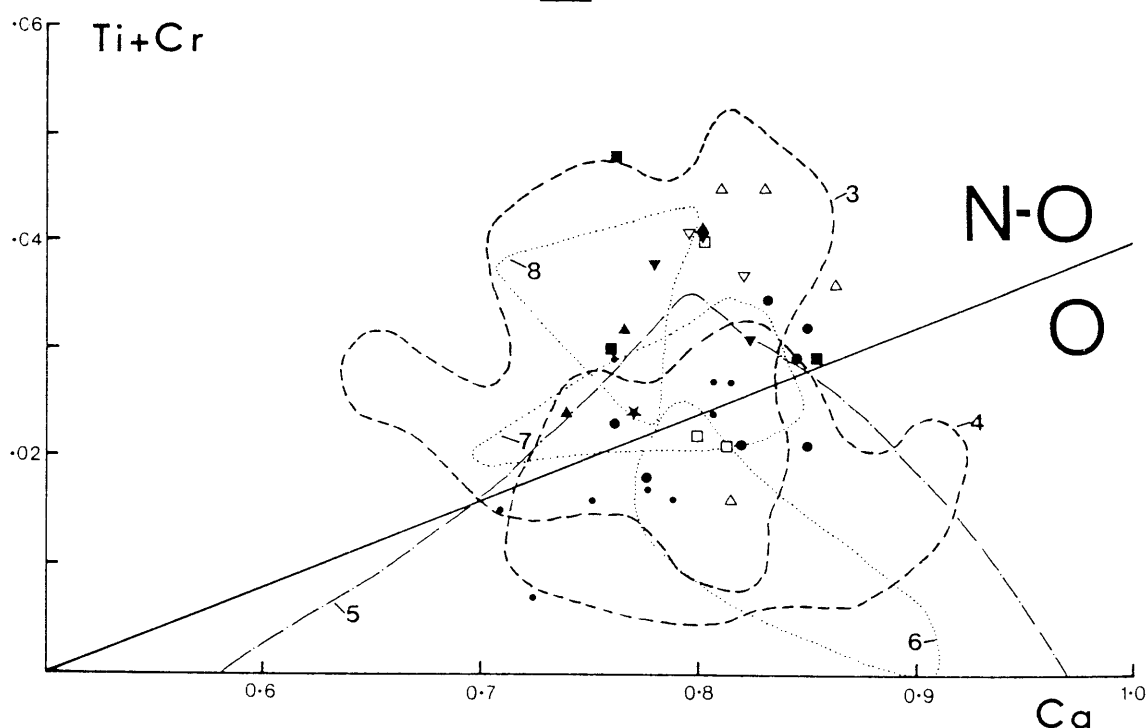
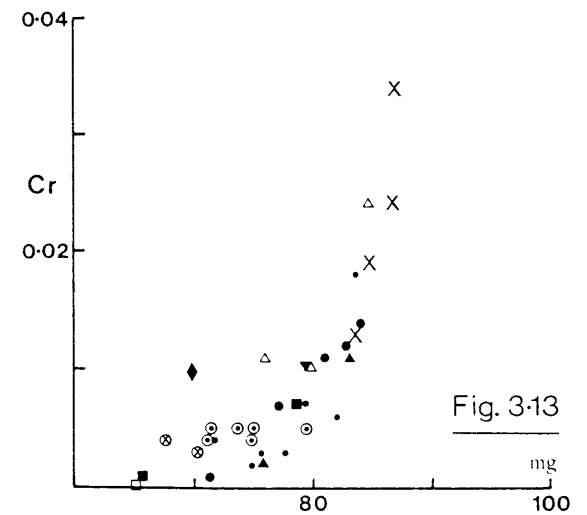
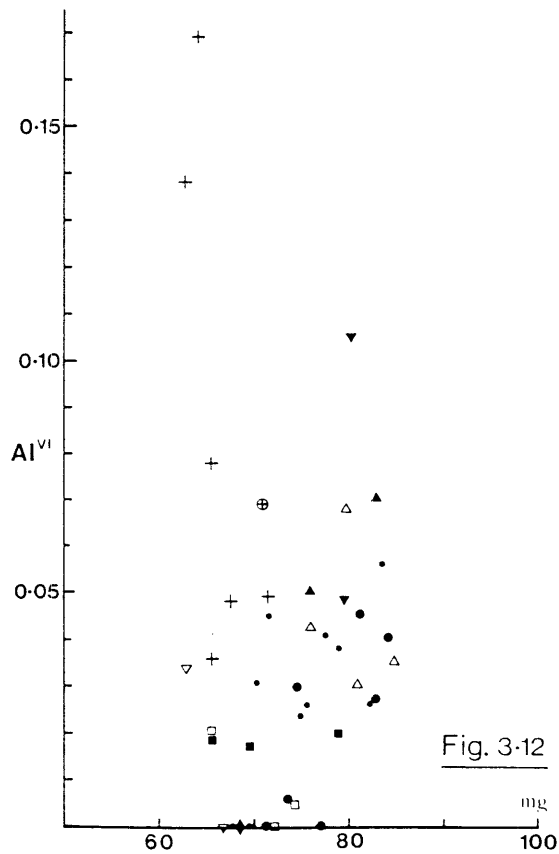
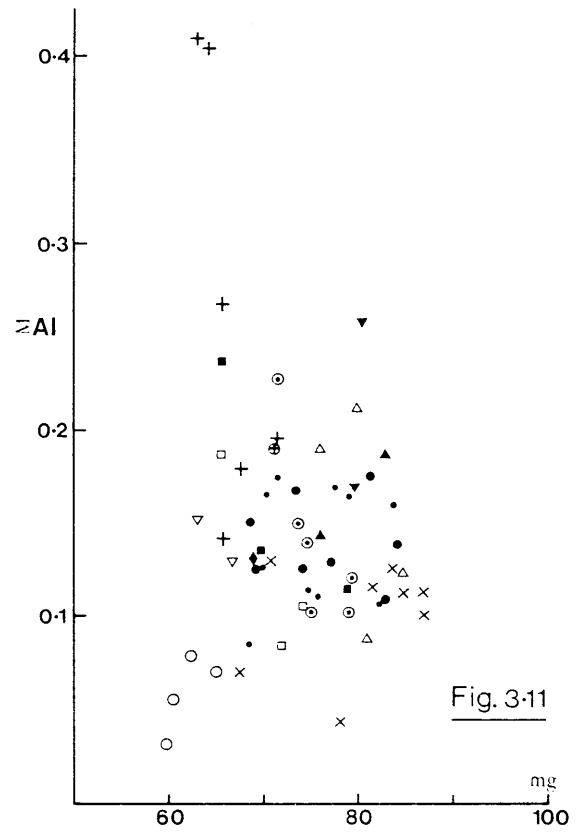
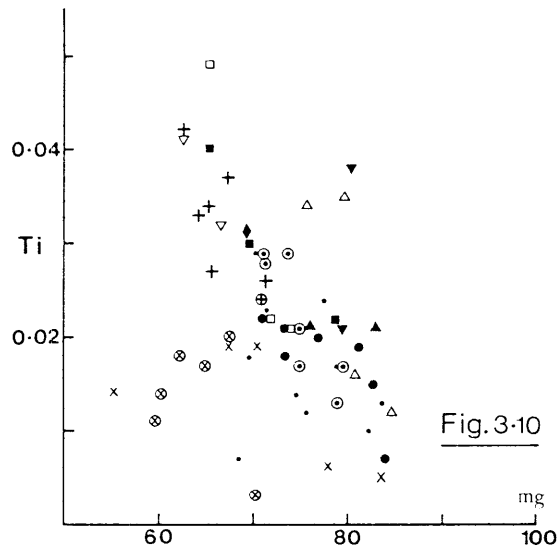


Fig. 3.9: Ti+Cr:Ca relations of Ca-rich pyroxenes from basaltic rocks in the Woolomin Association and Tamworth Belt. 81% of Ca-rich pyroxenes from non-orogenic basalts plot in field N-O and 80% of Ca-rich pyroxenes from orogenic basalts plot in field O, see Leterrier *et al.* (1982). Symbols as in Table 3.0
Fields for all Ca-rich pyroxenes from: subalkaline basalts = 1, alkaline basalts = 2, non-orogenic basalts = 3 and orogenic basalts = 4 (Leterrier *et al.*, 1982); Woolomin basaltic rocks, Glenrock Station area = 5, Tamworth Group basaltic rocks, Glenrock Station area, doleritic intrusives = 6, extrusives = 7 (Offler, 1979) and Nundle area = 8 (Vallance, 1969c, 1974a).



Figs 3.10-3.13: Variation in Ti, ΣAl , Al^{VI} and Cr relative to *mg* in the cores of Ca-rich pyroxenes from basaltic rocks in the Myra beds and the Tamworth Belt. Symbols as in Table 3.0.

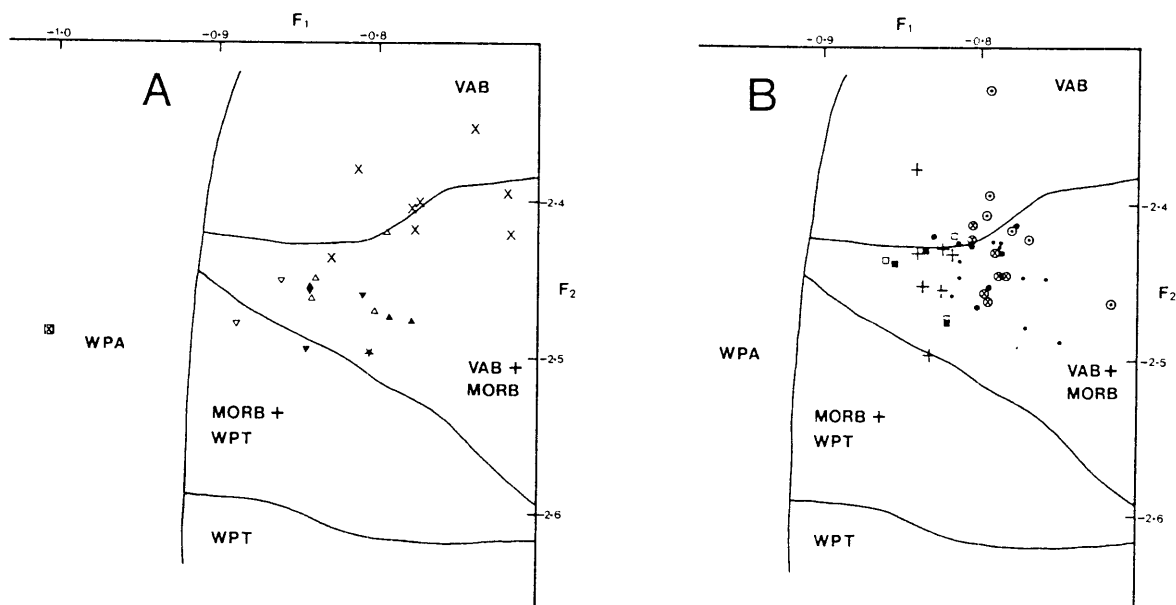


Fig. 3.14: F_1 vs F_2 discriminant diagram (see Nisbet and Pearce, 1977) for Ca-rich pyroxene core compositions from basaltic rocks in the Woolomin Association (A) and in the Tamworth Belt (B). Symbols as in Table 3.0. Abbreviations as in Appendix L.

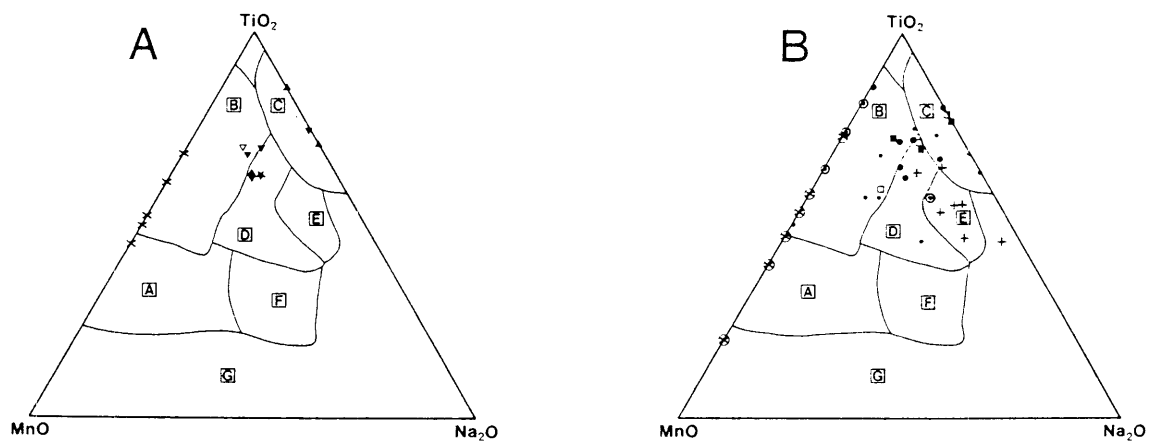


Fig. 3.15: TiO_2 : MnO : Na_2O relations for Ca-rich pyroxene cores from basaltic rocks in the Woolomin Association (A) and the Tamworth Belt (B). Fields for Ca-rich pyroxenes from various basaltic hosts after Nisbet and Pearce (1977). A = VAB, B = MORB, C = WPA, D = all, E = VAB+WPT+WPA, F = VAB+WPA, G = WPA. Symbols as in Table 3.0. Abbreviations as in Appendix L.