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R. J. Squire <sup>a</sup>; J. McPhie <sup>a</sup>

<sup>a</sup> ARC Centre for Excellence in Ore Deposits, University of Tasmania, Hobart, Tas, Australia

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# Complex volcanic facies architecture of the Forest Reefs Volcanics near Cadia, New South Wales, associated with prolonged arc-related volcanism

R. J. SQUIRE\* AND J. McPHIE

ARC Centre for Excellence in Ore Deposits, University of Tasmania, Private Bag 79, Hobart, Tas. 7001, Australia.

The Ordovician to Lower Silurian Forest Reefs Volcanics in the Cadia–Neville region, northeastern Lachlan Orogen, represent the product of at least two shoshonitic volcanic centres intercalated with a volcanoclastic apron. The two episodes of shoshonitic volcanism in the Forest Reefs Volcanics are separated by between 15 and 20 million years. The Forest Reefs Volcanics are informally divided into lower and upper parts, separated by an inferred unconformity that broadly coincides in age with a limestone-forming hiatus in volcanism (449–447 Ma) and emplacement nearby of medium-K calc-alkaline dacitic intrusions (448–445 Ma). The lower part includes shoshonitic basaltic andesite, feldspar-rich sandstone, volcanic lithic breccia and lesser black mudstone; polymictic volcanic conglomerate with sandstone matrix and calcareous sandstone are important near the top. The basaltic facies association occurs near the base of the lower Forest Reefs Volcanics and could represent a submarine basaltic volcano at least 12 km in diameter. A major change in provenance for the upper Forest Reefs Volcanics is reflected in the increased abundance of ferromagnesian crystals and coarse mafic volcanic fragments, particularly in the mafic volcanic sandstone, polymictic volcanic conglomerate with coarse volcanic matrix and polymictic hornblende andesite breccia. The trachyandesite facies association records another episode of shoshonitic volcanism that probably occurred late in the accumulation of the upper Forest Reefs Volcanics and could represent an intrusive complex or the initial, largely shallow intrusive stages of a cone volcano. Highly porphyritic basalt to basaltic andesite intrusions were emplaced as sills before the volcanoclastic succession was lithified. The final magmatic activity generated coarsely equigranular, mafic to intermediate intrusions. The trachyandesite facies association, the highly porphyritic basalt to basaltic andesite intrusions and the coarsely equigranular intrusions were emplaced successively in a relatively short time (about 443–439 Ma). The complex facies architecture of the Forest Reefs Volcanics thus represents the product of prolonged broadly arc-related shoshonitic volcanism, separated by limestone deposition and the subsequent emplacement of medium-K calc-alkaline dacitic intrusions.

**KEY WORDS:** Cadia, Forest Reefs Volcanics, intra-oceanic volcanism, Lachlan Orogen, Ordovician, peperite, submarine volcanics.

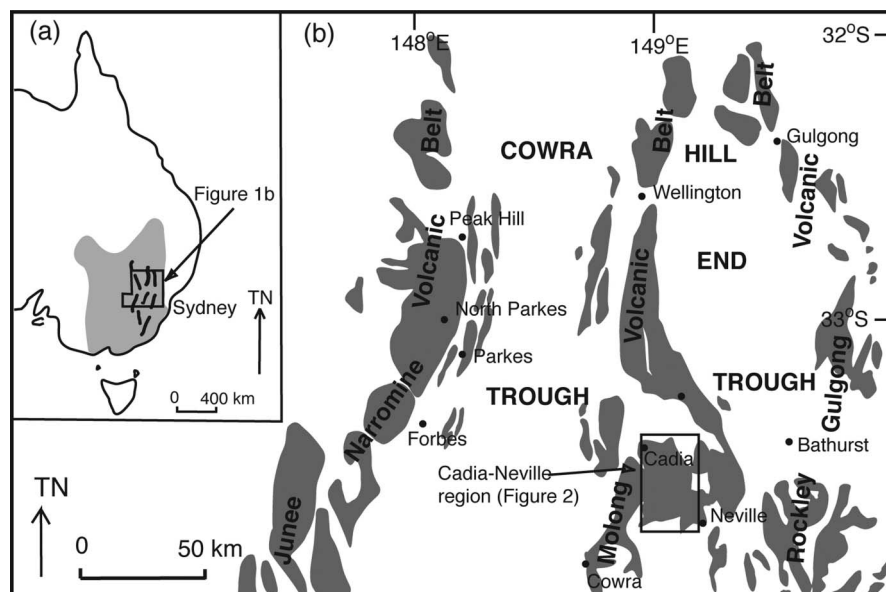
## INTRODUCTION

The Forest Reefs Volcanics host the world-class Cadia Au–Cu porphyry copper deposits (Holliday *et al.* 2002) and thus provide vital information about the volcanic evolution of the southern Molong Volcanic Belt and the broadly coincident major metallogenic event at about 440 Ma (Figure 1). Wyborn and Henderson (1996) interpreted the volcanic and intrusive rocks in the Cadia–Neville region to represent the products of a major Late Ordovician volcanic island. The shoshonitic basaltic andesites near the base of the Forest Reefs Volcanics were considered to record the initial submarine development of a single major volcanic edifice. The more evolved trachyandesites and coeval dioritic, monzonitic and syenitic intrusions were associated with the final

subaerial evolution of the volcano, which included a large caldera. However, biostratigraphic and radiogenic age determinations (Perkins *et al.* 1990, 1992; Pogson & Watkins 1998; Packham *et al.* 1999; Squire & Crawford 2007) suggested that the two episodes of shoshonitic volcanism were separated by between 15 and 20 million years. In addition, evidence from recent mapping and drillcore logging suggests that the Forest Reefs Volcanics include the products of at least two intrabasinal shoshonitic volcanic centres intercalated with a volcanoclastic apron, and that deposition and volcanism were entirely submarine.

In this paper, we describe and interpret the principal facies of the Forest Reefs Volcanics as a basis for reconstructing the facies architecture of the Cadia–Neville region; the magmatic evolution of the region is

\*Corresponding author and present address: School of Geosciences, Monash University, Vic. 3800, Australia (rick.squire@sci.monash.edu.au).



**Figure 1** (a) Location of the Lachlan Orogen (light grey) in eastern Australia, showing approximate distribution of the Ordovician volcanic belts (black). (b) Distribution of the three northernmost Ordovician volcanic successions in the Lachlan Orogen (Junee–Narromine; Molong; Rockley–Gulgong) and the Siluro-Devonian Cowra and Hill End Troughs; the Kiandra Volcanic Belt is located to the south. Modified from Glen *et al.* (1998).

discussed in Squire and Crawford (2007). There are differences in provenance and facies associations between the lower part (up to the top of the upper Eastonian calcareous sandstones) and the overlying upper part of the Forest Reefs Volcanics. These differences, together with a variation in the strike of bedding between the lower and upper parts of the Forest Reefs Volcanics near Junction Reefs (Figure 2) mark a discordance that may reflect the presence of a late Eastonian to middle Bolindian unconformity, although the unconformity was not observed. The timing of the change in provenance and facies associations, and the proposed unconformity, are broadly coincident with an inferred change in tectonic setting recorded by regional hiatus in volcanism and sedimentation (Packham *et al.* 1999) and emplacement of the medium-K calc-alkaline Copper Hill Suite dacitic intrusions (Squire & Crawford 2007). The complexity in facies geometry and facies relationships in the Forest Reefs Volcanics thus reflects volcanism in a long-lived arc-related setting.

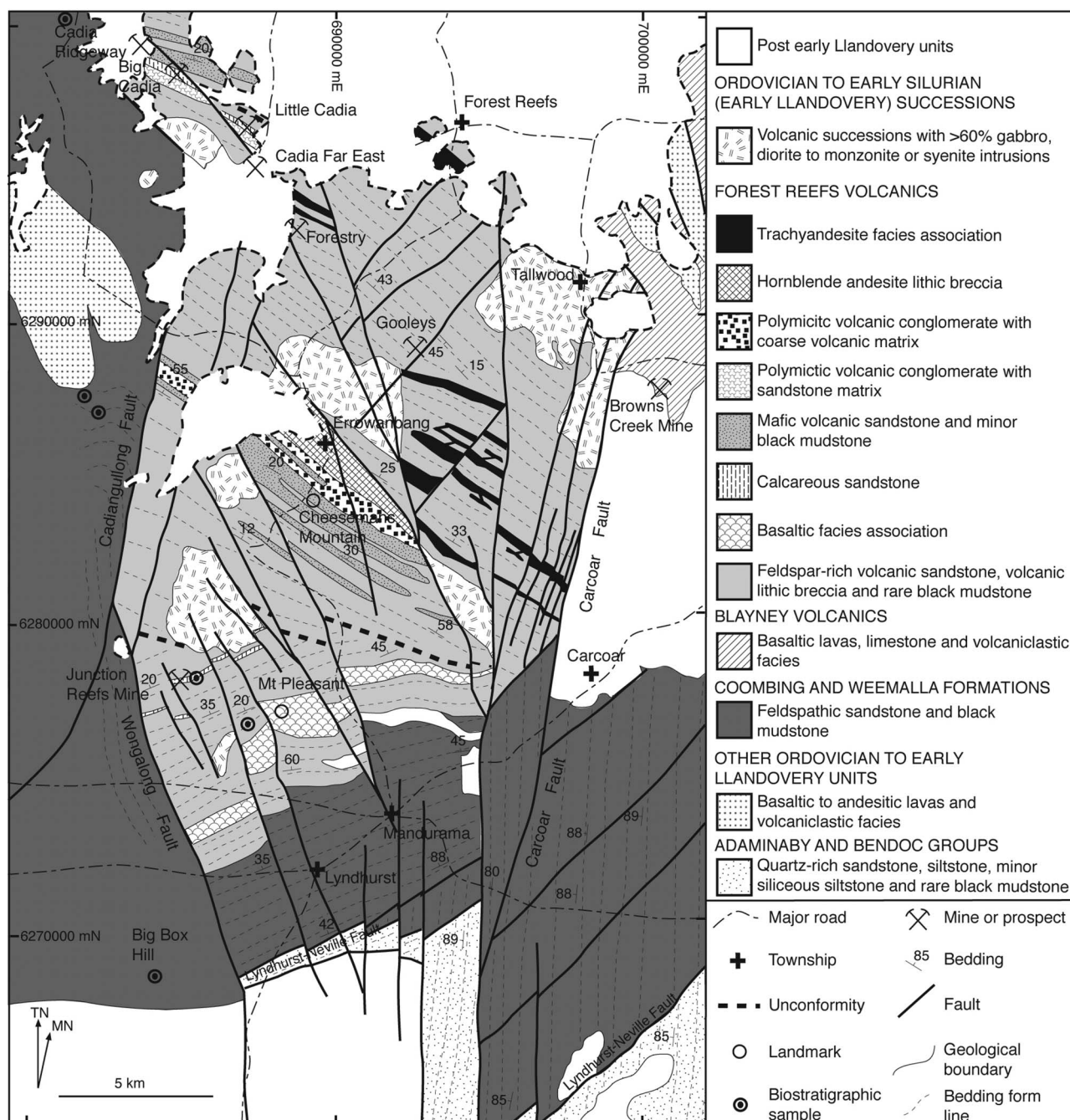
## REGIONAL GEOLOGICAL SETTING

The Forest Reefs Volcanics are part of the Early Cambrian to Carboniferous Lachlan Orogen that dominates eastern Australia (Packham 1960). Quartz-rich turbidites and lesser pelagic mudstone and chert dominate the Ordovician to Lower Silurian successions (Cas 1983; Powell 1983; Cas & VandenBerg 1988). However, in the northeastern part of the Lachlan Orogen, there are three, separate, north–south-elongated, narrow belts of volcanic and shallow intrusive rocks of Early Ordovician to Early Silurian age (Figure 1) (Wyborn & Chappell 1983; Wyborn 1992); the Kiandra Volcanic Belt is located farther south. The volcanic and intrusive successions are mafic to intermediate and have medium-K calc-alkaline to shoshonitic compositions, broadly similar to modern intra-oceanic backarc lavas

(Wyborn 1992; Crawford *et al.* 2007; Squire & Crawford 2007). From west to east, the three belts are known as the Junee–Narromine, Molong and Rockley–Gulgong Volcanic Belts (Figure 1) (Glen *et al.* 1998). The Forest Reefs Volcanics are part of the southern Molong Volcanic Belt. Glen *et al.* (1998) postulated that extension after the Early Silurian Benambran Orogeny dismembered the Macquarie Arc, a single Ordovician arc and arc-apron sequence, into three, now separate, volcanic belts. The volcanic and intrusive rocks of the Junee–Narromine Volcanic Belt were thought to represent the core of the Macquarie Arc, and subduction was inferred to be west-directed (present-day coordinates).

The dominant structures of the Molong Volcanic Belt are numerous north-northwest- to north-northeast-striking faults (Glen & Wyborn 1997; Glen & Walshe 1999). Meakin *et al.* (1997) interpreted the structure of the Molong Volcanic Belt to be dominated by Devonian (to Carboniferous?) age, west-directed thrusts along the eastern margin and east-directed thrusts farther to the west and the north. Folds and cleavage are rare, though where present, axial surfaces and cleavages are generally subparallel to the regional faults. All Ordovician rocks in the Cadia–Neville region contain mineral assemblages consistent with metamorphism to prehnite–pumpellyite and lower greenschist facies (Smith 1966).

North of Orange, the Molong Volcanic Belt is generally less than 15 km wide, and the Ordovician strata are predominantly steeply dipping and west younging (Meakin *et al.* 1997; Raymond *et al.* 1998). In contrast, the southern Molong Volcanic Belt is up to 70 km wide, less strongly deformed, and generally moderately to gently dipping and younging to either the northeast or the northwest (Raymond *et al.* 1998). Pogson and Watkins (1998) suggested that the increase in width might be attributed to variations in thickness of the volcanic succession, reflecting proximity to volcanic centres in the south (e.g. Forest Reefs and Cargo).



**Figure 2** Distribution of the principal lithofacies of the Ordovician volcanic successions in the Cadia–Neville region, southern Molong Volcanic Belt, New South Wales (simplified from Squire 2001). The stratigraphic boundaries for the Forest Reefs Volcanics are significantly different from those proposed by Wyborn & Henderson (1996). The Mt Pleasant Basalt Member of Wyborn & Henderson (1993) is also referred to as the basaltic facies association. The Nullawonga Latite Member of Wyborn & Henderson (1993) is not a single map unit and is replaced by the trachyandesite facies association.

### GEOLOGICAL SETTING OF THE SOUTHERN MOLONG VOLCANIC BELT

Middle Ordovician feldspathic turbidites that belong to the Coombing and Weemalla Formations are the oldest known rocks in the southern Molong Volcanic Belt, and are conformably overlain by the upper Middle Ordovician to lower Llandovery volcanic successions of the Forest Reefs Volcanics (Wyborn & Henderson 1996; Percival & Glen 2007). The Weemalla Formation was

previously interpreted to extend east of the Wongalong and Cadiangullong Faults, although the lithofacies east of the faults include basaltic lava, conglomerate, mafic sandstone and calcareous sandstone, whereas the Weemalla Formation west of the faults consists mainly of feldspathic sandstone (Figure 2). The eastern units are closely similar in age, stratigraphic position, and geochemical and lithological characteristics to the Forest Reefs Volcanics (discussed below). Therefore, we include the Weemalla Formation defined by Wyborn

and Henderson (1996) east of the Wongalong and Cadian-gullong Faults in the Forest Reefs Volcanics (Figure 2) (see Appendix 1 for stratigraphic nomenclature).

*Glyptograptus* n. sp. in the black mudstone overlying the basaltic lavas at the base of the Forest Reefs Volcanics near Mandurama (GR 687080E 6276820N: Stevens 1954, 1957) is late Darriwilian (Da4) to late Gisbornian (Gi2) (462–454 Ma) (VandenBerg & Cooper 1992). The trachyandesite facies near the top of the Forest Reefs Volcanics is about 443 Ma, based on U–Pb in zircon SHRIMP age determinations on broadly comagmatic trachyandesite facies with similar stratigraphic relationships at North Parkes in the Junee–Narromine Volcanic Belt (Squire & Crawford 2007). Therefore, the depositional history for the Forest Reefs Volcanics and the time break between the two episodes of shoshonitic volcanism (i.e. basaltic and trachyandesitic) spanned between 15 and 20 million years.

Conodonts, bryozoans, echinoderms, ostracods, radiolarians and calcareous algae have been identified in the calcareous sandstone facies between the basaltic lavas near the base of the Forest Reefs Volcanics and the trachyandesite facies near the top (Pickett 1992; Trotter & Webby 1995; Packham *et al.* 1999; Zhen *et al.* 1999). These fossils occur in similar facies elsewhere in central New South Wales and were interpreted by Packham *et al.* (1999) to be associated with a late Eastonian (Ea3 to Ea4: 449–447 Ma) hiatus in volcanism and deposition. The age of the hiatus is broadly coincident with emplacement of medium-K calc-alkaline dacitic intrusions in the region (447–445 Ma: Crawford *et al.* 2007; Squire & Crawford 2007). These two events apparently occurred between the two episodes of shoshonitic volcanism in the Forest Reefs Volcanics (Crawford *et al.* 2007; Squire & Crawford 2007). Also, differences in facies associations and the strike of bedding in the Forest Reefs Volcanics (discussed below) suggest that the Forest Reefs Volcanics may be separated into lower and upper parts (Figures 2, 3). The boundary between the lower and upper parts occurs just above the late Eastonian calcareous sandstone facies, and although the contact between the lower and upper parts is not exposed, it may be an angular unconformity near Junction Reefs and a disconformity near Cadia.

## PRINCIPAL FACIES OF THE FOREST REEFS VOLCANICS

The Forest Reefs Volcanics have an inferred total thickness of about 2–2.5 km and a post-faulting lateral extent of at least 12 km. Sixteen principal facies have been recognised in the Forest Reefs Volcanics and are grouped into five main facies associations: (i) well-stratified clastic; (ii) very thick, diffusely stratified clastic; (iii) basaltic (i.e. Mt Pleasant Basalt Member: Wyborn & Henderson 1996); (iv) trachyandesite (i.e. Nullawonga Latite Member: Wyborn & Henderson 1996); and (v) highly porphyritic basalt to basaltic andesite facies associations. The well-stratified clastic and basaltic facies associations are generally more abundant in the lower parts of the Forest Reefs Volcanics, whereas the very thick, diffusely stratified clastic and

trachyandesite facies associations are generally more abundant in the upper parts of the Forest Reefs Volcanics. The highly porphyritic basalt to basaltic andesite facies association is common in both the lower and upper Forest Reefs Volcanics, and also occurs in the underlying Weemalla Formation at Cadia.

Descriptions of the facies are based on observations made during mapping and logging of diamond drillcore from the Cadia–Neville region. The thickness and lateral extent of the principal facies are approximate, based on generally poor and discontinuous outcrop disrupted by numerous faults and less common folds.

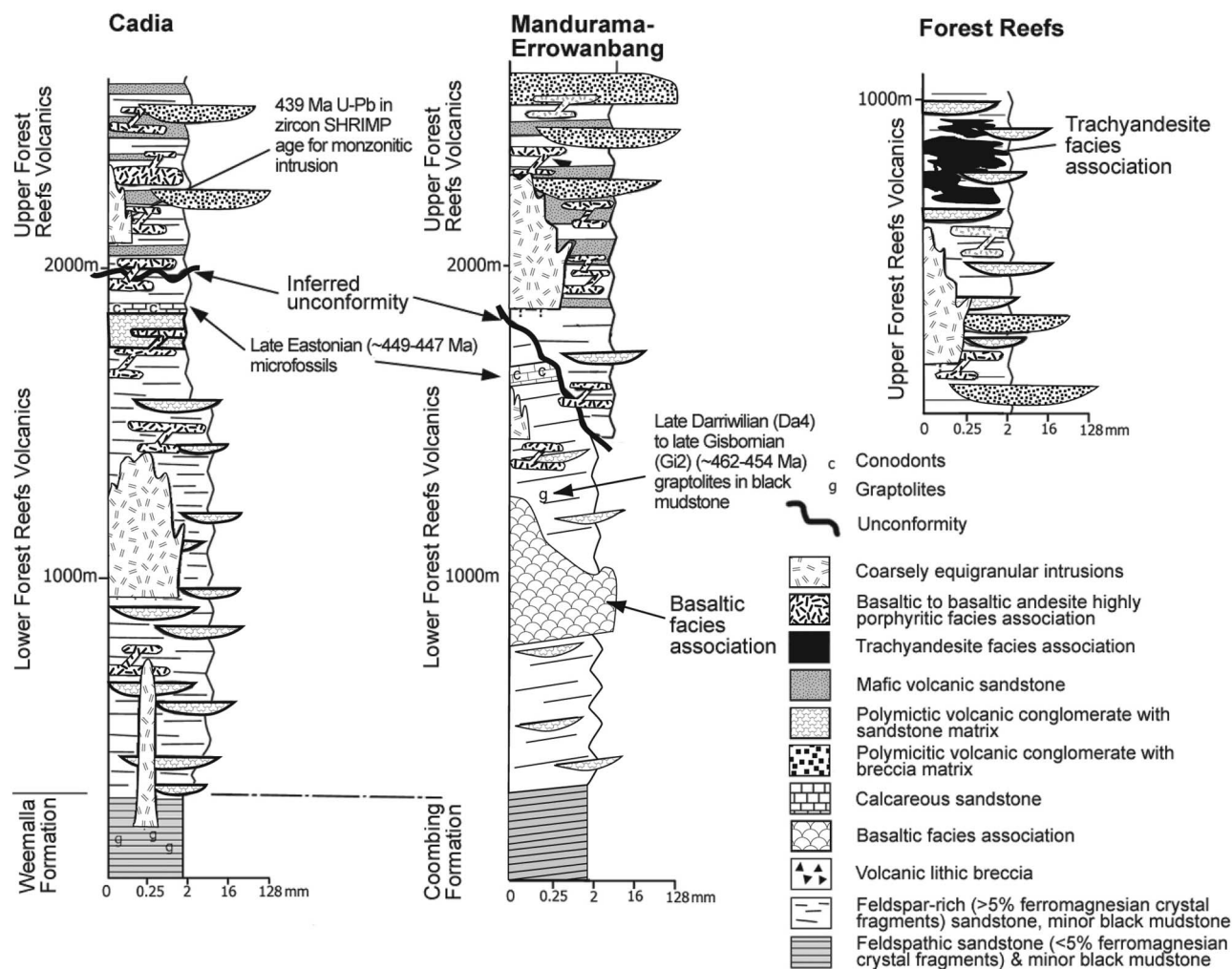
## Well-stratified clastic facies association

The well-stratified clastic facies association is characterised by laterally extensive, thin to medium beds that comprise about 40% of the thickness of the Forest Reefs Volcanics and includes: (i) laminated mudstone; (ii) feldspar-rich volcanic sandstone (Figure 4a); (iii) black mudstone; (iv) mafic volcanic sandstone; (v) calcareous sandstone; and (vi) volcanic lithic breccia (Figure 4b, c) (Table 1). The calcareous sandstone and the mafic volcanic sandstone occur only in the lower and upper parts, respectively, of the Forest Reefs Volcanics, whereas the other facies of this association, though generally more abundant in the lower part, are present throughout the Forest Reefs Volcanics.

## INTERPRETATION OF TRANSPORTATION, DEPOSITION AND PROVENANCE

The occurrence of laterally extensive, massive to graded and parallel-stratified beds, a diverse range of marine fossils and the absence of wave-generated sedimentary structures such as symmetrical ripples suggest that deposition of the well-stratified clastic facies association occurred in a marine, below-wave-base setting. Well-developed normal grading in most beds indicates that fluid turbulence was probably the most important particle-support mechanism, though buoyancy may have been important for coarser particles in the medium- to thick-bedded volcanoclastic lithic breccia (Hampton 1979; Lowe 1979). Only Bouma a- and b-,  $\pm$ d-,  $\pm$ e- and very rare c-divisions are present in this facies association. The basal, massive to graded sand of Bouma a-division is indicative of deposition by direct suspension sedimentation from high-density currents (Middleton 1967), whereas the overlying Bouma b-, c- and d-divisions were deposited from the residual low-density currents and trailing suspensions (Lowe 1982). The near-absence of Bouma c- (and commonly d-) division is somewhat analogous to the 'middle-absent turbidites' described by Walker (1967). These were interpreted to form where rapid deposition inhibited traction in the waning current. Such turbidity currents may, therefore, have travelled only a relatively short distance and not been fully turbulent (Walker 1967).

The 40 m-thick interval of strongly folded and faulted, feldspar-rich sandstone near the base of the Forest Reefs Volcanics at Cadia has characteristics that are typical of open-cast slumps (Martinsen 1989). Open-cast slumps result from downslope mass movement of



**Figure 3** Schematic graphic logs of the Forest Reefs Volcanics and underlying Coombing and Weemalla Formations. The section from Cadia represents a composite of the stratigraphy observed from drillcore exposure in the northeast of the field area between Cadia Ridgeway and Cadia Far-East. The Mandurama–Errowanbang section is from the central part of the field area, and the Forest Reefs section is compiled from drillcore exposure in the northern region. At Cadia and Mandurama, the lower Forest Reefs Volcanics overlie feldspathic turbidites and comprise coarser-grained and more mafic-rich detritus than the underlying units, together with locally important lavas (basaltic facies association) and calcareous sandstone facies. The upper Forest Reefs Volcanics are composed of a thick succession of coarse-grained volcanoclastic facies, and lavas and shallow intrusions of the trachyandesite facies association. Thick, tabular, highly porphyritic basalt to basaltic andesite intrusions are common in the upper Forest Reefs Volcanics together with the coarsely equigranular intrusions.

unconsolidated, fine-grained sediment accompanied by complex internal deformation (Martinsen & Bakken 1990). They may be produced on very-low-gradient slopes, especially where sedimentation rates of fine-grained sediment are high.

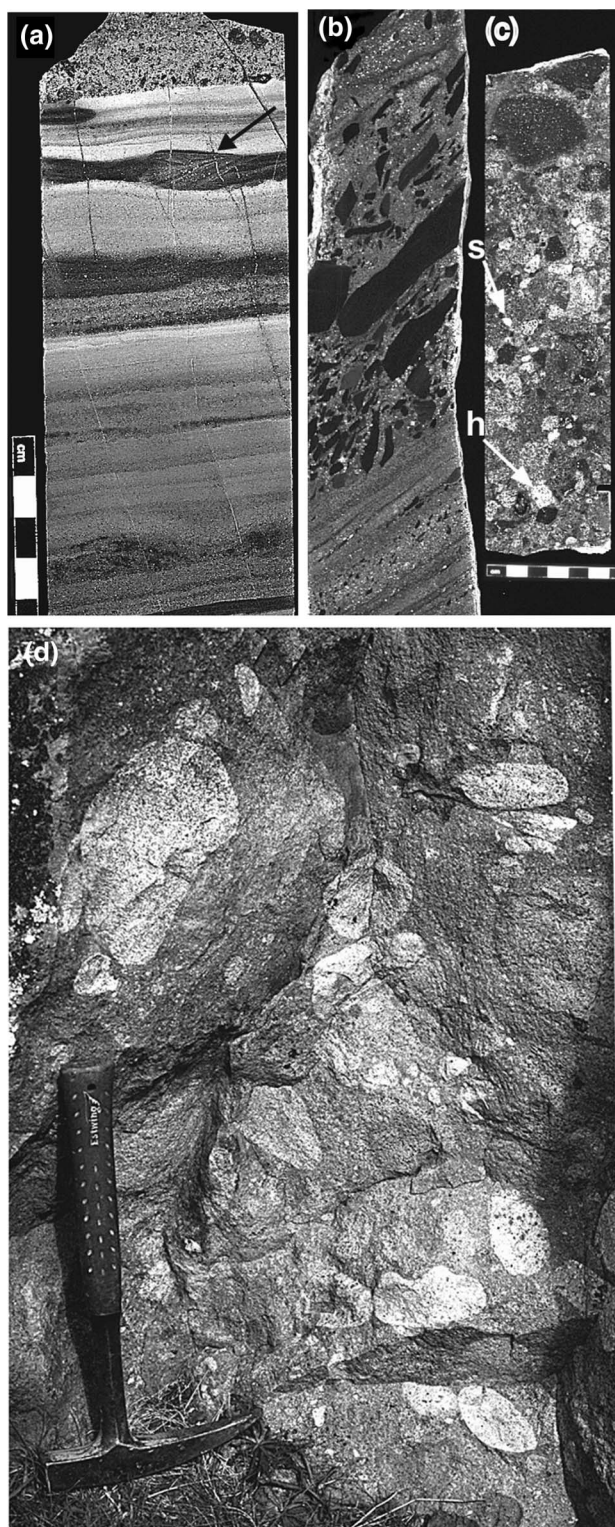
Facies in the well-stratified clastic facies association have diverse provenance (Table 1). The presence of feldspar and clinopyroxene grains and basalt to basaltic andesite lithic fragments, and no volcanic quartz, indicates that derivation was from mafic to intermediate volcanic sources. The volcanic lithic fragments are angular, non- to poorly vesicular and highly porphyritic with fine formerly glassy to microcrystalline groundmasses, and were most likely derived from lavas or shallow intrusions. Quartz grains are rare and consist exclusively of vein quartz, suggesting derivation from source rocks that have undergone brittle or

brittle–ductile deformation. The subangular to sub-rounded clast shapes and relatively well-sorted nature of this facies association suggest that it probably passed through a high-energy subaerial or shoreline environment prior to deposition. Thus, provenance for this facies association was predominantly from a mafic to intermediate volcanic island or landmass; a more mafic, phenocryst-rich volcanic source from the middle Bolindian (about 445 Ma) is indicated by the dominance of clinopyroxene grains in the mafic sandstone facies in the upper part of the Forest Reefs Volcanics. The presence of abundant detrital calcite grains and a diverse range of silicified marine fossils in the calcareous sandstone facies are indicative of a marine carbonate source originally within the photic zone (<120 m water depth: Bosscher & Schlager 1992) during the late Eastonian (449–447 Ma).



### Very thick, diffusely stratified clastic facies association

The very thick, diffusely stratified clastic facies association comprises about 30% of the Forest Reefs Volcanics and includes (Table 2): (i) polymictic volcanic conglomerate with sandstone matrix; (ii) polymictic volcanic conglomerate with coarse volcanic matrix (Figure 4d); and (iii) polymictic hornblende andesite breccia.



This association generally occurs in the upper parts of the Forest Reefs Volcanics and forms intervals up to 150 m thick and at least 5 km in lateral extent. The polymictic volcanic conglomerate with sandstone matrix is the only facies of this association that occurs in the lower Forest Reefs Volcanics and is best exposed at Cadia where it underlies the calcareous sandstone facies (Figures 2, 3). The polymictic volcanic conglomerate with coarse volcanic matrix and the polymictic hornblende andesite breccia are best exposed near Cheesemans Mountain (Figure 2).

### INTERPRETATION OF TRANSPORTATION, DEPOSITION AND PROVENANCE

The thick, tabular bed geometry, coarse grainsize, poor sorting and weak stratification and grading of the two polymictic volcanic conglomerate facies and the polymictic hornblende andesite breccia facies suggest that a variety of particle-support mechanisms operated. Depending on particle size, density and concentration, it is likely that fluid turbulence, dispersive pressure and buoyancy operated to keep the finer clasts in suspension. A combination of traction, rolling, sliding and saltation transported the large, dense clasts as bedload (Middleton & Hampton 1973; Pickering *et al.* 1989; Shanmugam *et al.* 1995). Therefore, this facies association mainly involved deposition from high-density turbidity currents and debris flows (Middleton & Hampton 1973; Shanmugam *et al.* 1995).

The polymictic volcanic conglomerate with sandstone matrix is different from the other facies of this association because the matrix, which forms up to 80% of the facies, is composed of moderately sorted, massive volcanic sandstone. The beds are also very thick (up to 40 m at Cadia), and diffuse stratification is rare. Kneller and Branney (1995) argued that massive sands might aggrade from steady or quasi-steady, non-uniform (depletive) high-density turbidity

**Figure 4** (a–c) Well-stratified clastic facies association of the Forest Reefs Volcanics: (a) feldspar-rich volcanic sandstone facies with planar, massive to normally graded, very thin beds and rare cross-lamination (arrow) in the dark mudstone units (sample MORS0064 from Cadia-Ridgeway drill-hole NC484, 114.0 m); (b) a reversely graded bed of volcanic lithic breccia with abundant, angular, internally laminated mudstone clasts; the matrix consists of angular feldspar crystal fragments up to 2 mm, minor mudstone and rare clinopyroxene and basaltic fragments (sample BLRS0078, near Mt Pleasant (GR 690155E 6275363N); scale bar marked in centimetres); (c) volcanic lithic breccia dominated by angular clasts of hornblende-phyric basaltic andesite (arrow 'h'); other clast types include basalt and basaltic andesite, silicified coral fragments (arrow 's') and black mudstone intraclasts; feldspar and clinopyroxene grains are also common in the matrix (sample MORS0059, Cadia-Ridgeway drillhole NC484, 67.75–68.0 m; scale bar marked in centimetres). (d) Polymictic volcanic conglomerate with coarse volcanic matrix from the very thick, diffusely stratified clastic facies association. Well-rounded clasts of basalt and basaltic andesite are set in a coarse lithic- and crystal-rich matrix. Hammer is 32 cm long. Northern slope of Cheesemans Mountain (GR 689500E 6284300N).

**Table 1** Characteristics of the well-stratified clastic lithofacies association, Forest Reefs Volcanics.

Facies	Description
Laminated mudstone	Pale-grey laminated mudstone and minor fine sandstone; laminae are normally graded or massive, planar, even and continuous in outcrop; intervals up to 4 m thick and at least 2 km in lateral extent; scours, convolute beds and cross-beds are rare; grain compositions are dominantly feldspar with minor clinopyroxene and <5% zoned spessartine garnet; rare graptolites.
Feldspar-rich volcanic sandstone (Figure 4a)	Pale-brown to pale-grey sandstone; well sorted, massive and normally graded beds that vary from <2 cm up to 15 cm thick with rare cross-beds up to 3 cm thick; rare strongly folded and faulted units up to 40 m thick occur between undeformed, parallel-bedded intervals; intervals up to 60 m thick and at least 5 km in lateral extent; contain feldspar, with lesser clinopyroxene and hornblende crystal fragments, and basaltic and basaltic andesite fragments and rare brachiopod fossils.
Mafic volcanic sandstone	Dark-green, clinopyroxene-rich, coarse sandstone; moderately sorted, medium to thinly bedded; laterally continuous in outcrop with massive to normally graded beds and sharp erosional bed bases; intervals up to 40 m thick (generally <20 m) and at least 5 km in lateral extent; contain >40% clinopyroxene crystal fragments, abundant feldspar grains and lesser rounded to subangular basaltic fragments.
Black mudstone	Dark-grey to black, medium to thinly laminated units up to 5 cm thick; present at the tops of normally graded beds of feldspar-rich and mafic sandstone and siltstone; laterally continuous in outcrop; graptolites are rare, and include <i>Glyptograptus</i> n. sp. A (Stevens 1954, 1957).
Calcareous sandstone	Cream to pale-grey, thinly to very thinly bedded, well sorted, calcareous sandstone; intervals up to 40 m thick and at least 5 km in lateral extent; predominantly composed of calcite grains with lesser feldspar and minor clinopyroxene crystal fragments; diverse range of microfossils (Packham <i>et al.</i> 1999); at Junction Reefs, massive to normally graded; at Cadia, internally massive and rhythmically interbedded with feldspar-rich sandstone and siltstone.
Volcanic lithic breccia (Figures 4b, c)	Pale-grey to cream, typically normally graded, thickly to thinly bedded, poorly sorted beds; beds are planar, laterally continuous in outcrop, and have sharp erosional bases; intervals up to 15 m thick and at least 2 km in lateral extent; diverse range of angular to subangular clasts up to 15 cm including basaltic to dacitic fragments, laminated carbonaceous mudstone clasts and rare vein quartz and coral fragments.

**Table 2** Characteristics of the very thick, diffusely stratified clastic lithofacies association, Forest Reefs Volcanics.

Facies	Description
Polymictic volcanic conglomerate with sandstone matrix	Very thick (up to several tens of metres), internally massive, diffusely planar stratified beds of moderately sorted, feldspar-rich volcanic sandstone and well-rounded basaltic to basaltic andesite clasts; matrix-supported; intervals up to 80 m thick and at least 5 km in lateral extent; clasts composed of weakly to non-vesicular basalt, may be up to 50 cm in size and form between 10 and 60% of the facies; the clasts are rarely concentrated at the bed bases.
Polymictic volcanic conglomerate with coarse volcanic matrix (Figure 4d)	Very thick (at least 5 m), poorly sorted, internally massive to weakly graded or diffusely planar stratified beds; intervals up to 80 m thick and at least 5 km in lateral extent; contain >40% well-rounded clasts up to 50 cm; matrix-supported; clasts range in composition from basalt to basaltic andesite; matrix consists of variable proportions of angular sandstone, siltstone and black mudstone clasts, and mafic volcanic fragments up to 5 cm and feldspar and clinopyroxene crystal fragments.
Polymictic hornblende andesite breccia	Very thick (2–4 m), internally massive or weakly graded, diffusely planar stratified beds; poorly sorted; matrix-supported; intervals up to 100 m thick and at least 5 km in lateral extent; angular clasts (up to 20 cm) of hornblende-phyric basaltic andesite (70%) and laminated carbonaceous siltstone (30%); matrix consists of variable proportions of feldspar and clinopyroxene crystal fragments, angular hornblende-phyric lithic fragments, carbonaceous and rare non-carbonaceous siltstone clasts and minor basaltic and basaltic andesite fragments.

currents. Steady depletive currents maintain a constant velocity with respect to a particular point but decrease in velocity downcurrent (Kneller 1995).

Formation of the polymictic volcanic conglomerate with sandstone matrix may have involved aggradation from a sustained high-density turbidity current



at the base of which well-rounded volcanic pebbles and cobbles were transported as bedload and periodically engulfed by the aggrading sand. The high degree of rounding of the clasts in both polymictic volcanic conglomerate facies was the result of traction transport and reworking in a high-energy subaerial, shoreline and/or shallow-marine setting prior to final deposition.

The very thick, diffusely stratified clastic facies association is interbedded with the well-stratified clastic facies association, and is thus also interpreted to have been deposited in a marine, below-wave-base environment. The abundance of subangular feldspar grains and mafic to intermediate cobbles in the polymictic volcanic conglomerate (Table 2) with sandstone matrix suggests that this facies had a similar provenance to the well-stratified clastic facies association in the lower Forest Reefs Volcanics. However, the polymictic volcanic conglomerate with coarse volcanic matrix and polymictic hornblende andesite breccia in the upper Forest Reefs Volcanics have greater variety in shape, size and composition of the particles than the other facies (Tables 1, 2) and were derived from more diverse mafic to intermediate volcanic sources. Clasts from the polymictic volcanic conglomerate with coarse volcanic matrix have relatively high Ti/Zr ratios at given MgO contents (Squire 2001) that match closely the basaltic lavas from the Blayney Volcanics (i.e. upper Blayney Basalt: Crawford *et al.* 2007) and the basaltic intrusions in the Coombing Formation east of the Carcoar Fault (i.e. Eagle Hawk Basalt: Wyborn & Henderson 1996), indicating that the source of the clasts was broadly comagmatic with the igneous units to the east and southeast.

### Basaltic facies association

The basaltic facies association occurs only in the lower Forest Reefs Volcanics in the southern part of the Cadia–Neville region (Figure 2), and was named the Mt Pleasant Basalt Member by Wyborn and Henderson (1996). This association occurs as a series of fault-bounded slices from Carcoar to about 2 km northwest of Lyndhurst (Figure 2) and is divided into basal and upper parts based on geochemical characteristics (Squire & Crawford 2007). However, the facies characteristics are largely independent of the geochemical subdivision. *Glyptograptus* n. sp. in the black mudstone overlying the basaltic facies association near Mandurama (Stevens 1954, 1957) constrains the age of

this association to late Darriwilian (Da4) to late Gisbornian (Gi2) (462–454 Ma).

The basaltic facies association occupies about 10% of the Forest Reefs Volcanics, and consists of basaltic massive and pillow facies (Table 3; Figure 5). Pillows are relatively well exposed. Massive basalt is poorly exposed and accounts for less than 5% of the outcrops.

### FACIES RELATIONSHIPS AND INTERPRETATION

Pillows are produced by lavas emplaced under water (Moore *et al.* 1973; Teply & Moore 1974) and are also known from intrusions into wet sediment (Kano 1991). Intrusive pillows are irregular in shape and size, and have peperitic margins, and pre-existing sediment infills the pillow interstices (Kano 1991). The pillows in the basaltic facies association are most likely to be extrusive in origin, as they are very regular and closely packed, and interpillow spaces are not filled by sediment. The pillow and massive facies in the Forest Reefs Volcanics are overlain by well-stratified clastic facies including black mudstone that contains graptolites, indicating that the setting was marine and below wave-base.

The long axes of pillows from three separate localities are consistently oriented north–south with gentle (10–20°) northerly plunges (Table 4). Although the palaeoflow measurements are consistent with local flow directions being from either the north or the south (present-day coordinates), they are insufficient in number or quality to determine the location of the vent. Locally, the massive facies is up to several tens of metres thick and may represent mega-pillows (Walker 1992), sheet lavas or sills, although incomplete exposure has made interpretation difficult.

The pillow facies exposed at Mt Pleasant is at least 10 m thick and >200 m in lateral extent, and is interpreted to form part of an interval of pillow and massive basaltic andesite between 100 and 480 m thick. The pillow facies at the base of the basaltic facies association is composed of clinopyroxene-poor basaltic andesite that is more evolved than the clinopyroxene-rich ( $\pm$ olivine) pillow facies near the top (Squire & Crawford 2007). Therefore, the greater thickness of the basaltic facies association near Mt Pleasant than exposed elsewhere probably represents a thick, near-source accumulation and is unlikely to be the result of repetition by faulting. This may reflect accumulation in a palaeo-depression or closer proximity to the source near Mt Pleasant.

**Table 3** Characteristics of the basaltic facies association, Forest Reefs Volcanics.

Facies	Description
Massive basalt	Thick (at least 3 m), weakly to non-vesicular units of plagioclase + clinopyroxene $\pm$ olivine $\pm$ apatite-phyric basalt; intimately associated with the pillow basalt facies; glassy margins (10–30 mm thick) display rare perlitic fractures.
Pillow basalt (Figure 5)	Conformable units at least 5 m thick and 200 m wide of close-packed basaltic pillow lobes up to 3 m long; intervals up to ~480 m thick and at least 12 km in lateral extent; glassy pillow margins commonly exhibit perlitic fractures; vesicles, up to 20 mm, occur in the 20 cm thick zone adjacent to the pillow margins; interpillow spaces (<10% of the facies) filled by secondary silica.

Trachyandesite facies association

The trachyandesite facies association comprises about 20% of the thickness of the Forest Reefs Volcanics and occurs in a central 8 × 15 km region (Figure 2) where the upper Forest Reefs Volcanics are exposed. This association is composed of three separate facies (Table 5): coherent trachyandesite, and polymictic trachyandesite breccia Types I and II (Figure 6). Two types of trachyandesite occur in this association: sparsely plagioclase–clinopyroxene ± biotite ± apatite ± FeTi oxide-phyric trachyandesite (about 15–25 modal% phenocrysts), and highly plagioclase–clinopyroxene ± biotite ± apatite ± FeTi oxide-phyric trachyandesite (about 35–50 modal% phenocrysts). The sparsely porphyritic trachyandesite was only observed in diamond drillcores from Forest Reefs, Cadia Far-East and Forestry, whereas the less well-exposed highly porphyritic trachyandesite occurs in the area south of Gooleys and east of Errowanbang. The abundance of sparsely porphyritic trachyandesite in drillcore provided the best data for interpreting the genesis of this association.

FACIES RELATIONSHIPS AND INTERPRETATION

Contacts among the three facies of this association are generally gradational, as are contacts with the enclosing well-stratified clastic facies (Figure 7). Transitions from one facies to the other occur through stratigraphic thicknesses of 0.25–1 m. Rare units of massive, sparsely



**Figure 5** Cross-sectional exposure of basaltic pillows from the basaltic facies association. The lower margins of the pillows mantle the arcuate upper margins of subjacent pillows, indicating younging. Hammer is 32 cm long. About 3 km southwest of Mt Pleasant (GR 686430E 6273690N).

porphyritic, coherent trachyandesite near Forest Reefs have sharp, slightly irregular upper and lower contacts, and are interpreted to be syn-volcanic sills and dykes (Figure 3).

Both types of polymictic trachyandesite breccia contain distinctive trachyandesite clasts. Variable proportions of subangular to subrounded basaltic to andesitic lithic fragments identical to those in the adjacent volcanic lithic breccia facies are also present. The composition and grainsize of the matrix of the polymictic trachyandesite breccias also display striking similarities with the matrix in the adjacent facies. In the polymictic trachyandesite breccia type I, the angular, polyhedral shapes of the trachyandesite clasts suggest that they originally formed by brittle fragmentation of trachyandesite. The dominance of this clast type, presence of groups of clasts that show jigsaw-fit texture and absence of stratification suggest that fragmentation of the trachyandesite occurred *in situ*. Similar polyhedral trachyandesite clasts occur in the polymictic trachyandesite breccia type II, together with wispy and fluidal trachyandesite clasts that must have been molten and ductile, at least at the moment of fragmentation.

The presence of polyhedral clasts with fine originally glassy margins, jigsaw-fit texture, fluidally shaped trachyandesite clasts, gradational contacts into adjacent facies and the absence of stratification, indicate that the polymictic trachyandesite breccia types I and II are varieties of peperite generated by intrusion of trachyandesite into unconsolidated coarse volcanic sediment (Busby-Spera & White 1987; Squire & McPhie 2002). The angular and fluidal trachyandesite clasts are the juvenile igneous component of the peperite variably admixed with the volcanoclastic host succession. The coherent trachyandesite facies adjacent to the polymictic trachyandesite breccias is interpreted to represent the intrusion. The contacts of the intrusion(s) appear to be highly irregular.

Domains dominated by the angular, polyhedral trachyandesite clasts (polymictic trachyandesite breccia type I) that are transitional into the adjacent stratified clastic facies can be interpreted as blocky peperite (Busby-Spera & White 1987). The domains dominated by the wispy trachyandesite clasts (polymictic trachyandesite breccia type II) can be interpreted as fluidal peperite (Busby-Spera & White 1987). The numerous, poorly exposed tabular units of highly porphyritic trachyandesite southeast of Errowanbang could be either sub-volcanic sills or lavas (Figure 7).

Wyborn and Henderson (1996) named the rocks of this association the Nullawonga Latite Member, in which was included subaerial latitic ignimbrite and

**Table 4** Direction of elongation of pillow lobes in pillow basalts of the basaltic facies association in the Forest Reefs Volcanics.

Easting	Northing	Elongation direction (plunge/trend)	Outcrop type and (number of measurements)
686430	6273690	15°/020 ± 20°	Large 3D outcrop of pillow facies (2)
688840	6276960	10–20°/005 ± 20°	Pavement exposure of pillow facies (4)
687580	6276460	15/010 ± 20°	Large 3D outcrop of pillow facies (2)

Note a sector range rather than a specific direction is given for irregular and two-dimensional outcrops.

**Table 5** Characteristics of the trachyandesite facies association, Forest Reefs Volcanics.

Facies	Description
Coherent trachyandesite (Figure 6a)	Subconformable to discordant units generally <10 m thick and up to 200 m in lateral extent of sparsely to highly porphyritic trachyandesite and lesser trachydacite; planar or strongly folded and irregular internal foliation; subangular to subrounded basaltic, andesitic and volcanoclastic fragments up to 10 cm in size may comprise up to 25% of the facies; lower and upper contacts are generally transitional into polymictic trachyandesite breccia types I and II; rare exposures up to 20 m thick have a uniform, unfoliated texture and sharp, slightly irregular upper and lower contacts.
Polymictic trachyandesite breccia type I (Figure 6b)	Non-stratified, poorly sorted units; comprise up to 60% angular fragments <4 cm across of weakly to non-vesicular trachyandesite; trachyandesite clasts have curvilinear, formerly glassy margins (<2 mm thick) and commonly display jigsaw-fit textures in the matrix-poor domains; matrix is dominated by feldspar, with lesser clinopyroxene and hornblende crystal fragments and basaltic fragments, and rare carbonaceous siltstone and claystone clasts similar to the adjacent feldspar-rich sandstone and siltstone and volcanic lithic breccia facies; matrix grain size is generally <10 mm; subangular to subrounded clasts up to 15 cm of basalt and basaltic andesite that do not have formerly glassy margins, may form up to 20% of the facies; contacts are gradational with the coherent trachyandesite, polymictic trachyandesite breccia type II and adjacent facies (predominantly feldspathic sandstone and volcanic lithic breccia); highly variable stratigraphic thicknesses up to 4 m.
Polymictic trachyandesite breccia type II (Figure 6c)	Non-stratified, unsorted to poorly sorted, matrix-supported units at least 2 m thick; 10–75% of the clasts are trachyandesite up to 4 cm across that have blocky shapes with curvilinear margins or fluidal and wispy shapes with delicate, irregular, feathery margins; trachyandesite clasts have an internal planar or strongly folded and irregular foliation; angular to subangular basaltic and volcanoclastic fragments may form up to 90%; contacts are gradational with the coherent trachyandesite, polymictic trachyandesite breccia type I and the adjacent feldspar-rich sandstone and siltstone and volcanic lithic breccia facies; matrix has similar composition and grain size to the polymictic trachyandesite breccia type I facies.

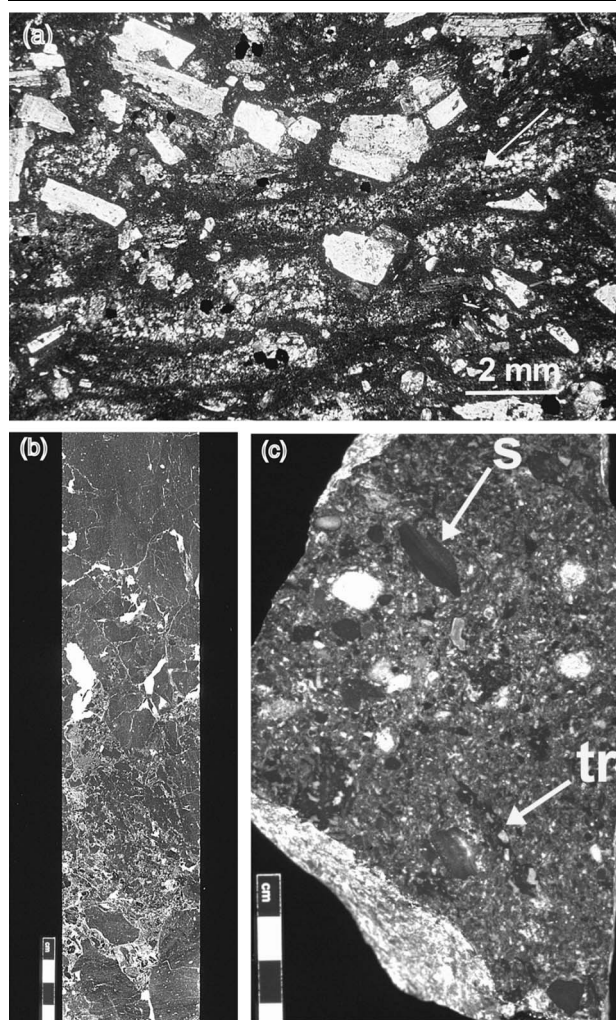
a 6–8 km diameter trachyandesite ring dyke. They interpreted the distinct foliation in the coherent trachyandesite facies (Figure 6a) as eutaxitic texture in subaerial welded ignimbrite. However, the foliation more closely resembles flow banding, being defined by aligned plagioclase phenocrysts and aggregates of fine radiating crystals interpreted to be spherulites. The lack of vitriclastic textures and of internal, lateral and vertical textural zonation, and constraints given by the facies relationships and geometry of the trachyandesite facies association, strongly suggest an intrusive setting and that a pyroclastic origin is implausible.

### Highly porphyritic basalt to basaltic andesite facies association

The highly porphyritic basalt to basaltic andesite facies association is composed of fine to medium, highly porphyritic plagioclase–clinopyroxene  $\pm$  FeTi oxide  $\pm$  apatite  $\pm$  olivine  $\pm$  hornblende-phyric basalt to basaltic andesite units that have high-K calc-alkaline to shoshonitic affinities (Squire & Crawford 2007). The groundmass is generally holocrystalline, and contains albite-altered plagioclase  $\pm$  clinopyroxene microphenocrysts. This facies association includes massive and fluidal-clast breccia facies (Figure 8). These facies are present throughout most of the Cadia–Neville region, though they are more abundant between Cadia–Ridgeway, Forest Reefs, Gooleys and about 5 km southwest of

Errowanbang, where they comprise up to 20% of the thickness of the upper Forest Reefs Volcanics. However, near Cadia, this association is locally abundant in the lower Forest Reefs Volcanics and the Weemalla Formation.

The highly porphyritic basalt to basaltic andesite units in this association are tabular, generally subparallel to regional bedding and up to several tens of metres thick (e.g. Big Cadia). In some cases, the central parts of the highly porphyritic basalt to basaltic andesite units grade into equigranular dolerite and gabbro. In contrast, thinner (0.25–2 m thick) intervals at the margins of the units contain <75% fluidally shaped clasts with similar compositions, phenocryst populations and degrees of vesicularity to the adjacent massive basalt or basaltic andesite (e.g. Cadia Far-East). The vesicles are irregularly shaped, quartz- and calcite-filled, up to 15 mm across, comprise <30 modal% and generally occur in an interval about 5 m thick near the margins of the thicker units. The clasts near the margins of the massive units have fine originally glassy groundmasses, and the clast margins (up to 4 mm thick) are either planar or highly irregular in shape (Figure 8). The matrix varies from feldspar-rich sandstone, in which bedding is commonly preserved (NC497, 270–290 m), to volcanic lithic breccia (NC497, 293–300 m), mafic volcanic sandstone and polymictic volcanic conglomerate with breccia or sandstone matrix, all of which are similar to and gradational into the adjacent



**Figure 6** Trachyandesite facies association. (a) Coherent trachyandesite facies. Aligned plagioclase phenocrysts and variations in the groundmass (arrow) define an irregular foliation interpreted as flow banding. Wyborn & Henderson (1996) interpreted this photomicrograph (plane-polarised light) of highly porphyritic trachyandesite to be welded ignimbrite. Sample 91844180 (GR 695300E 6284900N), Geoscience Australia, Canberra. (b) Polymictic trachyandesite breccia type I containing abundant polyhedral clasts of trachyandesite with curvilinear margins that show jigsaw-fit texture. This sample is the basal contact of a unit of sparsely porphyritic coherent trachyandesite (upper half) that is gradational into polymictic trachyandesite breccia type I (lower half), and has a matrix dominated by feldspar-rich sandstone. Polymictic trachyandesite breccia type I is interpreted as blocky peperite. Sample ORRS0010 from Cadia-Far East drillhole, NC497, 156.5–156.75 m. Scale bar marked in centimetres. (c) Polymictic trachyandesite breccia type II with abundant wispy trachyandesite clasts (tr) and angular clasts of laminated black mudstone (s). This sample is interpreted to be fluidal peperite. Sample BLRS0587, about 4 km east-southeast of Errowanbang (GR 692680E 6285550). Scale bar marked in centimetres.

volcaniclastic host units. Rare angular clasts of thinly bedded or laminated sandstone (up to 20 cm across), similar to the feldspar-rich sandstone, also occur randomly in the massive basalt and basaltic andesite.

#### FACIES RELATIONSHIPS AND INTERPRETATION

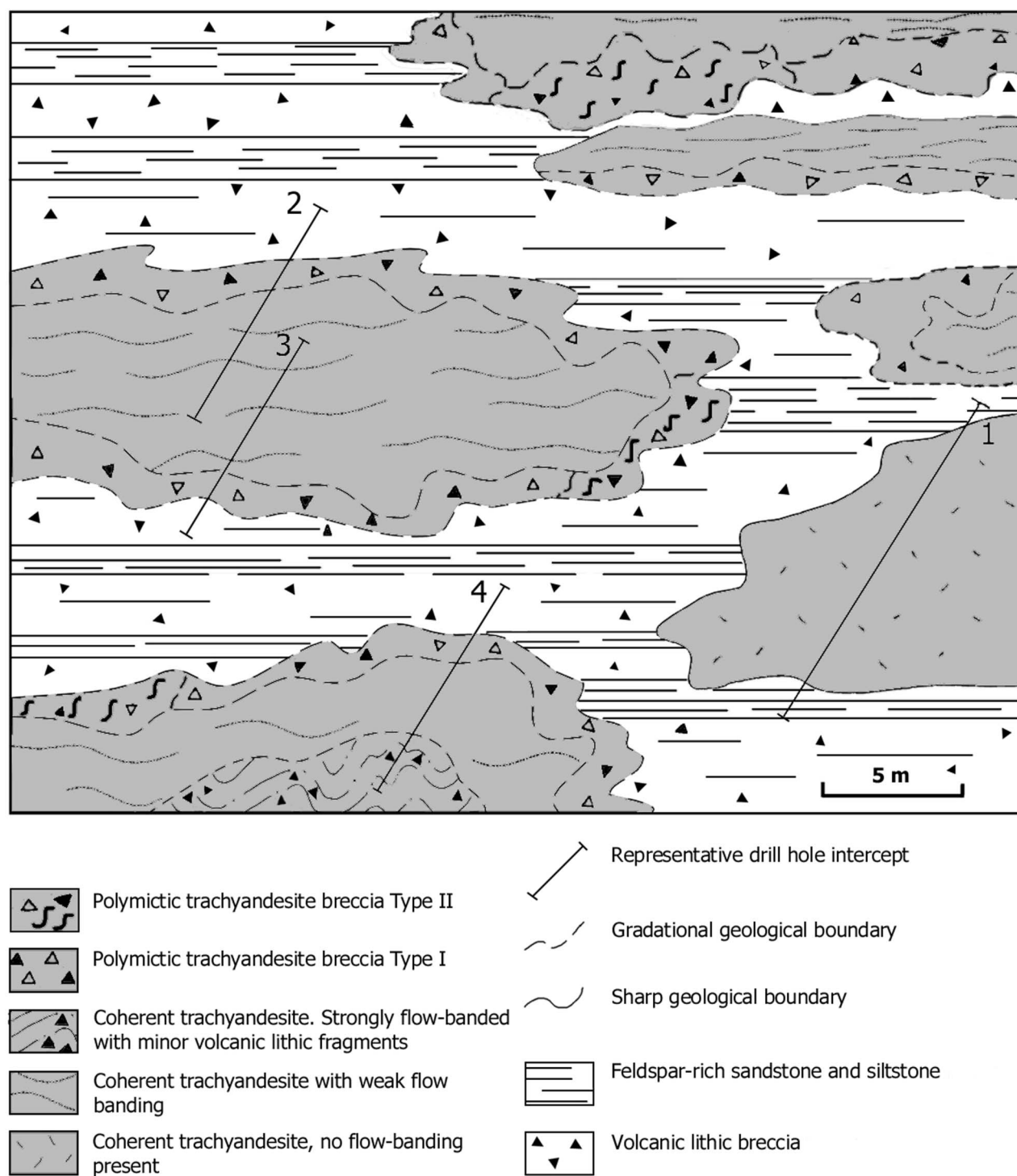
The intervals of fluidally shaped clasts with gradational contacts into massive basalt and basaltic andesite are interpreted to represent fluidal peperite and indicate that the highly porphyritic basalt to basaltic andesite units at Cadia were intruded into unconsolidated sediment (Busby-Spera & White 1987). Some of the clasts were probably interconnected in three dimensions and form part of intrusive lobes or apophyses. Being broadly conformable, the highly porphyritic intrusions are most likely to be sills. There are no firm constraints on the depth of emplacement of the sills, though the depths must have been sufficiently shallow for the host succession to be unconsolidated or poorly consolidated. The highly porphyritic basalt to basaltic andesite intrusions display rare cross-cutting relationships with the trachyandesite facies association but are intruded by, and thus pre-date, the coarsely equigranular intrusions (about 443 Ma: Squire & Crawford 2007). Therefore, the trachyandesite facies association, highly porphyritic basalt to basaltic andesite intrusions and coarsely equigranular intrusions were emplaced successively in a relatively short period.

No texturally or compositionally similar extrusive volcanic units occur at or above the stratigraphic level of the highly porphyritic basalt to basaltic andesite sills. Therefore, the sills are unlikely to have been the intrusive parts of lavas. Instead, the variety in compositions and geochemical affinities of the intrusions suggests that they probably represent a number of sill complexes (Staudigel & Schmincke 1984) that intruded thick, largely unconsolidated or poorly consolidated volcanoclastic successions of the Forest Reefs Volcanics.

#### Coarsely equigranular intrusions in the Cadia–Neville region

The dioritic, monzodioritic, monzonitic and syenitic intrusions are distinguished by their coarsely equigranular texture. They cut all the facies associations described above and occur predominantly in the upper Forest Reefs Volcanics between Cadia, Forest Reefs, Tallwood and Junction Reefs; rare coarsely equigranular intrusions are present in the lower Forest Reefs Volcanics and the uppermost parts of the Weemalla Formation at Cadia (Figures 2, 3). Plagioclase, clinopyroxene and K-feldspar are the dominant minerals, with biotite, hornblende and FeTi oxide phases also common (Squire & Crawford 2007). K-feldspar also occurs as a rim on earlier plagioclase or as large interlocking crystals that poikilitically enclose clinopyroxene and plagioclase crystals. The dioritic to syenitic coarsely equigranular intrusions have high-K calc-alkaline to shoshonitic affinities.

The coarsely equigranular intrusions have sharp, slightly irregular margins and are up to several hundred metres thick. At Cadia-Ridgeway, an equigranular monzodioritic and monzonitic intrusion is narrow (50–100 m across), pipe-shaped and several hundred metres in vertical extent sub-perpendicular to bedding, whereas at Cadia Hill, the equigranular monzonitic

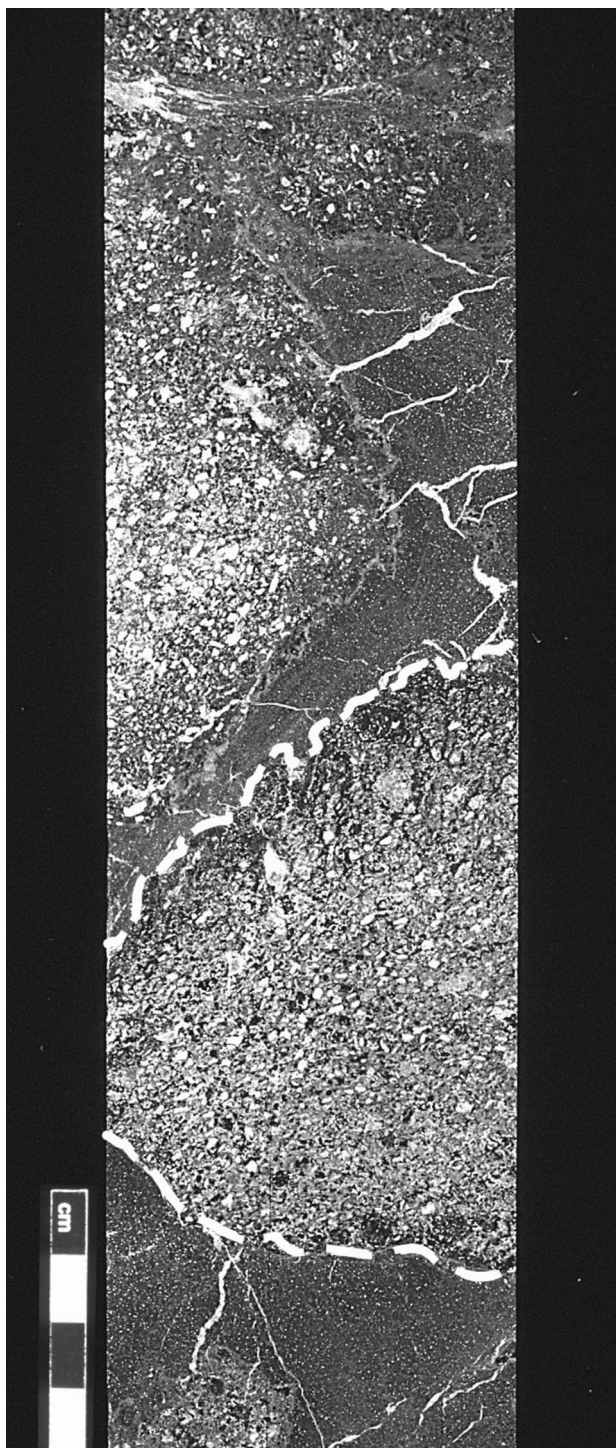


**Figure 7** Schematic representation of the contact relationships between the trachyandesite facies association and the adjacent volcanic successions. Representative drillhole intercepts are: 1, FRNC6, 456–465 m; 2, FRNC6, 215–225 m; 3, FRNC6, 232–242 m; 4, NC497, 147–162 m (Squire 2001). Note the flow-banded trachyandesite with non-peperitic upper margins near the top right-hand corner is interpreted as lava, as may occur east of Errowanbang.

intrusion is equant and larger (at least  $3 \times 1.5 \times 1$  km) (Holliday *et al.* 2002). The dioritic to syenitic intrusions are interpreted to represent a series of composite stocks that include several near-vertical apophyses intruded mainly about 439 Ma (Squire & Crawford 2007).

## DEPOSITIONAL SETTING OF THE FOREST REEFS VOLCANICS

Basaltic pillows, abundant turbidites and a diverse range of marine fossils, indicate that the depositional environment for the Forest Reefs Volcanics in the



**Figure 8** Fluidally shaped clasts of highly vesicular, plagioclase-rich basalt from the highly porphyritic basalt to basaltic andesite facies association. The clasts have formerly glassy margins that are highly irregular and crenulate (dashed lines around bottom clast). This interval has gradational contacts with the adjacent feldspar-rich sandstone and massive basalt facies and is interpreted to represent fluidal peperite. Sample ORRS0018 from Cadia Far-East drillhole NC497, 230.25–230.5 m. Scale bar marked in centimetres.

Cadia–Neville region was submarine and below wave-base. However, the depth of storm wave-base in modern oceans is highly variable and ranges from about

10 m to 200 m (Reading 1998 p. 238); thus the minimum depth for depositional setting of the Forest Reefs Volcanics is weakly constrained.

The well-stratified and very thick, diffusely stratified clastic facies associations of the Cadia–Neville region display a broadly upward-coarsening and thickening trend from the underlying feldspathic turbidites of the Coombing Formation to the very thick, diffusely stratified clastic facies association near the top of the Forest Reefs Volcanics (Figure 3). Turbidite-dominated successions are commonly interpreted in terms of the submarine-fan model of Walker (1978, 1984). The Coombing Formation and well-stratified clastic facies association in the lower Forest Reefs Volcanics could represent the mid to lower fan region, whereas the coarser and thicker units of the very thick, diffusely stratified clastic facies association in the upper Forest Reefs Volcanics could represent the feeder-channel sub-environment. The Coombing Formation and Forest Reefs Volcanics could, therefore, be considered simply in terms of a prograding submarine-fan model (Walker & Mutti 1973). However, the laterally extensive, tabular form of the mapped intervals of coarse-grained facies in the upper parts of the Forest Reefs Volcanics (i.e. the very thick, diffusely stratified facies association) suggests sheet-like facies geometries, rather than the lenticular geometries expected for channel-fill in the upper parts of a fan.

The turbidites of the Forest Reefs Volcanics are similar to the ‘middle-absent turbidites’ described by Walker (1967) and are interpreted to indicate rapid deposition from high-particle-concentration currents in which traction was inhibited. These characteristics suggest that the clastic facies associations of the Forest Reefs Volcanics represent a submarine volcaniclastic apron (Karig & Moore 1975; Cas *et al.* 1981; Carey & Sigurdsson 1984). The diverse range in composition, shape and size of the volcanic particles in the very thick, diffusely stratified clastic facies association (Table 2) reflects derivation from several sources. In addition, the high degree of rounding of the clasts in the polymictic volcanic conglomerate facies indicates that the clasts passed through a sub-aerial, shoreline and/or shallow-marine setting prior to deposition.

## INTRABASINAL VOLCANISM

The basaltic and trachyandesite facies associations are dominated by primary volcanic facies produced by intrabasinal volcanic centres. The differences between these facies associations reflect differences in the style of volcanism, the type of volcanic edifice and proximity to the source vents.

### Basaltic facies association

The basaltic facies association has an interpreted maximum thickness of about 480 m and present-day lateral extent of at least 12 km. The absence of pyroclastic deposits (Batiza *et al.* 1984) and feeder dykes (Fisher 1984; Head *et al.* 1996) suggests that the basaltic facies association was emplaced in a proximal to medial



setting relative to the source. The abundance of pillow and massive facies and absence of abundant autoclastic facies indicates that the lavas were emplaced on a gently dipping palaeoslope. These characteristics are consistent with the gently sloping, flanks of a basaltic seamount (Lonsdale & Batiza 1980; Batiza & Vanko 1983; Searle 1983). Seamounts are constructed of numerous lavas erupted from central and/or flank vents (Fornari & Ryan 1984; Wright & Gamble 1999). In cases where the edifice emerges above sea-level, subaerially erupted basaltic lavas may reach the coast and advance subaqueously (Moore *et al.* 1973; Tribble 1991). The preserved sections through the basaltic facies association are entirely submarine and there are no traces of shallow-water or subaerial environments having been important, so in this case, the edifice was probably completely submerged.

### Trachyandesite facies association

The trachyandesite facies association consists of trachyandesite intrusions and abundant peperite, and occurs through a stratigraphic interval up to several hundred metres thick and at least several kilometres in lateral extent (Figures 2, 3). The trachyandesite magma intruded diverse, thickly bedded, coarse volcanogenic mass-flow and turbidity current deposits (e.g. feldspar-rich sandstone, volcanic lithic breccia) at the medial to distal parts of a volcanoclastic apron. In view of the shallow level of emplacement, probably just beneath the sea floor, lavas could also be present although none have been identified. This association may represent the initial stages of growth of a seafloor volcanic cone, the extrusive parts of which are not preserved.

### Subaerial collapse caldera model for the Forest Reefs Volcanics

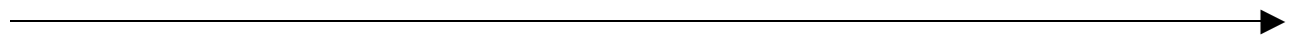
Wyborn and Henderson (1996) postulated that the Cadia–Neville region included the remains of a subaerial caldera: eruption of latitic ignimbrite led

to the piston-like foundering of Forest Reefs Volcanics roof rocks into the underlying monzodioritic to syenitic magmas. The collapse caldera was defined by centripetal bedding measurements and a ring-dyke complex (Nullawonga Latite Member) about 8 km in diameter. During (and after?) caldera collapse, thick units of reworked (pyroclastic?) volcanic breccia were deposited mainly in the intracaldera environment, together with thick ignimbrites and minor basaltic lavas.

However, detailed mapping and drillcore logging have revealed that the trachyandesite facies association is more widespread than first interpreted, and is composed of northwest-striking, gently northeast-dipping conformable intervals of coherent trachyandesite and polymictic trachyandesite breccia, collectively up to several hundred metres thick (Figure 2). The trachyandesite facies association does not have a semicircular outcrop pattern. In fact, large changes in bedding orientation occur only adjacent to major north-, north-northwest- and north-northeast-striking faults. Furthermore, no evidence has been found to support the presence of ignimbrite anywhere in the Forest Reefs Volcanics. Instead, the units previously described as ignimbrite (i.e. parts of the Nullawonga Latite Member) are now assigned to the trachyandesite facies association and interpreted as shallow intrusions with peperitic margins. Thick, conformable units of the trachyandesite facies association are equally distributed both within and outside the postulated caldera. Although there is very little evidence to support the caldera interpretation of Wyborn and Henderson (1996), we agree that the trachyandesite facies association delineates a centre for igneous activity.

### FACIES ARCHITECTURE AND EVOLUTION OF THE CADIA–NEVILLE REGION IN THE ORDOVICIAN

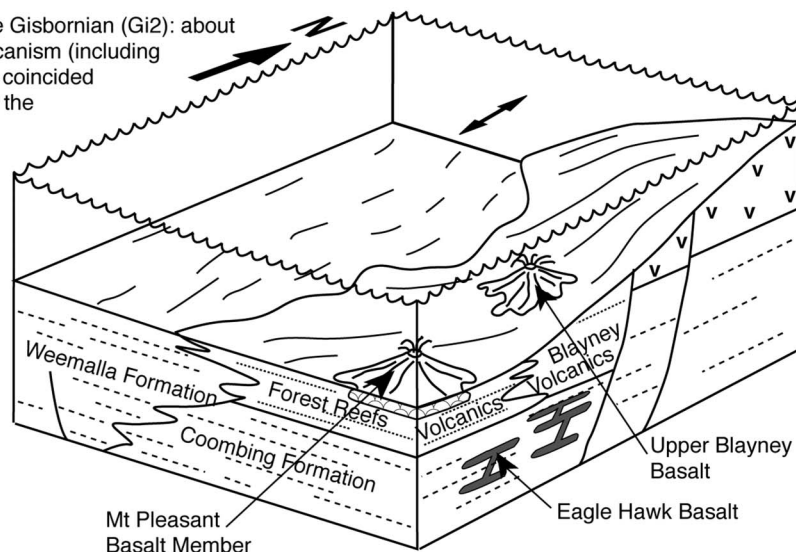
The Coombing and Weemalla Formations are part of an extensive Middle Ordovician feldspathic turbidite succession that formed the substrate upon which the upper



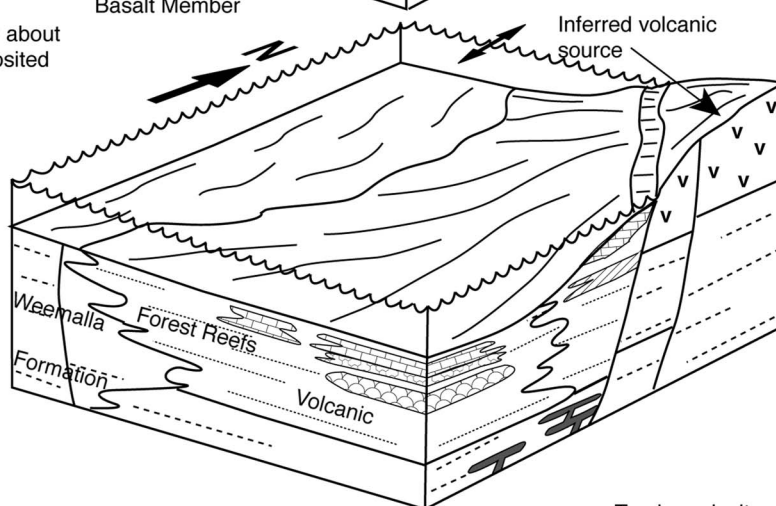
**Figure 9** Schematic palaeogeographic reconstruction and facies model for the Cadia–Neville district in the southern Molong Volcanic Belt during the Middle Ordovician to early Llandovery. (a) (Stage 1) Deposition of the lower Forest Reefs Volcanics is recorded by the influx of coarser grained and more ferromagnesian-rich detritus than the subjacent Weemalla and Coombing Formations, and represents the products of a volcanoclastic apron. The basaltic facies association of the lower Forest Reefs Volcanics, lavas of the upper Blayney Basalt and intrusions of the Eagle Hawk Basalt were emplaced broadly coeval with each other, and represent an episode of shoshonitic volcanism in the region. Two-headed arrow indicates most likely location of inferred source for the feldspathic turbidites. (b) (Stage 2) Deposition of the late Eastonian (449–447 Ma) calcareous sandstone facies near the top of the lower Forest Reefs Volcanics coincided with a hiatus in shoshonitic volcanism. Two-headed arrow indicates most likely location of inferred source for the feldspathic turbidites. (c) (Stage 3) Emplacement of the medium-K calc-alkaline felsic intrusions (Copper Hill-type dacite) at about 448–445 Ma probably coincided with development of the inferred unconformity separating the lower and upper Forest Reefs Volcanics. At about the middle Bolindian (*ca* 445 Ma), deposition recommenced. The upper Forest Reefs Volcanics are composed of thick intervals of polymictic conglomerate and breccia and mafic sandstone (at **a**). The basaltic clasts from the polymictic volcanic conglomerate with coarse volcanic matrix in the Cheesemans Mountain region are comagmatic with the Upper Blayney Basalt and Eagle Hawk Basalt, and may have been sourced from uplifted successions in the east (at **b**). The early Llandovery shoshonitic and high-K calc-alkaline magmatism included shallow intrusions of trachyandesite with peperitic margins (trachyandesite facies association) (at **c**), thick (several tens of metres), highly porphyritic basalt to basaltic andesite sills with fluidal peperite margins (at **d**), and dioritic to syenitic equigranular intrusions (at **e**). The shallow intrusions of the trachyandesite facies association could represent the initial (pre-cone) growth stage of a trachyandesite cone.



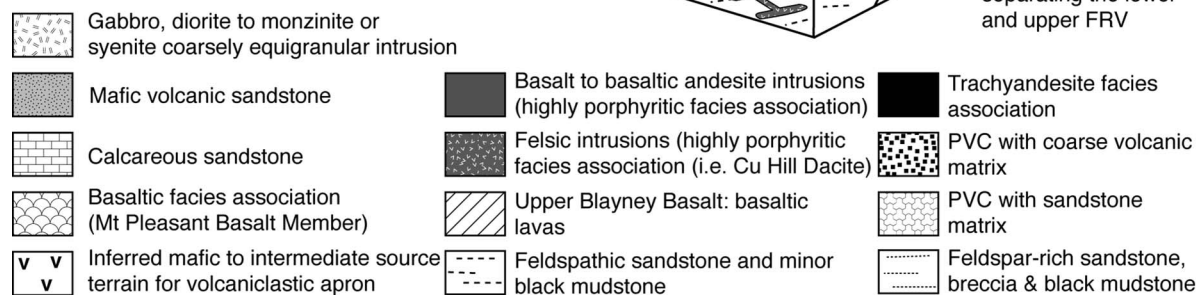
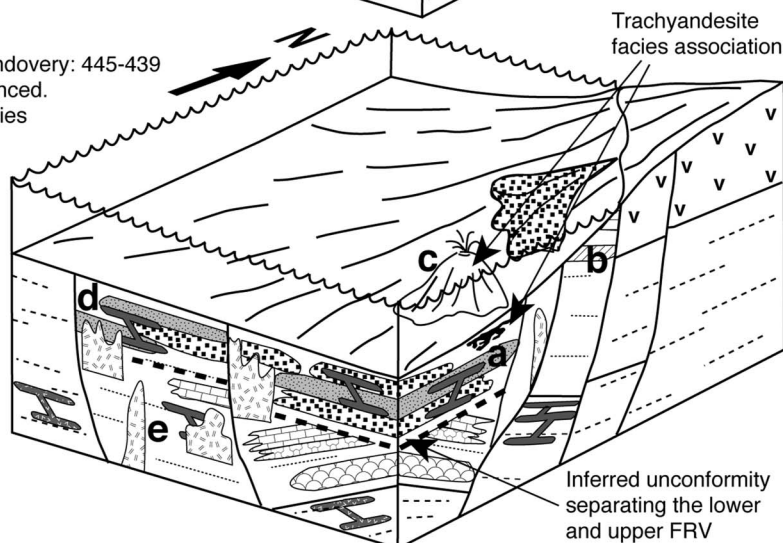
(a) Stage 1: (late Darriwilian (Da4) to late Gisbornian (Gi2): about 462 to 454 Ma). Shoshonitic basaltic volcanism (including the Mt Pleasant Basalt Member) broadly coincided with the commencement of deposition of the (lower) Forest Reefs Volcanics



(b) Stage 2: (Eastonian to early Bolindian: about 454-445 Ma). Calcareous sandstone deposited near the top of the lower FRV during a regional limestone-forming hiatus. Emplacement of the felsic intrusions (Copper Hill-type Dacite) at about 447-445 Ma occurred broadly coincident with development of the inferred unconformity separating the lower and upper FRV (see Figure 9c).



(c) Stage 3: (middle Bolindian to early Llandovery: 445-439 Ma). Deposition of the upper FRV commenced. Shoshonitic volcanism (trachyandesite facies association) and emplacement of highly porphyritic mafic sills and dykes and gabbroic to syenitic equigranular intrusions occurred at about 439 Ma.



Middle Ordovician to lower Llandovery Forest Reefs Volcanics were deposited (Figure 9a). The Forest Reefs Volcanics are divided into lower and upper parts that are separated by an inferred unconformity dated at about the late Eastonian to middle Bolindian (448–445 Ma) (Figure 3). The informal subdivision of the Forest Reefs Volcanics is used here to avoid confusion in stratigraphic nomenclature and as an acknowledgement of the uncertain significance or existence of the unconformity. The inferred unconformity (Figure 2) may alternatively represent a major fault, which could equally well account for the variation in strike of bedding between the lower and upper Forest Reefs Volcanics near Junction Reefs. However, the fault would be fortuitously located at the boundary between a major change in provenance and facies associations in the Forest Reefs Volcanics (i.e. the lower and upper parts of the Forest Reefs Volcanics). This position also marks the approximate time of the hiatus in volcanism and sedimentation (i.e. limestone formation: Packham *et al.* 1999; Percival & Glen 2007) and emplacement of the medium-K calc-alkaline Copper Hill suite intrusions, which represent a marked, but short-lived change in the tectonic setting of the Macquarie Arc in the late Eastonian to middle Bolindian. Although we cannot preclude the existence of a fault separating the two parts of the Forest Reefs Volcanics, if future work establishes the unconformity, the Forest Reefs Volcanics should be replaced by two formations corresponding to the informal lower and upper Forest Reefs Volcanics.

### Lower Forest Reefs Volcanics

The lower Forest Reefs Volcanics are dominated by feldspar-rich sandstone, and minor volcanic lithic breccia and black mudstone facies, and are distinguished from the underlying Coombing and Weemalla Formations by the presence of >5% mafic to intermediate lithic fragments and clinopyroxene and hornblende crystals. In addition, there was a progressive change from distal turbidites with well-developed Bouma a- to e-divisions in the Coombing and Weemalla Formations to volcanoclastic apron turbidites dominated by Bouma a- and b-divisions in the Forest Reefs Volcanics.

Shortly after the influx of more mafic-rich detritus of the Forest Reefs Volcanics began, basaltic volcanism in the southern part of the Cadia–Neville region generated a broad, submarine volcano recorded by the basaltic facies association (Figure 9a). Marine fossils in the overlying units indicate that deposition continued in a submarine, below-wave-base environment. Deposition of the calcareous sandstone facies at the top of the lower Forest Reefs Volcanics, in the late Eastonian (Figure 9b), was followed by emplacement of medium-K calc-alkaline dacitic intrusions in the Weemalla Formation, Coombing Formation and Blayney Volcanics (i.e. Copper Hill-type dacite intrusions: Squire & Crawford 2007) at about 448–445 Ma. This resulted in the development of the inferred unconformity separating the lower and upper parts of the Forest Reefs Volcanics.

### Upper Forest Reefs Volcanics

The upper Forest Reefs Volcanics are dominated by the very thick, diffusely stratified facies association, trachyandesite facies association, highly porphyritic basalt to basaltic andesite facies association and mafic volcanic sandstone, with lesser feldspar-rich sandstone, volcanic lithic breccia, and minor laminated mudstone and black mudstone (Figure 3). The higher abundance of mafic volcanic lithic and ferromagnesian crystal fragments and generally subordinate feldspar grains in the volcanoclastic facies of this part of the Forest Reefs Volcanics distinguishes them from the lower Forest Reefs Volcanics. Some of the clasts from the polymictic volcanic conglomerate with coarse volcanic matrix are comagmatic with the lavas from the Blayney Volcanics and intrusions in the Coombing Formation (Squire 2001), implying that provenance for at least some of the detritus may have been from uplifted successions in the east (Figure 9c). The upper Forest Reefs Volcanics include thick, laterally extensive turbidites dominated by Bouma a- and b-divisions that are interpreted to represent a submarine volcanoclastic apron, as are the uppermost parts of the lower Forest Reefs Volcanics (e.g. polymictic volcanic conglomerate with sandstone matrix near Cadia). The thick volcanogenic sedimentary successions of the upper Forest Reefs Volcanics that include well-rounded conglomerate clasts and well-sorted mafic and feldspar-rich sandstone facies indicate the presence nearby of a substantial, at least partly subaerial, andesitic volcanic centre(s).

The trachyandesite facies association was emplaced onto and into this major volcanoclastic apron sequence (Figure 9c). Much of the trachyandesite facies association is intrusive and could represent the initial stage of an intrabasinal submarine volcanic centre that is not preserved. The trachyandesite ‘plumbing system’ was substantial, perhaps >10 km in diameter. There is very little evidence to support the existence of a caldera or the products of explosive volcanism (Wyborn & Henderson 1996).

Shoshonitic volcanism in modern intra-oceanic arc-related settings show a temporal progression from mafic to more evolved compositions [e.g. the northern Mariana Trough (Fryer 1995; Fryer *et al.* 1997) or the Pliocene successions in Fiji (Gill & Whelan 1989; Rogers & Setterfield 1994)]. Such trends typically last for <2 million years. However, the basaltic and trachyandesite volcanism occurred at least 15 and perhaps as much as 23 million years apart. During that interval, medium-K calc-alkaline dacitic intrusions were emplaced (i.e. Copper Hill-type dacite intrusions: Squire & Crawford 2007) soon after a regional limestone-forming event. The basaltic and trachyandesite facies associations are therefore considered to represent the products of two separate, arc-related shoshonitic volcanic episodes.

The tabular, highly porphyritic basalt to basaltic andesite intrusions probably represent some sort of synsedimentary sill complex(es) (Staudigel & Schmincke 1984) emplaced soon after deposition of the upper Forest Reefs Volcanics, prior to consolidation of the sediments (Figure 9c). Although probably only

slightly younger and broadly comagmatic (Squire & Crawford 2007), the coarsely equigranular intrusions cross-cut all the facies associations of the Forest Reefs Volcanics (Figure 9c).

## CONCLUSIONS

The Forest Reefs Volcanics are a complex association of mafic to intermediate lavas, syn-volcanic intrusions and volcanoclastic facies considered to represent the products of at least two intrabasinal volcanic centres interleaved with a volcanoclastic apron. The volcanoclastic apron was derived from one or more at least partly emergent mafic to intermediate volcanic centres, and overlapped and partly buried older distal feldspathic turbidites (Coombing and Weemalla Formations). Deposition occurred entirely in a submarine, below-wave-base environment. Differences in provenance and facies associations enable the Forest Reefs Volcanics to be divided into lower and upper parts. Feldspar-rich sandstone, volcanic lithic breccia and lesser black mudstone dominate the lower Forest Reefs Volcanics; polymictic volcanic conglomerate with sandstone matrix and calcareous sandstone facies are important near the top. In contrast, the upper Forest Reefs Volcanics contain trachyandesite and an increased abundance of ferromagnesian crystals and coarse mafic volcanic fragments.

The basaltic facies association occurs near the base of the Forest Reefs Volcanics and could represent a submarine basaltic volcano at least 12 km in diameter. The trachyandesite facies association was generated by a separate phase of intrabasinal volcanism that probably occurred late in the accumulation of the upper Forest Reefs Volcanics and at least 15 and perhaps as much as 23 million years after the basaltic volcanism. No evidence has been found to support the presence of a major collapse caldera or subaerial environments in the Forest Reefs Volcanics (Wyborn & Henderson 1996). Instead, the trachyandesite facies association could represent an intrusive complex or the initial, largely shallow intrusive stages of a cone volcano >10 km in diameter. The basaltic and trachyandesitic facies associations, therefore, represent the products of two separate, arc-related volcanic episodes. Highly porphyritic basalt to basaltic andesite intrusions were emplaced as thick tabular sills before the volcanoclastic succession was lithified. The final magmatic activity generated coarsely equigranular, mafic to intermediate intrusions. The trachyandesite facies association, the highly porphyritic intrusions and the coarsely equigranular intrusions were emplaced successively in a relatively short period (probably <2 million years: Squire & Crawford 2007).

Differences in facies associations between the lower and upper parts of the Forest Reefs Volcanics (e.g. provenance, bed thicknesses, maximum clast sizes and the composition of shoshonitic volcanism), together with a variation in the strike of bedding between the two parts near Junction Reefs may reflect the presence of a late Eastonian to middle Bolindian unconformity. The timing of the change in facies associations is

broadly coincident with an inferred change in tectonic setting recorded by a limestone-forming hiatus (Packham *et al.* 1999) and emplacement of the medium-K calc-alkaline dacitic intrusions (Squire & Crawford 2007). The unconformity was not observed, and is therefore inferred.

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## APPENDIX 1: STRATIGRAPHIC NOMENCLATURE

The following definitions and descriptions apply to the redefined formations and members of the Cabonne Group described in this paper.

### Weemalla Formation (redefined)

**Status** (unchanged) Formation of the Cabonne Group (Wyborn, Krynen & Pogson *in* Pogson & Watkins 1998).

**Type locality** Belubula River (AMG 682200E 6284400N) to the northern boundary of the Weemalla property (AMG 682500E 6288700N) along Cadiangullong and Swallow Creeks (Taylor 1988).

**Distribution** (new) Occurs as scattered outcrops that extend as a narrow band about 35 km north to south and up to 10 km east to west from about 5 km southwest of Lyndhurst to about 10 km north of Four Mile Creek (Bathurst 1:250 000 sheet).

**Lithology** (new) Predominantly composed of medium- to thin-bedded, moderately well-sorted, fine- to medium-grained feldspathic sandstone with rare cross-beds and slumps (Squire 2001). Thin to thick, poorly sorted, internally massive to normally graded beds of volcanic lithic breccia are less important and medium- to thin-laminated beds of black mudstone are rare. Subangular feldspar crystal fragments are the dominant detrital component, and quartz, clinopyroxene and hornblende fragments are rare (<5%), although Packham *et al.* (2003) recorded up to 30% detrital quartz in a single sample. Minor angular to subangular lithic fragments up to 5 cm, composed of basalt to basaltic andesite and laminated black mudstone, are present in the volcanic lithic breccia. Microfossils and graptolites are present in the black mudstone (see references in Wyborn,

Krynen & Pogson *in* Pogson & Watkins 1998; Squire 2001).

**Boundary contacts** (new) The basal contact is not exposed. At Cadia, the Weemalla Formation is conformably overlain by Forest Reefs Volcanics; a similar conformable contact is inferred with the overlying Fairbridge Volcanics farther west and northwest. However, south of Cadia, the Wongalong and Cadiangullong Faults bound the eastern margin, and the Silurian Garland Granodiorite defines the southern boundary. To the north, the Weemalla Formation is unconformably overlain by Tertiary basalt, and elsewhere it is in fault contact with adjacent Siluro-Devonian successions.

**Remarks** (new) Deposition occurred mainly by direct fallout from turbidity currents (i.e. thick massive and normally graded beds) with lesser tractional and suspension sedimentation; deposited in a marine, below-wave-base setting (Squire 2001).

**Age** (new) Early Darriwilian (Da2) to late Eastonian (Ea4) (about 468–447 Ma).

### Forest Reefs Volcanics (redefined)

**Status** Formation of the Cabonne Group (Wyborn, Krynen & Pogson *in* Pogson & Watkins 1998). Includes one member, Mt Pleasant Basalt Member (Wyborn & Henderson 1996).

**Type locality** (new) The complex facies association of the Forest Reefs Volcanics preclude a single type locality (Wyborn & Henderson 1996); thus we present here a number of representative localities. Feldspar-rich sandstone, volcanic lithic breccia, calcareous sandstone and black mudstone are well exposed near Junction Reefs (AMG 684600E 6277750N). Polymictic volcanic

conglomerate with coarse volcanic matrix and mafic volcanic sandstone are present near Cheesemans Mountain (AMG 689500E 6284300N), and the trachyandesite and basalt to basaltic facies associations occur about 4 km east of Errowanbang (AMG 692680E 6285550N). The Mt Pleasant Basalt Member is very well exposed on Mt Pleasant (AMG 688900E 6276900N).

**Distribution** (new) The Forest Reefs Volcanics occur as scattered outcrops that extend about 15 km east to west and 20 km north to south from approximately Lyndhurst and Carcoar to Cadia, Forest Reefs and Tallwood (Bathurst 1:250 000 sheet). The Mt Pleasant Basalt Member extends broadly west to west-southwest for about 12 km from Carcoar to about 2 km northwest of Lyndhurst.

**Lithology:** (new) The Forest Reefs Volcanics have an inferred thickness of 2–2.5 km and generally occur as a gently to moderately northeast- and northwest-dipping package composed of 16 principal facies. These facies are grouped into five main facies associations: well-stratified clastic; very thick, diffusely stratified clastic; basaltic; trachyandesite; and highly porphyritic basaltic to basaltic andesite facies associations. Differences in provenance and facies associations and local variations in the strike of bedding enable the Forest Reefs Volcanics to be divided into lower and upper parts, separated by an inferred unconformity. Shoshonitic basaltic lavas (i.e. Mt Pleasant Basalt Member), feldspar-rich sandstone, volcanic lithic breccia and lesser black mudstone dominate the lower Forest Reefs Volcanics; polymictic volcanic conglomerate with sandstone matrix and calcareous sandstone facies are important near the top. In contrast, the upper Forest Reefs Volcanics contain shallow intrusions of shoshonitic trachyandesite and an increased abundance of

ferromagnesian crystals and coarse mafic volcanic fragments. The highly porphyritic basalt to basaltic andesite facies association is common in both the lower and upper Forest Reefs Volcanics, and also occurs in the adjacent Weemalla Formation at Cadia.

The Mt Pleasant Basalt Member is composed of plagioclase-clinopyroxene  $\pm$  olivine  $\pm$  apatite-phyric basaltic andesites (Squire & Crawford 2007) that form conformable units between 100 and 480 m thick of close-packed basaltic pillow lobes up to 3 m long with fine formerly glassy pillow margins and perlitic fractures. Vesicles, up to 20 mm, occur in the 20 cm thick zone adjacent to the pillow margins, and interpillow spaces are filled by secondary silica.

**Boundary contacts** (new) Conformably overlies the Coombing Formation in the south near Mandurama and Lyndhurst and the Weemalla Formation at Cadia. The Wongalong and Cadiangulong Faults define the boundary of the Forest Reefs Volcanics to the west and the Carcoar Fault to the east, and to the north an unconformity separates it from the Tertiary basalt. The basaltic facies of the Mt Pleasant Basalt Member occurs as a 100–480 m thick package that extends from Carcoar to about 2 km northwest of Lyndhurst.

**Remarks** (new) The Forest Reefs Volcanics are a complex association of mafic to intermediate lavas, syn-volcanic intrusion and volcanoclastic facies considered to represent the products of at least two intrabasinal volcanic centres interleaved with a volcanoclastic apron. Deposition occurred entirely in a submarine below-wave-base environment.

**Age** (new) Deposition commenced between the middle to late Darriwilian (Da3) and late Gisbornian (Gi2) (about 465–454 Ma) and ended in the early Llandovery (about 439 Ma).