BMR Journal of Australian Geology & Geophysics, 7, 99-112.

DISTRIBUTION AND GEOCHEMISTRY OF VOLCANIC ROCKS IN THE DUCHESS-URANDANGI REGION, QUEENSLAND

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Recent mapping in the Duchess-Urandangi region, covering most of the southern part of the Mount Isa Inlier, has shown that felsic and mafic volcanics occur in most Precambrian stratigraphic units exposed there. Five distinct geochemical suites of felsic volcanics are recognised, each suite probably having been derived from a chemically unique crustal source region. The Leichhardt suite is distinguished by high Sr, and low Zr, Nb and Y abundances, whereas the Argylla suite has low Sr and very high Zr and Nb concentrations. The Bottletree suite is characterised by high Ba, Sr, Zr, and Nb, the Duchess-Corella suite by low Sr and Zr, and high Nb and Y contents, and the Carters Bore suite by high K_2O and low Al_2O_3, Na_2O, CaO, Pb, Sr, and Ba. Most of the analysed mafic volcanics from the region are chemically similar, and there is no systematic change in composition from west to east. The mafic volcanics are characterised by low incompatible-element contents and are similar chemically to continental tholeiites of the Karroo province of southern Africa. Silica values for the volcanics and their intrusive equivalents show a well-defined bimodal distribution, probably indicating an extensional crustal regime.

Introduction

The Duchess-Urandangi region covers most of the southern part of the Mount Isa Inlier (Geological Survey of Queensland, 1975; Fig. 1). The inlier is generally considered to consist of a central basement belt flanked on either side by thick sequences of younger rocks, commonly referred to as the western and eastern successions, which consist mainly of Haslingden Group and Mary Kathleen Group rocks, respectively. This interpretation was first put forward by Carter & others (1961) and has been followed by most later workers (e.g., Plumb & Derrick, 1975; Derrick & others, 1977a; Plumb & others, 1980, 1981), but has been challenged by Blake (1980, 1981). Blake suggested that the Haslingden Group predates not only the eastern succession, but part of the basement belt, and that the Corella Formation, the most widespread unit of the Mary Kathleen Group, represents at least two quite separate units, one older than, and one younger than, the Haslingden Group.

Two major northerly trending fault zones, the Wonomo/Mount Annable/Mount Isa Fault system in the west and the Pilgrim Fault Zone to the east divide the Duchess-Urandangi region into three geographical parts: the western, central, and eastern areas (Fig. 1; Blake & others, 1981a). Correlations between these areas are generally uncertain.

The stratigraphy of the Duchess-Urandangi region is summarised in Figure 2 and the distribution of the main rock groupings is shown in Figure 3. Most Precambrian stratigraphic units in the region contain felsic or mafic volcanics (Fig. 3).

Petrographic and geochemical data on the volcanic rocks presented in this paper are based on the examination of several hundred thin sections and 125 chemical analyses. The samples were analysed at AMDEL (Australian Mineral Development Laboratories), Adelaide. Most element abundances were determined by X-ray fluorescence spectrometry; Co, Cr, Cu, Li, Zn, Ni, and V concentrations were determined by atomic absorption spectroscopy. Representative analyses of volcanic rocks from the region are listed in Tables 1 and 2. The complete list of analyses is given in Wyborn (in preparation). Mineral compositions in twenty samples (19 metabasites and one metadacite) were analysed using the TPD energy- dispersive microprobe at the Research School of Earth Sciences, Australian National University, following the methods of Reed & Ware (1975) and Ware (1981). All analysed amphiboles have been classified according to the scheme of Leake (1978).

Of the five felsic volcanic suites recognised in the Duchess-Urandangi region, two, the Leichhardt and Argylla, consist predominantly of felsic volcanic units, which extend to the north, where they have been studied by Wilson (1978). Wilson reported that the two sequences (mapped as Leichhardt Metamorphics and Argylla Formation) were chemically distinct, a conclusion with which we concur after the study of equivalent formations farther south. In contrast, the mafic volcanic rocks analysed from the Duchess-Urandangi region tend to be chemically uniform, and the variation in composition from west to east found by Glikson & others (1976) in equivalent formations to the north, is not apparent in the Duchess-Urandangi region.

Petrography and metamorphism

The volcanic rocks in the region have been regionally metamorphosed to either greenschist or amphibolite grade. The felsic volcanics are generally porphyritic, containing phenocrysts of mainly quartz and feldspar and, less commonly, biotite, hornblende, and opaque minerals in a fine-grained quartzofeldspathic groundmass, which commonly also contains minor biotite, muscovite, or hornblende. Amphibolite-grade rocks are difficult to distinguish, because the most common assemblage in the felsic volcanics is quartz + feldspar + biotite, which remains stable from upper greenschist to at least upper amphibolite grade. Greenschist-grade felsic volcanics contain chlorite, epidote, muscovite, biotite, actinolite, calcite, and plagioclase. The plagioclase grains are mostly albite partly replaced by sericite, muscovite, and epidote/clinozoisite. Some hornblende is generally present in amphibolite-grade felsic volcanics and chlorite, epidote, and actinolite show a decrease in abundance. Plagioclase compositions range from calcic oligoclase to andesine. Sphene, apatite, opaque minerals, allanite, zircon, and monazite are common accessory minerals in both greenschist and amphibolite-grade rocks.

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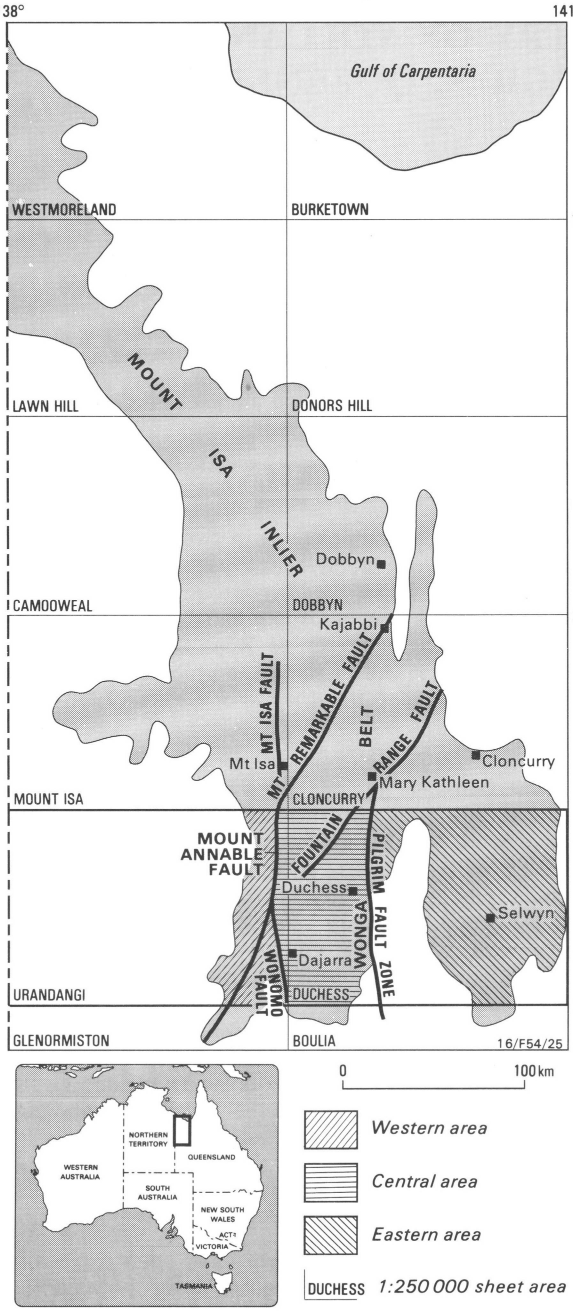

Figure 1. Major structural features and subdivisions of the Duchess-Urandangi region.

Greenschist-grade mafic volcanics contain albite, chlorite, actinolite, epidote/clinozoisite, biotite, quartz, sphene, potassium feldspar, apatite, and calcite. Primary igneous textures are generally preserved and some plagioclase grains have sericitised cores of labradorite and rims of oligoclase-andesine. Primary clinopyroxene is rare. Amphibolite-grade mafic volcanics contain coexisting tschermakitic to magnesiohornblende, or rarely, ferrohornblende and calcic oligoclase or andesine, and some garnet or actinolitic hornblende may also be present. Most primary igneous textures have been obliterated by recrystallisation effects.

Volcanic rocks of the central area

The central area bounded by the Wonomo/Mount Annable/Mount Isa Fault system to the west and the Pilgrim Fault Zone to the east, consists of three main structural divisions: the central Kalkadoon-Leichhardt block, which is flanked by the western succession in the west and the Duchess belt in the east. The Kalkadoon-Leichhardt block consists largely of igneous rocks—felsic and mafic volcanics of the Tewinga Group and granitic intrusives. Most stratigraphic units are dominated by volcanics, with only minor intercalated sediments. The Duchess belt (Bultitude & others, in press) consists mainly of the Corella Formation, a unit of calc-silicate rocks and subordinate felsic and mafic volcanics, but also contains some basement rocks (Plum Mountain Gneiss) and plutons of the Wonga Batholith. The highly deformed western part of the Duchess belt, which includes upper Tewinga Group rocks, is the southern extension of the Wonga belt of Derrick (1980). The western succession unconformably overlies rocks of the Kalkadoon-Leichhardt block and consists mainly of sedimentary and volcanic rocks of the Haslingden Group. The Bottletree Formation, which underlies this group, is also regarded by us as part of the western succession, rather than part of the basement sequence (*cf* Derrick & Wilson, 1981).

The Tewinga Group, as defined by Derrick & others (1976a) comprises three formations, from oldest to youngest, the Leichhardt Metamorphics, Magna Lynn Metabasalt and Argylla Formation. In the Kalkadoon-Leichhardt block, the Leichhardt Metamorphics of earlier workers are mapped partly as Leichhardt Volcanics, a formation of generally little-recrystallised felsic volcanic rocks, and partly as undivided Tewinga Group, which consists mainly of amphibolite-grade felsic gneissic rocks.

The felsic gneisses of the **undivided Tewinga Group** range from banded to massive, and many contain feldspar (mainly microcline) augen or feldspar megacrysts and small mafic inclusions. A few massive units show vague contorted flow banding and are probably metarhyolite lavas, but most of the gneisses may be meta-ignimbrites. Mafic volcanics are represented by massive to schistose and commonly amygdaloidal metabasalt (Blake & others, 1982). Four out of seven analysed zircon size fractions separated from a metadacite have yielded a U-Pb zircon age of 1866 $\pm$ 5 m.y. (Page, in preparation). Page interpreted this result as most probably representing the initial crystallisation age of the metadacite. The age is similar to that obtained for the Leichhardt Volcanics, and also for the Leichhardt Metamorphics north of the region (Page, 1978, in preparation). Seven samples have been chemically analysed, six felsic gneisses and one metabasalt.

The **Leichhardt Volcanics** (Blake & others, 1981b) consist mainly of massive rhyolitic to dacitic ignimbrites, which contain abundant to sparse phenocrysts (<5 mm) enclosed in a fine-grained quartzofeldspathic groundmass in which eutaxitic and devitrification textures are commonly preserved. Phenocrysts of euhedral sodic plagioclase are more abundant than those of euhedral to partly resorbed quartz and alkali feldspar; rare phenocrysts of biotite and hornblende, now recrystallised and altered, may also be present. The Leichhardt Volcanics also contain minor flow-banded rhyolite lavas, some possible high-level intrusions, and rare basaltic lava flows and clastic sediments (Blake & others, 1982; Bultitude & others, in press). The metamorphic grade appears to be predominantly greenschist; some higher grade areas are indicated by the

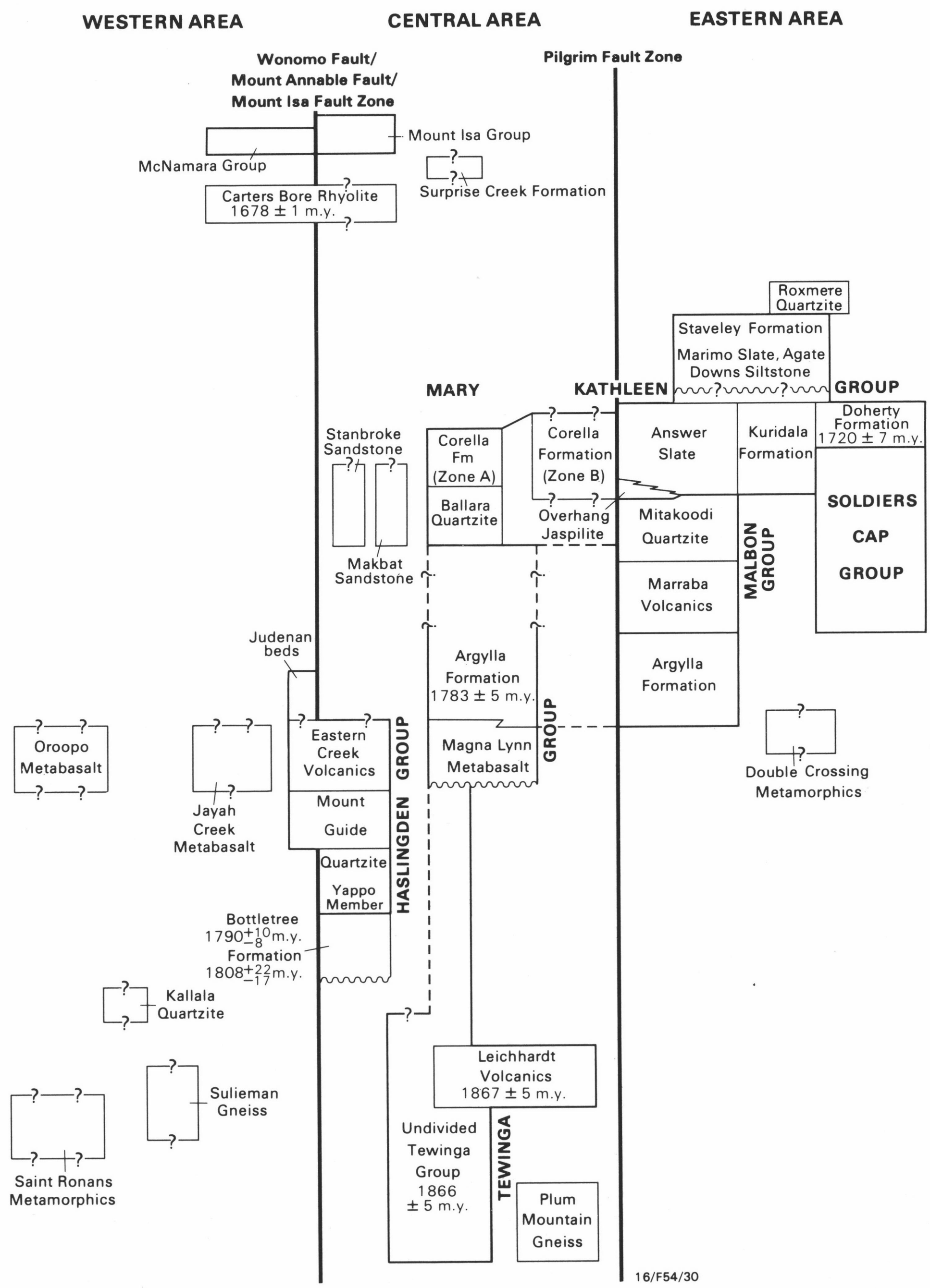

Figure 2. Stratigraphic correlation scheme for the Precambrian of the Duchess-Urandangi region.

presence of amphibolite-grade mafic dykes. A U-Pb zircon age of 1867±5 m.y. has been obtained by pooling data for 19 zircon fractions from the Leichhardt Volcanics and Leichhardt Metamorphics (Page, in preparation). Thirty-four samples from the Leichhardt Volcanics have been analysed.

The **Magna Lynn Metabasalt** (Derrick & others, 1976a) crops out in the northeastern part of the Kalkadoon-Leichhardt block and the Duchess belt. Metabasalt is the main rock type, with some meta-arenite, conglomerate, and minor felsic volcanics. Pillow structures and hyaloclastite structures are rare, suggesting that the basaltic volcanism was mainly subaerial. The Magna Lynn Metabasalt has been regionally metamorphosed, mainly to amphibolite grade, and is extensively recrystallised. A major unconformity (disconformity) representing about 80 m.y. separates the Leichhardt Volcanics from the overlying Magna Lynn Metabasalt and Argylla Formation (Page, 1978, in preparation). Three mafic volcanic samples have been analysed.

The **Argylla Formation** (Carter & others, 1961) crops out in the Kalkadoon-Leichardt block and the western part of the Duchess belt, and also in the western part of the eastern area, east of the Pilgrim Fault Zone. It consists mainly of extensively recrystallised to gneissic rhyolitic to dacitic metavolcanics (massive ignimbrite, together with minor felsic lava, agglomerate, and bedded tuff) and some possible high-level intrusives. The formation also includes interlayered shallow-water clastic metasediments, especially in the eastern area, and scattered mafic lava flows. The felsic volcanic rocks

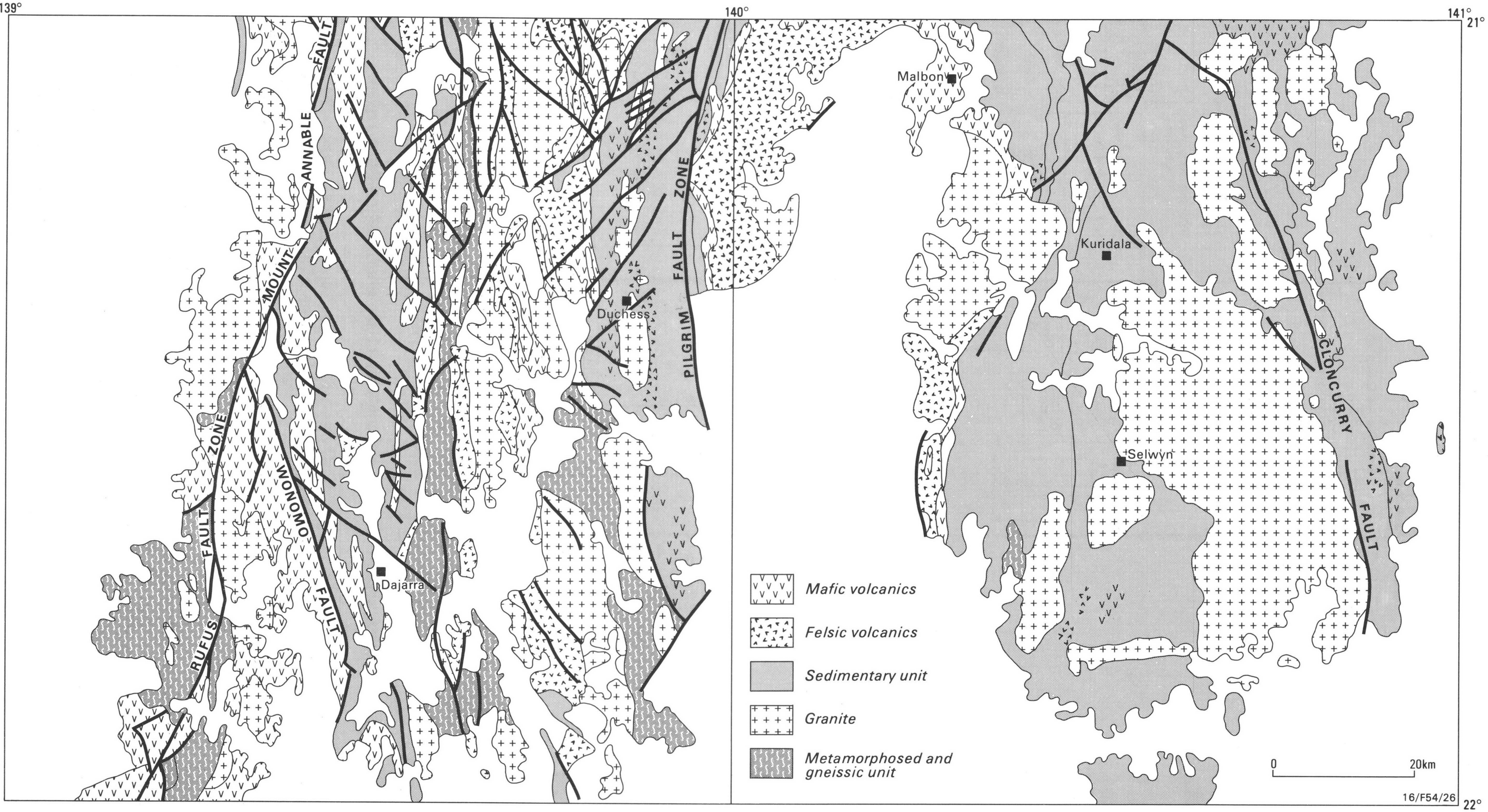

Figure 3. Generalised geological map of the Duchess-Urandangi region, showing the distribution of volcanic-bearing units.

commonly contain phenocrysts of potassium feldspar and subordinate smaller phenocrysts of sodic plagioclase and quartz. The formation has been regionally metamorphosed, mainly to amphibolite grade. Some interfingering of felsic and mafic volcanics at the base of the Argylla Formation and the top of the Magna Lynn Metabasalt indicate that the two formations are essentially the same age. The age of the Argylla Formation volcanism has been determined at 1783±5 m.y. (Page, in preparation). Thirteen samples of felsic volcanics from the Argylla Formation have been analysed.

The **Plum Mountain Gneiss** (Blake & others, 1981b) crops out in the southeastern part of the central area. The predominant rock types are quartzofeldspathic gneiss and augen gneiss, probably representing felsic volcanics and granite that have been regionally metamorphosed to amphibolite grade (Blake & others, 1981b). The non-intrusive quartzofeldspathic gneissic rocks may be correlated with those of the undivided Tewinga Group. Two analyses of Plum Mountain Gneiss have been obtained, but both are probably from intrusive, rather than extrusive units in the sequence.

The **Bottletree Formation** (Blake & others, 1981b), the oldest unit in the western succession, consists mainly of rhyolitic to dacitic lavas and ignimbrites, interlayered pebbly greywacke and greywacke conglomerate, and sheared, schistose and partly amygdaloidal basaltic lava flows (common near the base and top of the formation). In the porphyritic felsic volcanics the phenocrysts are predominantly plagioclase, but in some units potassium feldspar is the most abundant phenocryst; other phenocrysts include quartz, biotite, magnetite, and hornblende. The Bottletree Formation is extensively recrystallised and has been regionally metamorphosed to amphibolite grade. The formation extends northwards into the Mary Kathleen 1:100 000 Sheet area, where it has been mapped as part of the Argylla Formation (Derrick & others, 1977a). Isotopic data indicate that the Bottletree Formation is about the same age as or a few million years older than the Argylla Formation (Page, in preparation). Twenty-one rocks from the Bottletree Formation have been analysed, including two mafic lavas.

The **Eastern Creek Volcanics** (Carter & others, 1961) are part of the Haslingden Group, which conformably overlies the Bottletree Formation. Haslingden Group rocks have also been mapped in the western area (Bultitude & others, in press). Subdivision of the Eastern Creek Volcanics into Cromwell Metabasalt Member (oldest), Lena Quartzite Member, and Pickwick Metabasalt Member (youngest), following the practice of Derrick & others (1976b) in sheet areas to the north of the Duchess-Urandangi region, has not been possible. The Eastern Creek Volcanics consist of a series of predominantly subaerial tholeiitic basalt lava flows and interlayered clastic sediments. The formation has been regionally metamorphosed to greenschist and amphibolite grades. Five mafic rocks have been analysed from this formation.

The **Corella Formation** (Carter & others, 1961) of the Duchess belt is part of the Zone B Corella Formation of Blake (1982). It consists mainly of amphibolite-grade calc-silicate rocks, but includes interlayered felsic and mafic metavolcanic units. Extensively recrystallised, strongly foliated to gneissic felsic volcanics in the north probably represent mainly ignimbritic feldspar porphyry and non-porphyritic metarhyolite and metadacite (Bultitude & others, in press). In the south, medium to coarse quartzofeldspathic granofels may represent metamorphosed felsic tuff or possible arkose. Amphibolitic mafic lavas contain scattered amygdaloidal zones, rare possible pillows and flow-margin breccias, and are commonly closely associated spatially with felsic volcanic units. Traditionally, the Corella Formation has been thought to overlie the Argylla Formation (Plumb & others, 1980) and hence be younger than about 1780 m.y. (Page, 1978, in preparation). However, Blake (1980, 1981, 1982) considers that the Corella Formation in this belt may contain rocks older than 1870 m.y. One metabasite and fifteen felsic volcanics from the Corella Formation have been analysed.

Volcanic rocks of the western area

The **Sulieman Gneiss** (Blake & others, 1981b) crops out in the southern part of the western area between the Wonomo Fault and Rufus Fault Zone (Fig. 3), and consists of amphibolite-grade interlayered quartzofeldspathic gneiss and schist, augen gneiss, amphibolite, hornblende schist, quartzite, and some banded garnetiferous calc-silicate gneiss. Most of the protolith of this unit was probably rhyolitic to dacitic volcanics and interlayered volcaniclastic sediments; some of the augen gneiss may represent granite and/or intrusive feldspar porphyry. The Sulieman Gneiss may correlate with the Saint Ronans Metamorphics, undivided Tewinga Group, Yaringa Metamorphics, or May Downs Gneiss (regarded by Derrick & others, 1976b, as a metamorphosed equivalent of the lower Mount Guide Quartzite). Three samples have been analysed from this unit, including one metabasite.

The **Jayah Creek Metabasalt** (Blake & others, 1981b) also crops out between the Wonomo Fault and the Rufus Fault Zone. It consists of slightly to highly schistose, amphibolite-grade basaltic lava flows and interbedded sediments. Many individual lava flows have well-preserved amygdaloidal zones and marginal breccias. The Jayah Creek Metabasalt, which is thought to overlie the Sulieman Gneiss concordantly, may be equivalent to the Eastern Creek Volcanics. Three mafic volcanics have been analysed from this unit.

The **Saint Ronans Metamorphics** (Blake & others, 1981b), the oldest unit exposed west of the Rufus Fault Zone, is made up of amphibolite-grade arenites and argillites, and interlayered mafic and felsic volcanics. Interfingering of felsic and mafic volcanics occurs locally, indicating contemporaneous mafic and felsic volcanism. Remnant phenocrysts in the felsic volcanics are of feldspar (mainly albite to andesine), quartz and opaque oxide. Only one sample, an amphibolite, was analysed from this formation.

The **Oroopo Metabasalt** (Blake & others, 1981b) crops out west of the Rufus Fault Zone and consists of massive to amygdaloidal mafic lava flows and some interbedded quartzite, arenite, siltstone, and limestone, regionally metamorphosed to greenschist and lower amphibolite grades. The Oroopo Metabasalt, which overlies the Saint Ronans Metamorphics, may correlate with the Eastern Creek Volcanics which it closely resembles. Two metabasalts from the formation have been analysed.

The **Carters Bore Rhyolite** (Derrick & others, 1978) exposed in the northern part of the western area, is a thin sequence of rhyolitic ash-flow tuffs and minor lava flows, which have been regionally metamorphosed to greenschist grade. The volcanics contain phenocrysts of recrystallised quartz and potassium feldspar (mainly microcline) in a fine-grained granoblastic groundmass. Small, scattered outcrops of felsic volcanics in the southwestern part of the central area have also been tentatively assigned to this formation (Blake & others, 1982). The age of the Carters Bore Rhyolite has been determined at 1678±1 m.y. (Page, 1978). Three samples have been chemically analysed.

Volcanic rocks of the eastern area

Volcanic units in the eastern area, east of the Pilgrim Fault Zone, are much less voluminous than in the central and western areas, and most sequences are dominated by clastic metasediments or calc-silicate rocks.

The dominant rock types in the **Double Crossing Metamorphics** (Blake & others, 1981b) are gneiss and schist, which are thought to be mainly metamorphosed quartzofeldspathic sediments; however, the formation also contains some probable felsic and mafic metavolcanics (Blake & others, 1979). These rocks, which have been metamorphosed to amphibolite grade, may represent pre-Argylla Formation basement rocks or lateral equivalents of the Argylla Formation and Malbon Group rocks. One felsic gneiss, a possible metavolcanic has been analysed.

The **Marraba Volcanics** (Carter & others, 1961) the older formation of the Malbon Group (Derrick & others, 1976c), consists predominantly of basaltic lava flows and clastic metasedimentary rocks, but locally includes some felsic volcanics in the upper part (Noon, 1978, 1979). The mafic volcanics range from aphyric to porphyritic and from massive to vesicular and amygdaloidal. The grade of metamorphism increases from greenschist in the north to amphibolite in the south. One mafic volcanic rock has been analysed.

The **Mitakoodi Quartzite** (Carter & others, 1961), the younger formation of the Malbon Group, consists of meta-arenite, minor metasiltstone and limestone, and scattered lenses of felsic and mafic metavolcanics (Noon, 1978; Blake & others, 1979; Donchak & others, 1979). The metamorphic grade increases from greenschist in the north to amphibolite in the south. Two felsic volcanics were analysed.

The **Soldiers Cap Group** (Carter & others, 1961; Derrick & others, 1976d) crops out extensively in the eastern part of the region, mainly east of the Cloncurry Fault. It contains amphibolite-grade mica schist, gneiss, meta-arenite, and amphibolite bodies, which are thought to represent both extrusive lavas and intrusive metadolerites (Blake & others, 1979). Minor felsic volcanics are represented by metarhyolite and possibly garnetiferous quartzofeldspathic gneiss (Donchak & others, 1979). The age of the Soldiers Cap Group is uncertain. Metabasalts within the group have been correlated with the Marraba Volcanics and Eastern Creek Volanics (Plumb & others, 1980), but Blake (1980) suggested that the Eastern Creek Volcanics may be older than some of the volcanics of the Soldiers Cap Group. Three metabasites and one quartzofeldspathic gneiss have been analysed.

The main rock types in the **Kuridala Formation** (Carter & others, 1961), part of the Mary Kathleen Group (Derrick & others, 1977b) are metamorphosed interbedded greywacke, siltstone, and shale. The formation locally includes some metarhyolite containing small phenocrysts of quartz and alkali feldspar, associated agglomerate and bedded tuff, as well as minor basaltic volcanics (Blake & others, 1979; Donchak & others, 1979). Porphyroblastic garnet, andalusite, and staurolite have developed in the metasediments, indicating metamorphism to amphibolite grade. One metabasalt was analysed.

Calc-silicate granofels and massive calc-silicate breccia of the **Doherty Formation** in the eastern area were previously mapped as Corella Formation (*see* Blake & others, 1981b). The formation also contains lensoid bodies of metarhyolite up to 200 m thick and scattered bands of possibly amygdaloidal metabasalt and para-amphibolite (Blake & others, 1981b). The Doherty Formation has been regionally metamorphosed to amphibolite grade. Two metarhyolite samples have been analysed, from separate lenses, as well as two metabasites.

A small body of greenschist-grade metabasalt, not chemically analysed, occurs within the **Staveley Formation** (Blake & others, 1981b), a unit consisting predominantly of calcareous metasedimentary rocks.

Geochemistry

The volcanic rocks of the region have been regionally metamorphosed to either greenschist or amphibolite grade, and are commonly extensively recrystallised; hence element abundances, especially those for the more mobile elements, may be expected to depart significantly from original concentrations, particularly in the more extensively recrystallised rocks. However, the general consistency of element trends on variation diagrams shown by the various suites, some of which include samples from widely scattered locations throughout the Duchess-Urandangi region, suggests that although some remobilisation of elements, especially alkali elements, may have occurred, most analysed specimens are close to their original compositions. Wilson (1978) and Glikson & Derrick (1978), in studies of equivalent volcanic formations to the north of the Duchess-Urandangi region, also concluded that apart from some mobility of alkali elements the chemical compositions of most specimens have been little changed by metamorphism.

Felsic volcanics

Five major chemically distinct cogenetic groups or suites of felsic volcanics have been recognised in the Duchess-Urandangi region. The five suites, named after the main stratigraphic unit in which they are represented are the Leichhardt, Argylla, Bottletree, Duchess-Corella, and Carters Bore. All volcanic rocks of a particular suite are chemically, but not necessarily stratigraphically, related (*see* Chappell, 1979).

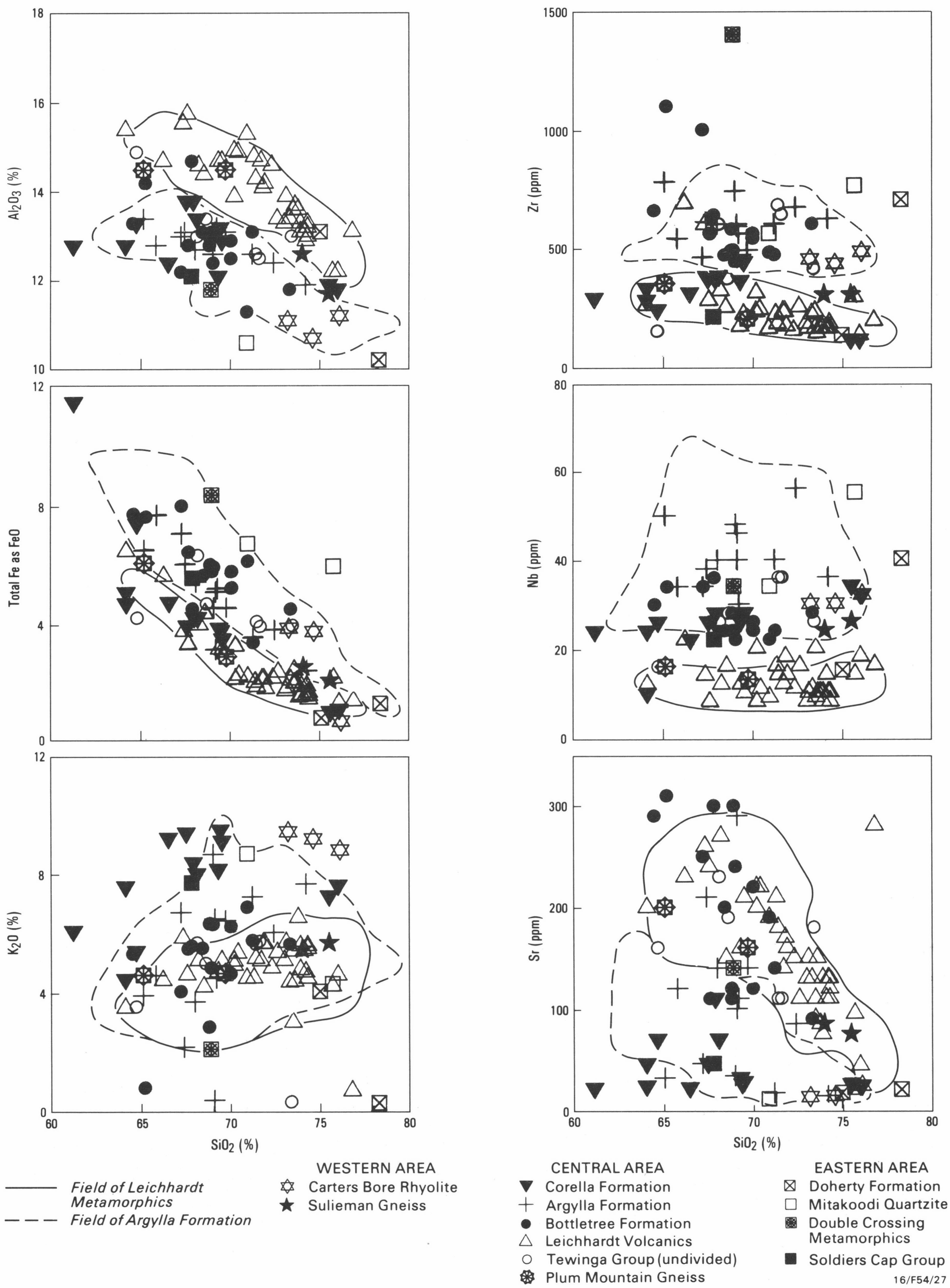

Figure 4. Abundances of selected major oxides and trace elements plotted against SiO_2 for the felsic volcanics of the Duchess-Urandangi region.

Also shown are the fields outlined by the Leichhardt Metamorphics (53 analyses) and Argylla Formation (79 analyses) from north of the region using data from Rossiter & Ferguson (1980) and Wyborn (in preparation).

Table 1. Representative chemical analyses of felsic volcanics from the Duchess-Urandangi region.

	Leichhardt Volcanics		*Argylla Formation*		*Bottletree Formation*		*Corella Formation*		*Carters Bore Rhyolite*		
No. of samples or	34		13		19		15		7653–	7653–	7653–
sample numbers*	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	1143A	1143B	1143C
SiO_2	72.36	2.59	69.03	2.52	70.00	3.60	67.40	4.24	76.10	74.60	73.20
TiO_2	0.23	0.11	0.62	0.20	0.64	0.15	0.48	0.24	0.47	0.45	0.44
Al_2O_3	13.84	0.86	12.82	0.38	11.93	2.97	12.88	0.67	11.20	10.70	11.10
Fe_2O_3	1.19	0.50	3.04	1.24	2.71	1.34	3.23	2.13	0.49	3.75	3.88
FeO	1.18	0.86	2.05	0.81	3.19	0.80	1.64	0.95	0.24	0.35	0.35
MnO	0.03	0.02	0.04	0.03	0.06	0.02	0.05	0.08	0.01	0.01	0.01
MgO	0.45	0.31	0.56	0.36	0.45	0.26	0.61	0.28	1.02	0.13	0.13
CaO	1.60	0.64	1.68	1.14	2.43	0.98	1.74	1.13	0.24	0.09	0.09
Na_2O	2.90	0.58	2.55	0.95	2.10	0.81	1.67	1.00	0.20	0.10	0.16
K_2O	4.84	0.96	5.52	1.70	4.76	1.60	7.71	1.58	8.82	9.20	9.44
P_2O_5	0.06	0.03	0.15	0.09	0.14	0.06	0.11	0.06	0.15	0.06	0.07
Ba	817	318	856	503	1483	523	1194	332	210	200	170
Rb	197	53	190	53	175	50	241	64	100	130	140
Sr	152	60	89	58	180	74	40	28	24	14	13
Pb	26	23	7	5	18	10	3	3	5	3	<2
Th	29	6	30	6	26	4	33	14	34	26	30
U	6	2	8	3	5	3	10	6	12	4	10
Zr	212	99	607	86	566	143	311	107	480	430	450
Nb	13	4	41	10	27	5	26	6	32	30	30
Y	27	7	77	17	52	14	50	20	46	50	50
La	64	16	87	21	93	19	62	34	90	90	110
Ce	115	40	172	46	175	28	107	56	180	160	190

Major oxides—wt%; trace elements—ppm.
* Where more than 4 samples from a formation have been analysed the mean ($\bar{x}$) of the analyses and standard deviation (s) are given.
n.a. = not analysed.

Table 2. Representative chemical analyses of mafic volcanics from the Duchess-Urandangi region, and some average analyses of mafic igneous rocks from north of the region.

	Cromwell Metabasalt Member[2]		*Pickwick Metabasalt Member*[3]		*Eastern Creek Volcanics*		*Bottletree Formation*		*Undivided Tewinga Group*	*Magna Lynn Metabasalt*			*Corella Formation*
No. of samples or	60		15		5		7653–	7653–	7753–	7753–	7753–	7753–	7753–
sample numbers[1]	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	5071	5100	0836	0452	2310	5077C	0148
SiO_2	48.25	2.70	49.54	1.18	50.49	3.07	50.20	50.90	49.70	49.60	53.50	49.90	49.60
TiO_2	2.77	0.68	1.43	0.16	1.30	0.49	1.86	1.21	1.97	1.79	1.29	1.40	1.83
Al_2O_3	13.28	1.00	14.09	0.66	14.47	0.81	15.80	15.40	13.30	14.60	14.00	15.10	12.80
Fe_2O_3	5.22	2.08	3.68	0.82	4.99	0.79	6.12	3.14	4.65	3.11	4.07	3.81	5.52
FeO	9.66	1.99	8.35	0.85	6.71	2.10	6.78	8.55	10.30	10.30	6.69	8.08	9.88
MnO	0.23	0.05	0.19	0.04	0.19	0.01	0.19	0.20	0.24	0.23	0.29	0.35	0.18
MgO	4.75	1.37	6.47	0.90	6.62	1.95	2.62	5.92	5.70	6.04	6.20	7.04	4.40
CaO	7.50	1.66	8.61	1.26	9.51	2.29	11.70	10.80	8.73	10.00	5.99	7.97	8.06
K_2O	1.63	0.93	1.71	0.44	1.04	0.52	0.70	0.33	0.83	0.60	2.21	1.52	1.18
Na_2O	2.44	0.82	2.46	0.61	2.70	0.44	1.35	1.65	1.65	1.94	2.46	3.12	3.68
P_2O_5	0.45	0.22	0.15	0.03	0.13	0.07	0.53	0.20	0.19	0.20	0.18	0.20	0.23
Ba	443	352	314	145	239	109	380	170	310	140	520	330	210
Rb	64	49	55	13	30	23	26	3	22	11	65	70	24
Sr	160	59	187	41	181	55	390	260	130	130	180	160	120
Pb	23	16	14	12	37	33	380	160	38	280	140	75	60
Zr	290	72	119	34	120	63	280	170	140	150	160	180	120
Nb	18	5	6	3	6	4	22	14	14	16	18	18	14
Y	51	12	27	7	26	11	34	26	28	30	32	32	26
La	41	24	32	12	38	25	40	35	15	50	30	30	30
Ce	97	27	47	13	42	19	180	55	30	40	80	70	90

Major oxides—wt%; trace elements—ppm.

1. Where more than 4 samples from a formation or member have been analysed the mean ($\bar{x}$) of the analyses and standard deviation (s) are given.
2. Analyses of the Cromwell Metabasalt Member of the Eastern Creek Volcanics from Glikson & Derrick (1978) and Wyborn (in preparation).
3. Analyses of the Pickwick Metabasalt Member of the Eastern Creek Volcanics from Glikson & Derrick (1978) and Wyborn (in preparation).
4. Analyses of Soldiers Cap Group metabasites from Glikson & Derrick (1978).

n.a. = not analysed.

For total Fe, TiO_2, CaO, K_2O, Al_2O_3, Sr, Pb, Th, U, Zr, Nb, Y, and Zn the distinction between the suites is quite marked at similar SiO_2 values. These differences for selected elements are shown on Harker variation diagrams (Fig. 4). Other plots, not presented here, show that Y has a similar trend to Nb, that TiO_2 follows FeO, that Pb and CaO follow Sr, that Th and U show trends similar to that of K_2O, and that Al_2O_3 and Zn have distinctly different trends, when plotted against SiO_2. The fields defined by samples from the Leichhardt Metamorphics and Argylla Formation collected north of the Duchess-Urandangi region are

Table 1 continued

Plum Mountain Gneiss		*Mitakoodi Quartzite*		*Double Crossing Metamorphics*	*Undivided Tewinga Group*			*Sulieman Gneiss*		*Soldiers Cap Group*	*Doherty Formation*	
7920–5314	7753–2551	8053–0099	8053–2040A	7853–4709	7753–2013	5 $\bar{x}$	s	7753–2364B	7853–2359	7853–1105	7853–0494	7853–0496
65.10	69.70	70.90	75.70	68.90	64.70	70.62	2.22	74.00	75.50	67.80	78.30	75.00
0.79	0.39	0.54	0.50	0.47	0.48	0.54	0.14	0.43	0.28	0.67	0.17	0.13
14.50	14.50	10.60	8.95	11.80	14.90	12.90	0.36	12.60	11.70	12.10	10.20	13.10
0.48	0.17	5.82	4.25	6.18	1.04	2.42	0.43	0.42	0.32	1.65	0.82	0.58
5.65	2.74	1.48	2.10	2.80	3.29	2.41	1.09	2.15	1.78	4.08	0.53	0.28
0.07	0.04	0.01	0.02	0.06	0.06	0.07	0.02	0.04	0.03	0.26	0.02	0.02
1.26	0.94	0.12	0.17	0.71	3.93	0.56	0.43	0.55	0.40	0.53	0.19	0.20
3.25	2.07	0.23	0.50	1.92	3.37	1.78	0.40	1.40	0.88	2.82	1.44	0.60
2.50	2.70	0.32	2.55	3.19	2.85	3.23	1.34	2.90	1.90	0.77	5.66	5.04
4.60	4.66	8.70	4.30	2.10	3.53	4.48	2.35	5.47	5.69	7.72	0.28	4.05
0.19	0.15	0.13	0.09	0.05	0.11	0.23	0.27	0.10	0.07	0.17	0.04	0.05
1300	600	1250	1100	580	450	1042	632	700	880	1100	30	250
170	250	140	55	46	190	200	102	230	210	280	2	90
200	160	11	22	140	160	164	53	85	75	46	20	17
19	19	<2	3	16	28	50	44	13	20	50	<2	<2
24	22	22	42	18	n.a.	31	2	30	42	n.a.	36	36
6	4	8	10	4	8	4	2	<4	4	n.a.	4	<4
350	200	560	760	1400	150	540	141	300	300	210	700	130
16	13	34	55	34	16	30	5	24	26	22	40	15
20	12	36	60	90	7	54	20	36	38	36	120	38
90	50	25	20	90	45	86	21	90	120	30	80	<20
130	92	75	25	200	70	166	47	160	220	60	160	20

Table 2 continued

Oroopo Metabasalt		*Jayah Creek Metabasalt*			*Saint Ronans Meta-morphics*	*Sulieman Gneiss*	*Soldiers Cap Group*[4]		*Soldiers Cap Group*			*Marraba Vol-canics*	*Kuridala Formation*	*Doherty Formation*	
7853–3020	7953–2376A	7853–2405D	7853–2408A	7853–3035	7953–2034	7953–2477	25 $\bar{x}$	s	7853–0166A	7853–4666	7853–4365	7853–4346A	7853–0821	7853–0065F	7853–0072C
54.50	51.00	52.80	52.40	56.70	51.40	49.60	48.69	2.57	48.30	48.80	49.30	51.10	50.80	49.20	50.10
0.87	0.92	1.02	1.21	1.25	0.92	1.56	1.62	0.61	2.85	1.62	1.43	2.03	1.42	2.23	1.59
13.20	14.40	14.30	14.30	13.90	14.90	15.10	14.04	1.81	12.90	13.70	13.90	12.80	13.70	12.10	12.50
2.51	4.93	3.84	6.43	4.36	3.61	6.65	4.41	1.82	0.48	5.26	0.34	5.95	4.73	6.01	7.55
7.67	6.18	6.67	5.29	7.33	7.43	5.39	9.68	3.02	14.10	10.00	11.20	9.37	7.14	9.02	6.65
0.17	0.14	0.20	0.17	0.14	0.18	0.19	0.23	0.08	0.49	0.21	0.24	0.21	0.47	0.15	0.12
6.61	6.14	6.10	4.60	5.65	6.49	6.80	5.40	1.44	5.85	5.40	6.50	5.14	5.87	4.96	5.20
10.70	9.06	9.48	9.61	3.95	9.55	10.20	10.21	2.96	9.10	8.25	11.20	7.83	8.67	8.78	8.80
0.22	1.48	1.32	0.54	0.85	0.65	0.36	0.82	0.65	1.72	0.61	0.73	0.54	0.49	0.81	1.12
1.51	2.00	1.70	3.34	2.86	2.20	1.88	2.57	1.32	1.03	3.77	2.66	2.20	4.12	3.89	4.90
0.10	0.16	0.14	0.17	0.14	0.13	0.19	0.16	0.07	0.30	0.17	0.15	0.19	0.12	0.19	0.18
55	350	460	360	460	240	170	247	196	200	140	100	150	780	410	150
2	32	34	17	48	22	10	28	28	85	16	20	15	7	26	24
120	230	130	230	110	190	190	186	113	70	60	150	110	300	120	95
65	5	120	60	36	150	13	8	4	5	<2	<2	22	38	36	26
70	130	140	160	130	110	100	137	45	170	120	95	140	80	150	140
8	8	16	16	14	14	16	n.a.		7	5	5	14	12	16	6
17	26	22	26	22	18	24	33	7	38	36	18	36	26	34	28
30	20	60	30	20	30	20	68	12	<20	<20	<20	15	40	25	40
20	30	70	60	50	60	20	n.a.		20	20	20	35	50	60	75

also shown on Figure 4. Representative analyses and average analyses of the various felsic volcanic suites and units are listed in Table 1.

Leichhardt suite. The Leichhardt suite consists of volcanics from the Leichhardt Volcanics in the Duchess-Urandangi region and from the stratigraphically equivalent and chemically indistinguishable Leichhardt Metamorphics to the north. Compared to the other suites the Leichhardt suite is characterised by low Y, Zr, Nb, TiO_2, and total Fe contents, relatively low K_2O, Th, and U abundances, relatively high Al_2O_3, Pb, Sr, Na_2O, and CaO contents, and intermediate Zn values. When plotted against SiO_2, most elements show inverse linear trends that are identical to those shown by the Kalkadoon Granite (Wyborn & Page, in preparation). The two samples from the Plum Mountain Gneiss also plot with the Leichhardt suite. However, it is difficult to distinguish felsic intrusive units from volcanics in the Plum Mountain Gneiss, and the samples analysed may be of granite or intrusive feldspar porphyry. The formation probably contains cogenetic intrusives and extrusives that are the highly metamorphosed equivalents of the Leichhardt Volcanics and Kalkadoon Granite.

Argylla suite. The Argylla suite consists mainly of felsic volcanics from the Argylla Formation. It is distinguished by high Zr, Nb, Y, TiO_2, and total Fe values, relatively high K_2O, Th, and U values and low Na_2O, Al_2O_3, Pb, Sr, and Zn contents. The Argylla suite includes the two analysed samples of felsic volcanics from the Mitakoodi Quartzite, as well as Argylla Formation volcanics from north of the Duchess-Urandangi region. The sample of Double Crossing Metamorphics plots with the Argylla suite except for TiO_2 values, which are relatively low, and Sr and Pb values, which are relatively high.

Bottletree suite. This suite is represented by felsic volcanics of the Bottletree Formation. Like the Argylla suite, it has high Zr, Nb, Y, TiO_2, and total Fe contents, relatively high K_2O, Th, and U values, and low Al_2O_3 contents. However, CaO, Sr, and Pb contents are significantly higher in the Bottletree suite, and are similar to those for the Leichhardt suite. Zn values are also distinctly high.

Duchess-Corella suite. This suite consists of volcanics from the Corella Formation of the Duchess belt. Nb and Y contents are high, as in the Argylla and Bottletree suites, but TiO_2, Zr, and total Fe contents are low and comparable to values for the Leichhardt suite. Sr, CaO, Na_2O, and Al_2O_3 contents are also low, and Pb is exceptionally low, whereas K_2O, Th, and U values are relatively high. This suite is spatially associated with the Wonga Batholith, which is made up of numerous chemically distinct plutons, but there are insufficient data available to establish a cogenetic relationship between these volcanics and any plutons of the Wonga Batholith.

Carters Bore suite. This suite contains the volcanics of the Carters Bore Rhyolite. The three rocks analysed have SiO_2 contents ranging from 73.2 to 76.1 per cent, and are characterised by very high K_2O and low Al_2O_3, Ba, Pb, Sr, Na_2O, and CaO contents; TiO_2 and MgO contents are also anomously high for such siliceous rocks. Although of minor occurrence in the Duchess-Urandangi region, the Carters Bore Rhyolite is probably a correlative of the Fiery Creek Volcanics (Hutton & others, 1981), which contain chemically similar felsic volcanic rocks (*see* analyses listed in Wyborn, in preparation).

Other felsic volcanic compositions

Undivided Tewinga Group (central area). Of the six analysed samples from the undivided Tewinga Group, one, that of a metadacite (77532013, Table 1) from an age-determination site (Page, in preparation), is indistinguishable both in age and chemistry from felsic volcanics of the Leichhardt suite. The remaining five analyses (Table 1) are unlike either the Leichhardt or Argylla suites: their high TiO_2, Zr, Nb, and Y, and low Al_2O_3 contents distinguish them from the Leichhardt suite, and their Pb, Sr and CaO contents are too high for the Argylla suite. Instead, they are closer to the Bottletree suite, although their CaO and total Fe contents are slightly lower.

Sulieman Gneiss (western area). The two analyses of Sulieman Gneiss plot close to the limits of the field for the Leichhardt suite except for their anomalously high Nb values. TiO_2, CaO, Zr, Y, and Ce plot close to the upper limits of the field defined by the Leichhardt suite.

Soldiers Cap Group (eastern area). The analysed sample of quartzofeldspathic gneiss from the Soldiers Cap Group has low Sr, Y, Zr, and Al_2O_3 and high TiO_2, total Fe, and K_2O contents and does not fit into any of the five main suites recognised.

Doherty Formation (eastern area). One (the age-determination sample) of the two analysed samples of metarhyolite from the Doherty Formation is enriched, and the other significantly depleted in incompatible elements. No clear genetic relationship has been discerned between these metarhyolites and plutons of the adjacent Williams Batholith, or the five major suites of felsic volcanics in the Duchess-Urandangi region.

Mafic volcanics

The mafic volcanics of the region have been less thoroughly sampled than the felsic volcanic units. Most analysed samples plot in the subalkaline field on an alkalies vs silica diagram (Irvine & Baragar, 1971), and show a trend of iron enrichment on an AFM diagram. In Figure 5, selected oxides and trace elements (after the analyses had been recalculated to 100 per cent free of volatiles) are plotted against M′ number, where $M' = 100\ Mg/Mg{+}0.85\ (Fe^{2+}{+}Fe^{3+})$ atomic (after Cox, 1980). Decreasing values of M' reflect fractionation of liquidus or near-liquidus phases. Differentiation Index (D. I., Thornton & Tuttle, 1960), which sums the (CIPW) normative salic components, was not used, because most of the lower-grade mafic volcanics contain abundant albite ± biotite, indicating probable mobilisation of the alkali elements and spurious D. I. values. The fields defined in Figure 4 by mafic volcanic rocks from north of the Duchess-Urandangi region are based on data obtained from Glikson & Derrick (1978) and Wyborn (in preparation). These data indicate that the Cromwell Metabasalt Member of the Eastern Creek Volcanics is characterised by significantly higher concentrations of TiO_2, P_2O_5, Zr and Y than the Pickwick Metabasalt Member, and that their respective fields are essentially mutually exclusive when these oxides and trace elements are plotted against M' (Fig. 5). The Soldiers Cap metabasites show compositional overlap with the Pickwick Metabasalt Member, but include some more highly fractionated variants. Average and representative analyses of mafic volcanic rocks from the Duchess-Urandangi region and the region to the north are listed in Table 2.

Central area. Analysed samples of metabasalt from the Eastern Creek Volcanics, Magna Lynn Metabasalt, Bottletree Formation and Corella Formation from the central area plot within the fields defined by analyses of Pickwick Metabasalt Member and Soldiers Cap Group from north of the Duchess-Urandangi region, except for one sample from the Bottletree Formation, which has anomously high P_2O_5 and Zr contents.

Western area. Mafic volcanic samples from the Jayah Creek Metabasalt, Oroopo Metabasalt, Saint Ronans Metamorphics, and Sulieman Gneiss are chemically similar to those of the central area, and hence to the Pickwick Metabasalt Member.

Eastern area. Analysed mafic volcanics from the Doherty Formation, Kuridala Formation, and Soldiers

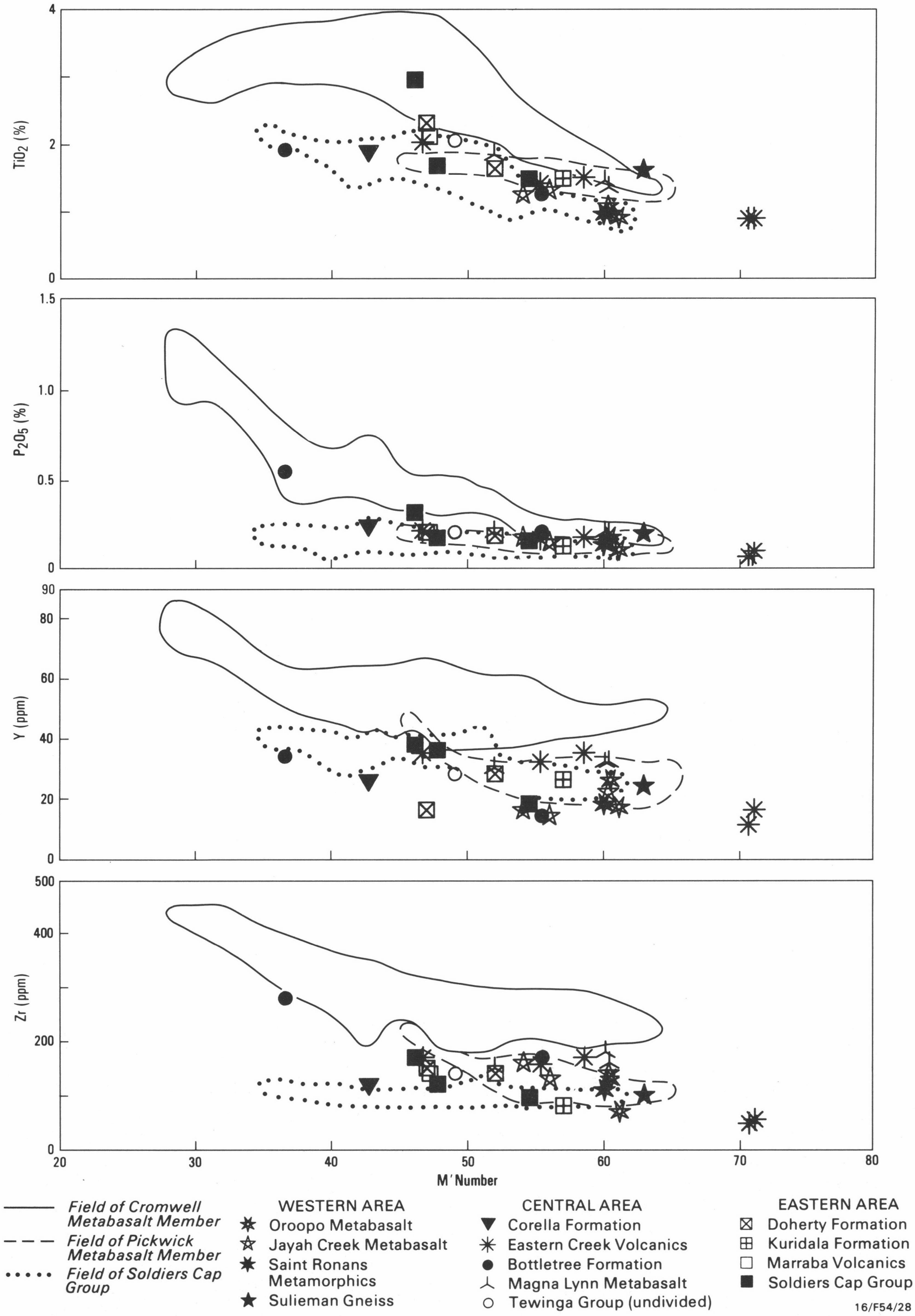

Figure 5. Abundances of selected major oxides and trace elements plotted against M' for the mafic volcanics of the Duchess-Urandangi region.
Also shown are the fields defined by the Cromwell Metabasalt Member (55 analyses) and Pickwick Metabasalt Member (14 analyses), based on data from Glikson & Derrick (1978) and Wyborn (in preparation).

Cap Group are virtually indistinguishable from one another, and are similar to most of the other mafic volcanics of the Duchess-Urandangi region. One sample (78530166, Table 2) from the Soldiers Cap Group has a relatively high TiO_2 content, but the other samples have element concentrations similar to those of the Soldiers Cap Group metabasites analysed by Glikson & Derrick (1978).

Discussion

Felsic volcanics

Source region composition and extent of partial melting are most likely to be the main factors controlling the chemistry of the felsic volcanic suites (*see* Chappell, 1979). According to van der Molen & Paterson (1979) about 30-35 per cent by volume of a source region must melt before the melt fraction separates from the refractory residue. The extraction of such volumes of material will extensively modify the composition of the source region, particularly as the first partial melt contains most of the available minimum-melt component, unless the source region is very extensive, both laterally and vertically. Hence, successive partial melting events involving the same source region are unlikely to repeatedly produce felsic volcanics of similar composition. Consequently, chemically similar felsic volcanics cropping out in the same general area are likely to be similar in age, and may be used in establishing stratigraphic relationships.

Thus, the occurrence of Argylla-suite volcanics in the Mitakoodi Quartzite, and in the Ballara Quartzite to the north of the Duchess-Urandangi region (*see* analyses listed in Wyborn, in preparation) may indicate that there was no major time break between the eruption of the Argylla Formation volcanics and the deposition of the two predominantly sedimentary suites (*see* Blake, 1980, 1981; also Derrick & Wilson, 1981 for some alternative interpretations), or that the Ballara and Mitakoodi Quartzites are possibly even laterally equivalent to parts of the Argylla Formation.

The close similarity in chemical composition of some quartzofeldspathic gneissic rocks to less-metamorphosed felsic volcanic rocks may indicate that the gneissic rocks are the more extensively deformed equivalents of the felsic volcanics, rather than part of a much older unrelated sequence. In this regard, five of the six analysed samples of felsic gneiss from the undivided Tewinga Group are chemically similar to the Bottletree suite and hence may be of similar age, rather than part of a much older sequence, as favoured by Blake (1980).

However, not all felsic volcanic units of similar age necessarily come from the same source region, especially if they are exposed in geographically separate areas. It is highly likely that the composition of the source regions will change, at least slightly, from one area to another. Thus, although the Bottletree and Argylla Formations are closely similar in age, the felsic volcanics of the Bottletree Formation are mainly dacites and relatively enriched in Pb, Ca, Sr, FeO, and Zn, compared with those (mainly rhyolites) of the Argylla Formation. These differences indicate that the source region for the Bottletree Formation felsic volcanics was more feldspar-rich and possibly more reduced than that for the Argylla Formation.

Mafic volcanics

Although only a few analyses from each formation are available, it does appear that the mafic volcanics of the region are chemically very similar to one another. They are characterised by low and uniform contents of most incompatible elements (Ti, P, Zr, and Y), and in this respect are similar to many of the basaltic lava flows (continental tholeiites) of the Karroo province, southern Africa (Cox & Hornung, 1966; le Roex & Reid, 1978). However, in one part of the Karroo province, the Nuanetsi border zone, the lavas have relatively high K, Ti, P, Ba, and Sr contents (Cox & others, 1965; Manton, 1968); these occur in a region where volcanism was coincident with strong downwarping (Carmichael & others, 1974).

The eastward progression from rocks of continental tholeiitic affinities characterised by high values of Ti P, K, Zr and Y to rocks of ocean-floor tholeiitic affinities, characterised by low values of these elements, as recorded by Glikson & others (1976) and Glikson & Derrick (1978) in the Mount Isa region, is not apparent in the Duchess-Urandangi region. Basalts of the Cromwell Metabasalt, the basal member of the Eastern Creek Volcanics in the Mount Isa region, have relatively high incompatible-element contents, and like the chemically similar basalts of the Nuanetsi border zone, Karroo province, may have been generated during a strong downwarping event. The apparent absence of this member in the Duchess-Urandangi region may indicate that the downwarping was less intense in the south than farther north.

Tectonic implications

Silica values for the volcanic rocks and their intrusive equivalents in the Duchess-Urandangi region show a well-defined bimodal distribution (Fig. 6). Igneous rocks of intermediate composition, typically the predominant rock types produced above subduction zones at convergent plate boundaries, are rare. A bimodal distribution is generally considered to be a product of extensional tectonics (e.g., Christiansen & Lipman, 1972; Martin & Piwinski, 1972) and implies that the dominant tectonic regime in the Duchess-Urandangi region was a tensional one, which probably resulted in crustal thinning, rifting and high heat flow. The favoured interpretation, that of an extensional tectonic regime, conflicts with the view of Wilson (1978) who stated that the Tewinga Group contains volcanic rocks typical of convergent plate margins.

Conclusions

- Volcanic rocks of felsic and/or mafic composition are present in most Precambrian stratigraphic units in the Duchess-Urandangi region.
- The volcanics have been regionally metamorphosed to amphibolite or greenschist grade.
- The volcanics form a distinctly bimodal suite, indicating that they probably evolved in a tensional tectonic regime.
- Five felsic volcanic suites have been identified. These may be useful time-markers.

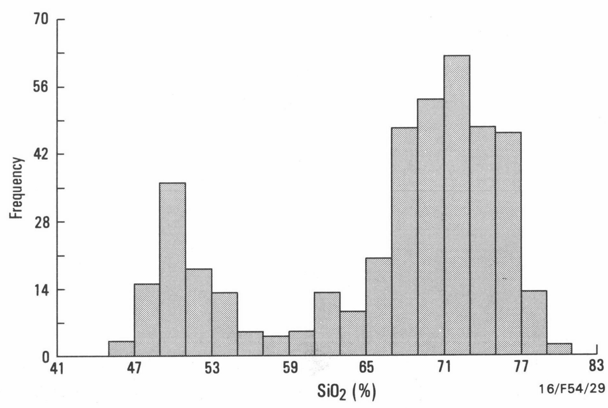

Figure 6. Absolute frequency distribution diagram for SiO_2 based on 412 analyses of igneous rocks from the Duchess-Urandangi region.
Data from Wyborn (in preparation).

- Some felsic rocks from relatively high-grade metamorphic sequences in the region are chemically similar to and may be the more deformed and recrystallised equivalents of felsic volcanics in lower-grade units, and not parts of much older 'basement' sequences.
- The analysed mafic volcanic rocks in the region appear to be chemically uniform and similar to continental tholeiites of the Karroo province of southern Africa. The compositional changes from west to east reported by Glikson & others (1976) and Glikson & Derrick (1978) to the north, are not apparent in the Duchess-Urandangi region.

Acknowledgements

We gratefully acknowledge helpful discussions with J. Knutson, P. J. T. Donchak, D. Wyborn, A. L. Jaques, and in particular, D. H. Blake. Some of the analyses used in this study were of samples collected by D. H. Blake, A. L. Jaques, I. H. Wilson, and G. M. Derrick. R. W. Page kindly provided a preprint and M. Owen wrote the computer programmes used in assessing and plotting the data. R. J. Bultitude publishes with the permission of the Director-General, Department of Mines, Queensland.

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