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The Whitsunday Volcanic Province, Central Queensland, Australia: lithological and stratigraphic investigations of a silicic-dominated large igneous province

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Abstract

Contrary to general belief, not all large igneous provinces (LIPs) are characterised by rocks of basaltic composition. Silicic-dominated LIPs, such as the Whitsunday Volcanic Province of NE Australia, are being increasingly recognised in the rock record. These silicic LIPs are consistent in being: (1) volumetrically dominated by ignimbrite; (2) active over prolonged periods (40–50 m.y.), based on available age data; and (3) spatially and temporally associated with plate break-up. This silicic-dominated LIP, related to the break-up of eastern continental Gondwana, is also significant for being the source of $> 1.4 \times 10^6$ km^3 of coeval volcanogenic sediment preserved in adjacent sedimentary basins of eastern Australia.

The Whitsunday Volcanic Province is volumetrically dominated by medium- to high-grade, dacitic to rhyolitic lithic ignimbrites. Individual ignimbrite units are commonly between 10 and 100 m thick, and the ignimbrite-dominated sequences exceed 1 km in thickness. Coarse lithic lag breccias containing clasts up to 6 m diameter are associated with the ignimbrites in proximal sections. Pyroclastic surge and fallout deposits, subordinate basaltic to rhyolitic lavas, phreatomagmatic deposits, and locally significant thicknesses of coarse-grained volcanogenic conglomerate and sandstone are interbedded with the ignimbrites. The volcanic sequences are intruded by gabbro/dolerite to rhyolite dykes (up to 50 m in width), sills and comagmatic granite. Dyke orientations are primarily from NW to NNE.

The volcanic sequences are characterised by the interstratification of proximal/near-vent lithofacies such as rhyolite domes and lavas, and basaltic agglomerate, with medial to distal facies of ignimbrite. The burial of these near-vent lithofacies by ignimbrites, coupled with the paucity of mass wastage products such as debris-flow deposits indicates a low-relief depositional environment. Furthermore, the volcanic succession records a temporal change in: (1) eruptive styles; (2) the nature of source vents; and (3) erupted compositions. An early explosive dacitic pyroclastic phase was succeeded by a later mixed pyroclastic-effusive phase producing an essentially bimodal suite of lavas and rhyolitic ignimbrite. From the nature and distribution of

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volcanic lithofacies, the volcanic sequences are interpreted to record the evolution of a multiple vent, low-relief volcanic region, dominated by several large caldera centres. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Early Cretaceous; large igneous province; Eastern Australia; ignimbrite; volcanic evolution

1. Introduction

Large igneous provinces (LIPs) are classically considered to be massive crustal emplacements of predominantly extrusive and intrusive mafic magma that are manifest as continental and ocean basin flood basalts, oceanic plateaux, volcanic passive margins, submarine ridges, and seamount groups (Coffin and Eldholm, 1994). They show a temporal relationship to continental plate break-up, and particularly characterise the Jurassic–Cretaceous break-up history of Gondwana (e.g. Karoo, Parana–Etendeka continental flood basalts, Ferrar Group and oceanic plateaux: Ontong-Java, Kerguelen, Manihiki; Coffin and Eldholm, 1994 and references therein; Elliot, 1992; Cox, 1992). Emplacement of continental flood basalt provinces typically occurs over time scales of 10^5–10^6 years (Coffin and Eldholm, 1994).

Some LIPs are known to have a significant silicic component, such as the Lebombo part of the Karoo (e.g. Cleverly et al., 1984), and the Parana–Etendeka (e.g. Milner et al.,1992) continental flood basalt provinces of southern Africa. However, it is increasingly recognised that LIPs can be silicic-dominated, such as the Early Cretaceous volcanic passive margin of eastern Australia (Bryan et al., 1997) and the almost entirely rhyolitic Lower–Middle Jurassic Chon-Aike Province of South America (Pankhurst et al., 1998; Riley and Leat, 1999). These silicic-dominated LIPs are: (1) volumetrically dominated by ignimbrite; (2) active over prolonged periods (40–50 m.y.), based on available age data; and (3) spatially and temporally associated with plate break-up.

The generation of large volumes of rhyolite, ultimately related to hot mantle upwelling and intrusion of basaltic magma into the crust, is thought to be due to the fertile nature of the crust. For both eastern Australia and the Chon-Aike Province, the basement comprises Palaeozoic–Mesozoic volcanic and sedimentary rocks accreted and/or deposited along continental margins (Ewart et al., 1992; Stephens et al., 1995; Pankhurst et al., 1998). The relatively hydrous nature of the crustal source and absence(s) of precursory magmatic episodes, which will remove the more fusible components from the lithosphere (e.g. Gibson et al., 1992), are thought to facilitate crustal partial melting. Considerable debate has centred on the petrogenesis of large volumes of rhyolite magma, and the relative roles of fractional crystallisation, assimilation/fractional crystallisation, and magma mixing (see discussion in Pankhurst et al., 1998; Ewart et al., 1998a,b).

Little is known in detail of these silicic-dominated LIPs. Only overviews of the lithological variation have been provided, while the stratigraphy, volcanic architecture and evolutionary trends remain unconstrained. Caldera complexes, thought to be source vents for the silicic volcanism, have proved difficult to identify due to the scale of volcanism (e.g. up to 2000 km strike length), burial, faulting, and later deformation.

This paper describes in detail, the lithology and stratigraphy of Early Cretaceous volcanic rocks of the Whitsunday Volcanic Province (Fig. 1), thereby allowing constraints to be placed on the volcanic architecture and evolution of this silicic-dominated LIP. This is achieved by focussing on the well exposed and tilted volcanic sequences in the Molle Group of islands (Bryan, 1991), which are located centrally within the main part of the province (Fig. 2). Detailed accounts of the mainland, Lindeman and southeast Whitsunday Island sequences (Fig. 2) by Parianos (1993); Downes (1991); Finnis (1999), respectively, are used to provide regional constraints on the stratigraphy and volcanic architecture. This LIP in eastern Australia is unusual in that a large proportion of its products are preserved as huge volumes ($>1.4\times10^6$ km^3) of coeval volcanogenic sediment in adjacent sedimentary basins (Fig. 1; see Bryan et al., 1997). Such substantial volumes of coeval volcanogenic sediment are not characteristic of other LIPs. Determining the character of this volcanic source terrane is important to shed light on why so much fine-grained volcanogenic sediment was generated at this time.

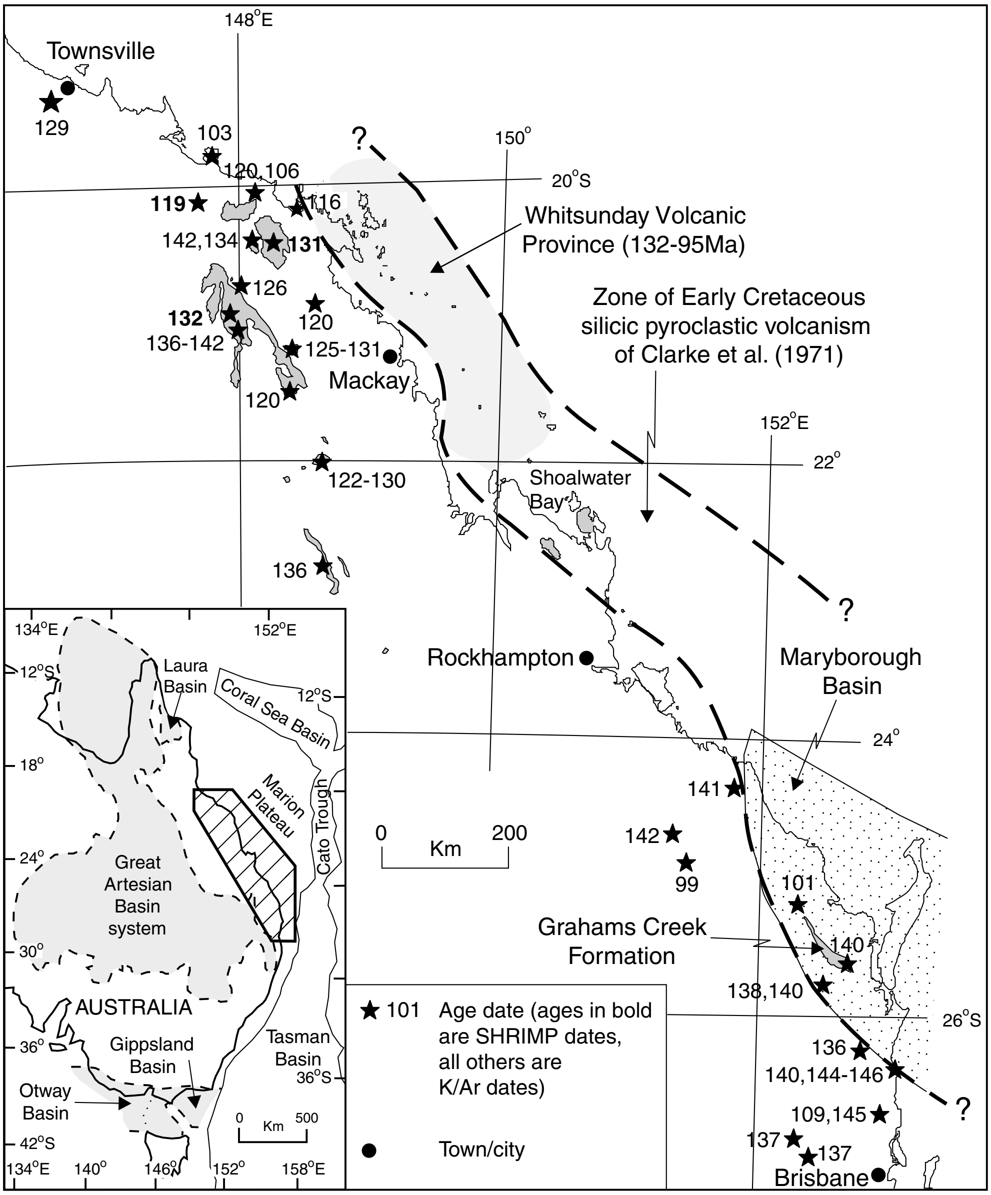

Fig. 1. Distribution of Early Cretaceous magmatism in eastern Queensland (Australia). The light shaded region represents the Whitsunday Volcanic Province, whereas the darker shade represents other Early Cretaceous igneous units of eastern Queensland. Age data sources: Allen et al. (1998); Ewart et al., (1992); Groen (1993); Parianos (1993) and references therein; Everndern and Richards (1962); Webb and McDougall (1968); Ellis (1968). K/Ar age dates have been corrected with reference to Steiger and Jäger (1977). Inset map shows the location of Early Cretaceous magmatism in eastern Queensland in relation to the major Cretaceous sedimentary basins of eastern Australia (shaded) that collectively contain $> 1.4 \times 10^6$ km^3 of coeval (Aptian–Albian) volcanogenic sediment (see Bryan et al., 1997). The Tasman Basin–Cato Trough–Coral Sea Basin system was formed by sea-floor-spreading between 84 and 56 Ma (Falvey and Mutter, 1981; Veevers, et al., 1991).

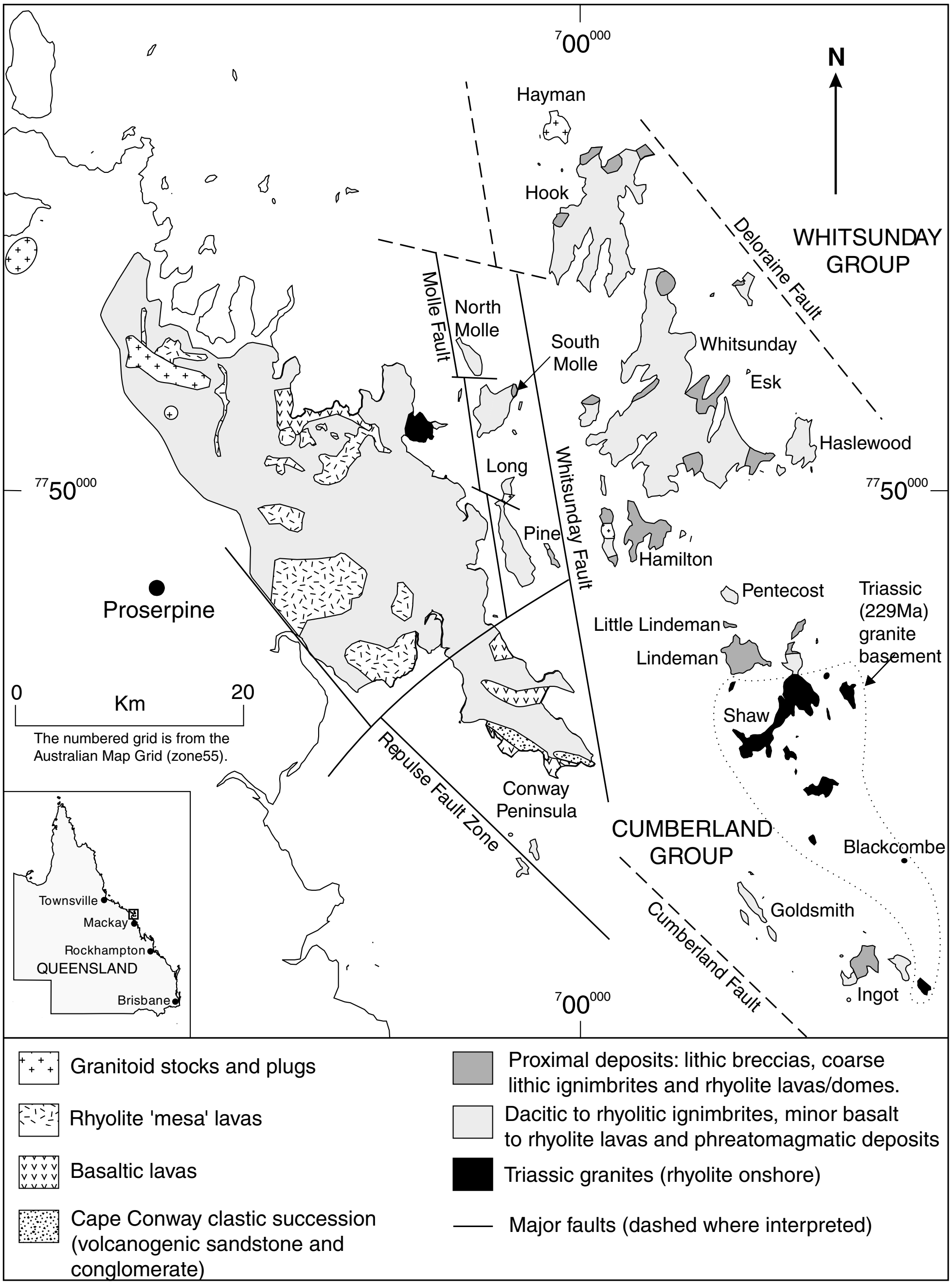

Fig. 2. Generalised volcanic geology of the northern region of the Whitsunday Volcanic Province. Islands referred to in the text are shown.

Table 1
Summary of the major Early Cretaceous LIPs. Note the volume estimate for eastern Australia includes coeval volcanogenic sediment sourced from LIP magmatism. References: 1, Renne et al. (1996); 2, Peate and Hawkesworth (1996); 3, Coffin and Eldholm (1994); 4, Leclaire et al. (1987); 5, Eldholm and Grue (1994); 6, Tarduno et al. (1991); 7, Mortimer and Parkinson (1996); 8, Bryan et al. (1997)

LIP	Type	Age (Ma)	Volume (10^6 km^3)	Area (10^6 km^2)
Paraná-Etendeka[1,2]	Continental flood basalt	129–132	> 0.8	1.3
Kerguelen[3,4]	Oceanic plateau	109–114	9.9–15.4	1.54
Ontong-Java[3,5]	Oceanic plateau	121–124	8.4	1.86
Manihiki[1,6]	Oceanic plateau	121–124	8.8–13.6	0.77
Hikurangi[7]	Oceanic plateau	115–125	3.5–5.25	0.35
Eastern Australia[8]	Volcanic passive margin	~ 132–95	> 1.5	> 0.5

2. Regional setting

A period of widespread rifting, global magmatism (Table 1) and continental break-up characterises the Early Cretaceous history of Gondwana (Anderson, 1994). In eastern Gondwana, igneous rocks of Early Cretaceous age are widespread, occurring primarily in eastern Queensland (Ewart et al., 1992; Bryan et al., 1997), as well as New Zealand (e.g. Mortimer and Tulloch, 1996, and references therein; Muir et al., 1994; Waight et al., 1997), Marie Byrd Land (Pankhurst et al., 1993; Weaver et al., 1994), and Lord Howe Rise (McDougall and van der Lingen, 1974).

A within-plate, silicic-dominated pyroclastic volcanic belt >2500 km long, is interpreted to have existed along the eastern Australian plate margin, with the peak in magmatic activity between ~125 and 100 Ma. This magmatic event heralded the onset of continental break-up in eastern Gondwana, and the formation of the eastern Australian passive margin in the Late Cretaceous–Tertiary (Bryan et al., 1997). Apatite fission track thermochronology has shown that kilometre-scale uplift and erosion began along the length of the eastern Australian highlands following the cessation of magmatism at 100–95 Ma (O'Sullivan et al., 1995, 1996, 1999; P. O'Sullivan, pers. comm., 1999). Sea-floor-spreading in the Tasman Basin began ~80 Ma and continued into the Early Tertiary until ~60 Ma (Veevers et al., 1991). The onset and widespread eruption of within-plate alkali basalts in eastern Australia (Johnson, 1989) began at ~80 Ma, and thus was coincident with sea-floor-spreading. Sea-floor-spreading patterns occurred in a "zippered" fashion, propagating northwards with time. Symonds et al. (1987) infer that seafloor-spreading ceased along the length of the Tasman Basin system (Fig. 1) by about 56 Ma. These time–space relationships between magmatism, highlands uplift and sea-floor-spreading are most readily explained by detachment models where eastern Australia is interpreted as an upper-plate passive margin (e.g. Lister and Etheridge, 1989).

3. Whitsunday Volcanic Province

The Whitsunday Volcanic Province (WVP; Figs. 1 and 2) has been defined as comprising the Early Cretaceous volcanic and intrusive rocks exposed in the Whitsunday, Cumberland and Northumberland Island groups, and onshore exposures to the east of Proserpine (Proserpine Volcanics of Clarke et al., 1971) along the central Queensland coast (Bryan et al., 1997). The province preserves the major portion of pre-break-up magmatism in eastern Australia as most of the products of this event are now preserved either as volcanogenic sedimentary rocks in Cretaceous sedimentary basins of eastern Australia, or interpreted to have been rifted off from the Australian continent and occur on submerged continental ridges and marginal plateaux (e.g. Lord Howe Rise; McDougall and van der Lingen, 1974; Bryan et al., 1997). The WVP does, however, form part of a silicic pyroclastic volcanic belt, first recognised by Clarke et al. (1971), which extends for over 900 km long, up to 100 km wide and over 1 km thick along the central Queensland coast (Fig. 1). Early Cretaceous volcanics cropping out to the south of the province in the Shoalwater Bay area near Rockhampton, and in the Maryborough Basin (Grahams Creek Formation; Ellis, 1968) define this silicic pyroclastic volcanic belt

(Fig. 1). Basement to the Early Cretaceous volcanics include Triassic granites offshore (Fig. 2) and Carboniferous to Triassic volcanic, sedimentary and granitic rocks onshore.

3.1. Eruptive volumes

Extrusive volume estimates are >30,000 km^3 for the WVP, but exceed 10^5 km^3 when the full extent of the silicic pyroclastic volcanic belt in eastern Queensland is taken into account (Bryan et al., 1997). These volume estimates are considerably smaller than other known silicic volcanic provinces (e.g. Sierra Madre Occidental, Chon-Aike Province; see Pankhurst et al., 1998 and references therein). However, when the volume of coeval volcanogenic sediment derived from this volcanism is included ($>1.4 \times 10^6$ km^3; see Bryan et al., 1997), this silicic-dominated LIP is comparable to, and in several cases, exceeds volume estimates of other better known continental flood basalt provinces (Table 1), and far exceeds any other known silicic-dominated LIP.

3.2. Petrology and geochemistry

Ewart et al. (1992) and Parianos (1993) have provided detailed accounts of the volcanic petrology and geochemistry, which have also been summarised by Bryan et al. (1997). Volcanic and intrusive rocks show a broad range of compositions from basalt through to rhyolite, although intermediate-silicic compositions volumetrically dominate. The volcanics also show calc-alkaline affinities, thus resembling modern destructive-plate margin volcanics rather than bimodal or alkalic volcanism associated with continental rifts. Based on trace element and isotopic studies, Ewart et al. (1992) concluded that the broad spectrum of compositions was generated by two-component magma mixing, with the two magma sources defined as: (1) a large volume, partial melt of relatively young, non-radiogenic, calc-alkaline crust, and (2) a within-plate tholeiitic basalt showing E-MORB affinities and a geochemical character similar to the Tertiary within-plate basalts of eastern Australia (Ewart et al., 1992; Stephens et al., 1995). Fractional crystallisation was superimposed in the rhyolites, as evidenced from pronounced Eu depletions.

3.3. Geochronology

Isotopic dating of the WVP has established an age range of 132–95 Ma, with a main period of igneous activity identified between 120 and 105 Ma (Ewart et al. 1992; Bryan et al., 1997). Recent K/Ar age data (Allen et al., 1998) from west of the WVP suggests precursory magmatic activity may have begun as early as 145 Ma, although lead isotopic zircon ages of granites from the same area do not replicate these older K/Ar ages (Fig. 1). However, it is being increasingly recognised that some Late Jurassic and Early Cretaceous K/Ar ages have been reset (e.g. Allen et al., 1998; Uysal, 1999), with resetting caused by the major thermal event associated with the emplacement of this LIP in the Cretaceous. The age range for magmatism defined by K/Ar dates must be considered somewhat suspect, and higher precision (e.g. zircon) dating is required to better constrain the true age range of LIP-related magmatism.

3.4. Structure

The volcanic sequences are gently tilted (<30°), but locally become steep (>60°) adjacent to faults. Two major NNW-trending faults cross-cut the sequences (Whitsunday and Molle faults, Fig. 2), which are defined by opposing steep (40–70°) and shallow-dipping strata on either side of the faults. The Whitsunday Fault is also coincident with a major NNW-trending aeromagnetic anomaly (Bureau of Mineral Resources, 1986). The decreasing tilts of strata upward within the Molle Group of island sequences (Fig. 3) are interpreted to reflect extensional faulting occurring during volcanism. Major sinistral strike-slip fault reactivation in the Mid-Late Cretaceous (~85–75 Ma) is responsible for most of the brittle deformation. This episode of faulting is poorly constrained and understood, but its effects are widespread in eastern Queensland (e.g. Holcombe et al., 1997).

4. Stratigraphy and volcanic lithofacies

A detailed lithological, stratigraphic and facies analysis of volcanism presented below is based on the geology of the following regions of the WVP: (1) the Molle Group of islands (hereafter MGI, Fig.

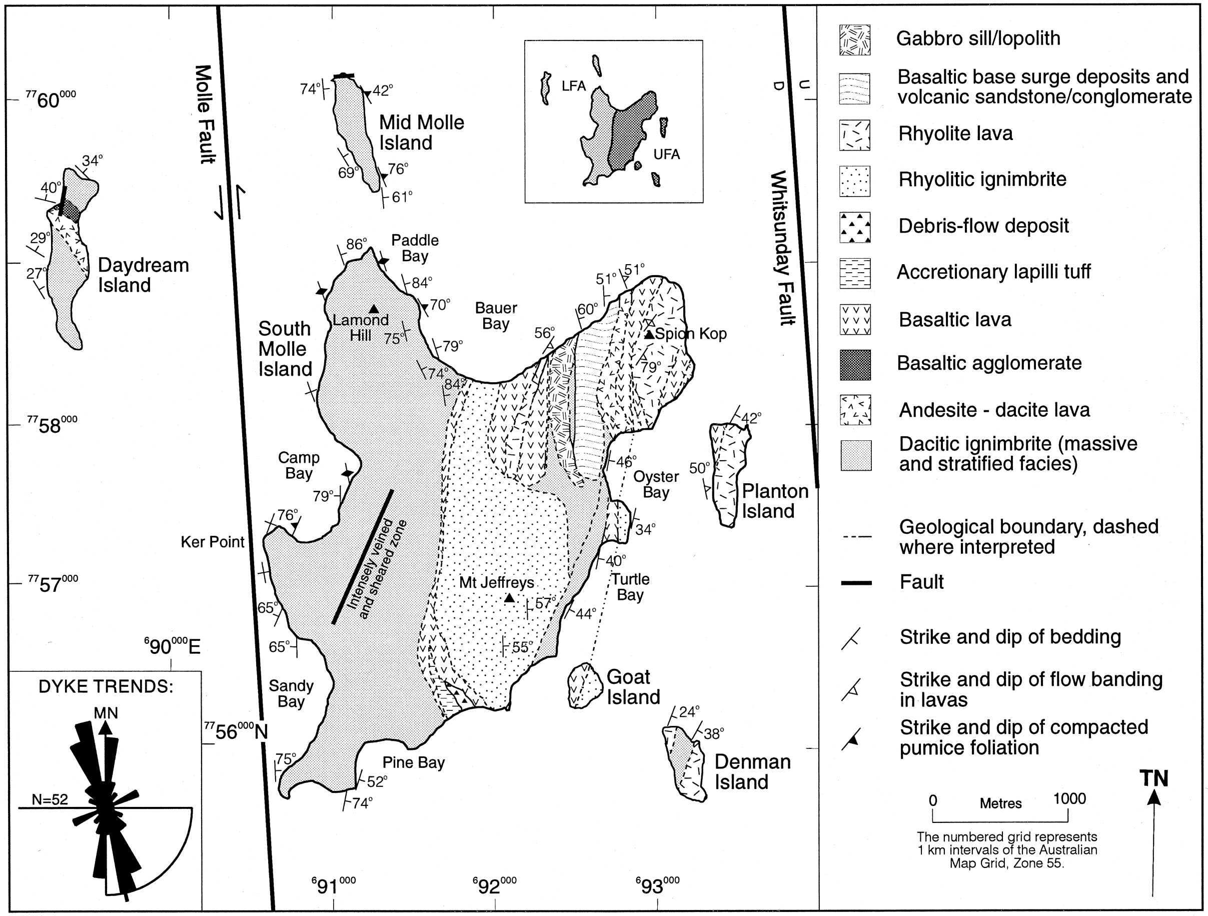

Fig. 3. Geology of the Molle Group of islands. Strata dip and young to the east, although there is a small fault-bounded, west-dipping sequence between Camp and Sandy bays. Tilting of the volcanic succession has provided cross-sectional exposure, allowing an insight into volcanic evolution. The rhyolite lava-dominated sequences of Planton and Denman islands cap the volcanic succession. Rose diagram shows dyke trends for all dykes in the Molle Group of islands. Plotting interval is 10°; *N* is the number of data points and plotting is by radius. Inset map shows the distribution of the two facies assemblages: LFA, Lower Facies Assemblage; UFA, Upper Facies Assemblage that are based on the distribution of lithofacies (see Section 5).

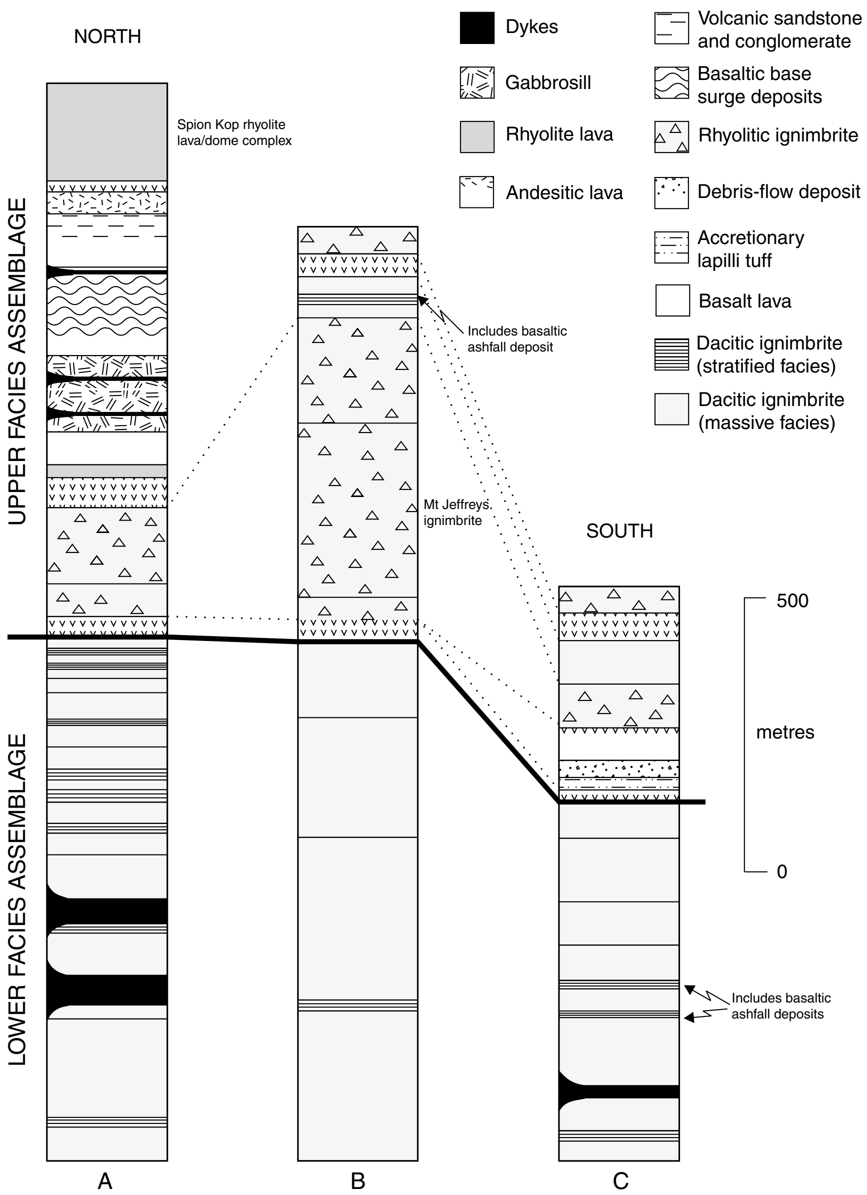

Fig. 4. Generalised stratigraphic sections for South Molle Island. Section A is based on northern coastal exposures between Paddle Bay and Spion Kop; section B has been constructed across the centre of the island (Camp to Oyster Bays), and section C is based on southern coastal exposures between Sandy Bay and Turtle Bay.

3; Bryan, 1991), where a minimum thickness of 1.5 km is exposed (Figs. 4 and 5); (2) the mainland sequences (Fig. 6; Parianos, 1993; and Proserpine Volcanics of Clarke et al., 1971); (3) Lindeman Island (Downes, 1991), which also preserves a >1-km-thick volcanic succession (Fig. 7); and (4) southeast Whitsunday Island (Finnis, 1999). The MGI sequences are of interest because they separate mainland sequences that contain abundant basalt, andesite and rhyolite lavas from the offshore, dominantly dacitic–rhyolitic pyroclastic sequences (Fig. 2). It is uncertain whether this lithological variation is spatial and/or temporal.

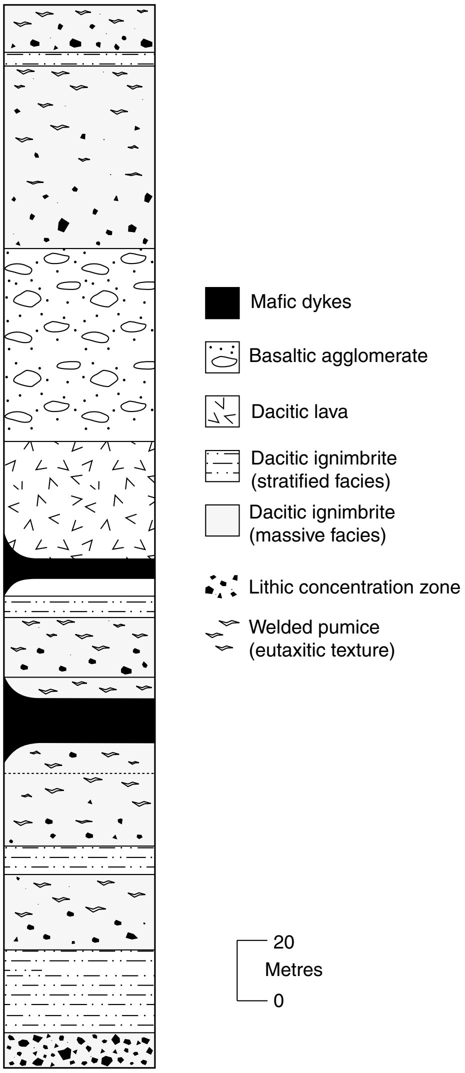

Fig. 5. Stratigraphic section for Daydream Island showing the interbedded nature of dacitic lava and near-vent facies basaltic agglomerate within a predominantly dacitic ignimbrite succession.

The dominant volcanic lithofacies and associated intrusions are described in this section (see Tables 2–4). Field locations described in this paper are in Australian Map Grid coordinates, zone 55.

4.1. Ignimbrites

Ignimbrite volumetrically dominates the exposed sequences (see Figs. 4–7). Ignimbrites are commonly thick (individual units up to 100 m thick), massive and lithic-rich, and one ignimbrite exposed on Whitsunday Island has a minimum thickness of 2–300 m (Finnis, 1999). Basal, matrix-supported lithic concentration zones (equivalent to layer 2bl of Sparks et al., 1973) are frequently developed (Fig. 8A), as are multiple, intra-ignimbrite lithic concentration zones at variable heights within the thicker ignimbrites. Lithic clasts within these concentration zones occasionally show organisation and stratification (long axes parallel to bedding). Fine-grained basal layers (equivalent to layer 2a of Sparks et al., 1973) are rarely observed. In the MGI and mainland sequences, lithic clasts are normally <10 cm in diameter, in contrast to the coarse lithic lag breccias (Table 2) observed on the eastern islands of Hook, Whitsunday, Hamilton and Lindeman that contain clasts up to 6 m diameter (Ewart et al., 1992). Rare, carbonised wood fragments occur in ignimbrite on Daydream Island (Fig. 3; $^{6}89^{225}$, $^{77}59^{410}$). Ignimbrites are moderately welded or medium- to high-grade (terminology of Walker, 1983), but rheomorphism is absent. No shard or vitriclastic textures are preserved because of a pervasive low-grade hydrothermal alteration.

Ignimbrites are predominantly dacitic in composition, characterised by the phenocryst assemblage: plagioclase, diopside–augite ± Fe–Ti oxides, whereas relatively crystal-rich rhyolitic ignimbrites with the phenocryst assemblage: quartz, plagioclase, hornblende, Fe–Ti oxides ± diopside–augite are distinctive in the upper parts of the preserved volcanic successions (Figs. 4, 6 and 7). Regionally, several other petrographic types of rhyolitic ignimbrite have been distinguished, based on the presence of sanidine and biotite (Ewart et al., 1992).

4.1.1. Dacitic massive ignimbrite

Dacitic ignimbrites are generally, relatively lithic-rich (15–52 modal percent) and phenocryst-poor (~5–15 modal percent) when compared to the rhyolitic ignimbrites. The dacitic ignimbrites are characterised by a lithic clast population that in the MGI and mainland sequences is dominated by coherent mafic to intermediate lavas (plagioclase-phyric textural varieties), whereas ignimbrite and rhyolite lava lithic clasts are more common in the Whitsunday and Lindeman Island sequences. Eutaxitic fabrics are well-developed in the pumice-rich upper parts of

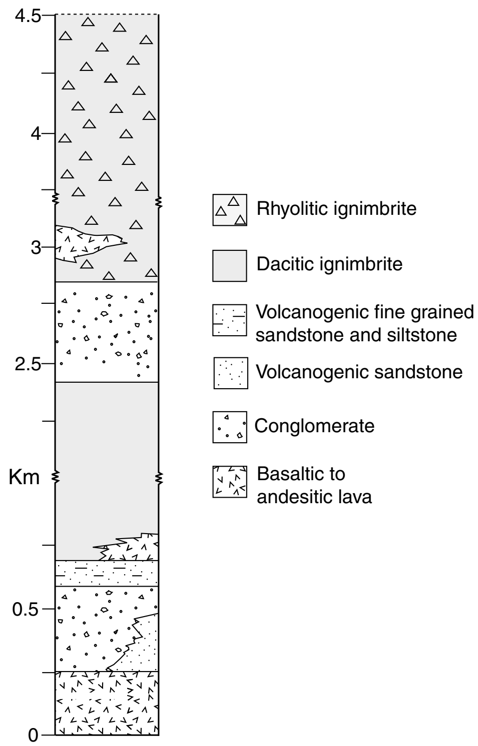

Fig. 6. Generalised stratigraphic section for the Conway Peninsula (mainland sequences) from Parianos (1993). Note the change in vertical scale.

massive ignimbrite beds (Fig. 8B), and tubed pumice textures (elongate, cylindrical and subparallel vesicles) are occasionally observed.

4.1.2. Rhyolitic ignimbrite

Rhyolitic ignimbrite is less abundant than dacitic ignimbrite, but in the mainland and MGI sequences, it is characterised by thicker individual beds (>60–100 m thick) that form generally more laterally extensive ignimbrite sheets. An example is the Mt Jeffreys ignimbrite on South Molle (see Figs. 3 and 4) that comprises at least three massive beds of ignimbrite (defined by intervening crystal-rich, planar to low-angle cross-stratified surge deposits), with a cumulative thickness of ~300 m. Excluding the lithic concentration zones, the rhyolitic ignimbrites typically contain a lower proportion of lithic clasts (2–4 modal percent), but comprise a wider variation of lithic compositions, including rhyolite lavas and inferred basement-derived

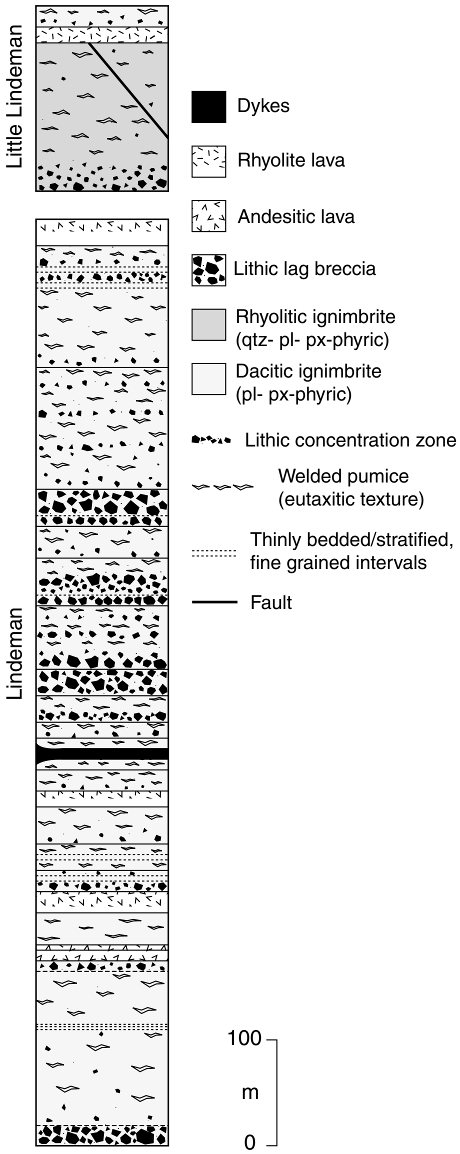

Fig. 7. Compiled stratigraphic section for Lindeman and Little Lindeman islands, based on the study of Downes (1991).

lithics (e.g. metasedimentary lithic clasts). The ignimbrites are crystal-rich (27–38 modal percent), and the Mt Jeffreys ignimbrite also shows petrographic zonation up sequence from quartz, plagioclase, hornblende (rhyolite) at the base to plagioclase, augite (dacite) at the top. The upper parts of the rhyolite ignimbrites exhibit minor concentrations of pumice, together with a moderately developed eutaxitic texture.

Table 2
Field, textural and petrographic characteristics of the main ignimbrite lithofacies of the WVP. Note that several petrographic types of ignimbrites have been recognised by Ewart et al. (1992) across the WVP. Phenocryst abbreviations: qtz, quartz; pl, plagioclase; hbl, hornblende; di–aug, diopside–augite; opx, orthopyroxene; aug, augite; bio, biotite; san, sanidine

Lithofacies	Phenocryst assemblage (modal%)	Thickness (m)	Field characteristics
Dacitic ignimbrite (massive facies)	Pl + di–aug + Fe–Ti oxides (4–27% total)	≤ 60 (MGI); ≤150 (mainland, Lindeman); >300 (Whitsunday)	Medium- to high-grade; lithic-rich with basal or multiple lithic concentration zones; lithic clasts dominantly coherent mafic to intermediate lavas in mainland and MGI sequences, rhyolite lava and ignimbrite clasts more common in Lindeman, Whitsunday sequences
Dacitic ignimbrite (stratified facies)	Same as for massive facies	≤ 28	Fine-grained (≤3 cm diameter); lithic-crystal-rich; thin bedded and planar stratified with some low-angle cross stratification and erosional scours; minor outsized lithic clasts (≤20 cm long); pumice minor
Lithic lag breccia		≤ 30 (Lindeman, Whitsunday)	Matrix- to clast-supported, massive to crudely stratified or normally graded, poorly sorted lithic breccia typically occurring at the top of the ignimbrite; Lithic clasts up to 6 m diameter, and dominated by shallow-derived lithologies: mafic to silicic lavas, dacitic–rhyolitic ignimbrites, plastic deformed ignimbrite and volcaniclastic sedimentary rocks
Rhyolitic ignimbrite	MGI, mainland: pl (20–30%) + hbl (2–4%) + qtz (1%) + Fe–Ti oxides (1%) ± aug; Lindeman: pl (38%) + qtz (≤2%) + di–aug (≤2%) + Fe-Ti oxides (≤1%)	≤ 300 (MGI); ≤150 (Lindeman); ≤120 (mainland)	Medium- to high-grade; typically crystal-rich and coarsely phenocrystic; relatively lithic-poor but with greater diversity of lithic clast types; hbl commonly pseudomorphed by epidote

4.1.3. Stratified dacitic ignimbrite

Commonly interbedded with massive beds of dacitic ignimbrite are discrete packages or intervals of finer grained, well-bedded and planar stratified ignimbrite (Table 2). Type exposures occur at Paddle Bay on South Molle ($^{6}91^{110}$, $^{77}59^{000}$; Fig. 3). These packages are mostly ≤10 m thick, but can be up to 28 m thick (e.g. Daydream Island, $^{6}89^{800}$, $^{71}58^{900}$).

Table 3
Field, textural and petrographic characteristics of lava lithofacies of the WVP. Phenocryst abbreviations the same as for Table 2

Lithofacies	Phenocryst assemblage (modal%)	Thickness (m)	Field characteristics
Basaltic lava	pl (10–40%) + di–aug (1–14%) + opx (<5–9%) + Fe–Ti oxides (<3%)	5–45	Dark grey to black, massive, amygdaloidal, fine to medium grained, opx pseudomorphed by uralite
Andesite lava	pl (15–30%) + opx (3–12%) + di–aug (1–10%) + Fe–Ti oxides (≤1%); pl (10–30%) + hbl (<5%)	10–40	Grey to dark grey, some planar flow banding; opx pseudomorphed by uralite
Dacite lava	pl (≤5%) ± Fe–Ti oxides; pl (5–20%) + aug (≤2%) ± hbl ± Fe–Ti oxides	5–40	Cream to light grey/brown; commonly planar flow banded; higher phenocryst contents than rhyolites
Rhyolite lava	pl (9–12%) + bio (≤1%); pl + qtz ± Fe–Ti oxides (≤5% total); pl (<15%) + san (<5%) + aug (<2%) + qtz (≤1%) ± hbl ± Fe–Ti oxides	10 to >50	Cream to light brown, planar to wavy flow banded or massive, minor lava breccia and spherulitic rhyolite domains; aphyric lavas common

Table 4
Field characteristics of other volcaniclastic rocks

Lithofacies	Thickness (m)	Field characteristics
Basaltic agglomerate	≤ 60	Poorly sorted, clast-supported breccia of highly vesicular, aphyric scoria clasts and fluidal to spindle-shaped bombs; massive to medium bedded
Base surge deposits	5–150	Basaltic to rhyolitic in composition; thinly to medium bedded, planar to wavy stratified and cross-stratified, convoluted bedding, slump folds and flame structures; peperitic intrusions on S Molle
Basaltic ash fall deposits	1–5	Maroon, ash-dominated, planar and thin bedded; commonly contain accretionary lapilli
Debris-flow deposit	20–30	Massive, poorly sorted, matrix-supported, pebble- to boulder-grade clasts of massive to amygdaloidal basaltic lava, coarse-tail normal grading
Volcanic sandstone, conglomerate/breccia	≤ 750 (mainland) 74 (S Molle) ≤50 (Whitsunday)	Feldspathic-lithic fine sandstone to pebble conglomerate and cobble/boulder-grade breccia; thin (≤1 cm) to thick (≥3 m) bedded, planar to low-angle cross-stratified; no trough or high-angle cross-stratification; siltstone/mudstone intraclasts; basement-derived granite (≤1.5 m diameter) and coal clasts in Cape Conway exposures

Each stratified package is difficult to trace laterally over any distance, but has sharp contacts (defined primarily by grain size) with the interbedded massive dacitic ignimbrites. Internally, bedding and stratification are not continuous along strike; beds/laminae thicken and thin over 10 cm to a few metres (Fig. 8C). Cross-bedding (Fig. 8D), inclined laminae, low-angle bedding, and erosional scours are also common.

Layering and planar stratification are defined by alternating fine (ash-rich) and coarse (crystal- and/or lithic-rich) laminae or beds (Fig. 8C). Fine and coarse grained beds range in thickness from ~1 to 50 cm. Individual beds/laminae show normal grading or are massive. Most beds/laminae are matrix-supported, although clast-support textures are observed in some of the coarser grained, lithic-rich beds. Lithic clasts are ≤3 cm diameter, but outsized lithic clasts up to 20 cm in diameter are observed. Outsized lithic clasts are mafic to intermediate composition lavas, and basaltic scoria lithics are distinctive in the type exposures on South Molle. Pumice clasts are mostly non-welded, and notably less abundant (up to 20–30 modal percent) and finer grained (≤2 cm diameter) than in the interbedded massive ignimbrites. Heavy constituents (e.g. lithic clasts and crystal grains) thus appear to be relatively concentrated in these stratified units.

The presence of cross-bedding, inclined laminae, low-angle bedding, erosional scours and pinch and swelling of individual layers distinguish these stratified units from pyroclastic fallout deposits, but are features that resemble pyroclastic surge deposits. The enrichment of heavy constituents (e.g. crystal and lithic grains) are also characteristic of pyroclastic surge deposits. However, the relatively poor sorting, which is accentuated by the presence of coarse, outsized lithic clasts up to 20 cm diameter, and the large cumulative thickness of the stratified units (up to 28 m thick), are more characteristic of ignimbrites. This lithofacies thus resembles both conventional ignimbrites and pyroclastic surge deposits. The preferred interpretation here is that these stratified units are probably gradational between end-member pyroclastic surge deposits and massive ignimbrites, and reflect deposition from turbulent pyroclastic density currents. Relatively lower sediment concentrations at the time of deposition allowed turbulence and shear to interact with the bed, hence the development of stratification and sorting of the heavy constituents. The Mt St Helens 1980 blast also laid down deposits that displayed both conventional pyroclastic surge and flow characteristics (e.g. Druitt, 1992). The outsized lithic clasts are interpreted to have been locally incorporated into the pyroclastic flow(s).

4.2. Lavas

Basaltic to rhyolitic lavas are subordinate to pyroclastic rocks. Of note is that regionally, rhyolitic lavas are characteristic of the upper parts of the preserved volcanic stratigraphy (Figs. 4 and 7). Lavas are typically 20–45 m thick and massive, with flow banding frequently developed in the more silicic lavas.

4.2.1. Basalt lavas

Several textural varieties of amygdaloidal basalt lava have been recognised, but all contain a phenocryst mineralogy of plagioclase, diopside–augite, orthopyroxene (now replaced by uralite) and Fe–Ti oxides (Table 3). Basaltic lavas are mostly restricted to the MGI and mainland sequences, being dark grey to black, and 20–35 m thick. Averaged chemical analyses of basaltic lavas are presented in Table 5. Locally, basaltic hyaloclastite is observed (e.g. South Molle, $^{6}92^{300}$, $^{77}58^{450}$) and the absence of jigsaw fit textures and presence of diffuse graded bedding suggests some remobilisation of the hyaloclastite before deposition (Fig. 9A).

4.2.2. Andesite–dacite lavas

Lavas of andesite to dacite composition are uncommon, but a few, relatively thin andesite lavas are interbedded with ignimbrite at Lindeman (Fig. 7), and are more abundant in the mainland volcanic sequences (Fig. 6; Parianos, 1993). Lavas are between 5 and 40 m thick, and commonly flow banded. Andesites contain a similar phenocryst assemblage to the basalt lavas, but are petrographically distinguished by containing a lower proportion of augite, and slightly higher proportion of plagioclase (Table 3). Averaged chemical analyses of andesite and dacite lavas are given in Table 5.

4.2.3. Rhyolite lavas

Rhyolite lavas and domes predominate at the top of the exposed sequences (Figs. 4 and 7), and extensive fluidal rhyolite covering >300 km^2 caps the mainland sequences (‘mesa’ lavas of Parianos, 1993; Fig. 2). Rhyolitic lavas also occur interbedded with thick dacitic ignimbrite units on Whitsunday Island (Finnis, 1999). Rhyolite lavas are characteristically cream to light brown, dense, poorly to non-vesicular, and flow banded (Table 3). Both aphyric and plagioclase phenocrystic varieties have been recognised. Averaged chemical analyses of rhyolite lavas, including the mesa lavas from the mainland sequences, are given in Table 5. Note that the rhyolites are not strongly fractionated in terms of their trace and light rare earth element abundances (see Ewart et al., 1992).

4.3. Phreatomagmatic deposits

Laterally impersistent, but thick ($\leq$15 m thick) exposures of accretionary lapilli tuffs and base surge deposits of basaltic to rhyolitic composition are common across the province. The general ash-rich nature, and lack of abundant wallrock lithic material in the phreatomagmatic deposits are more consistent with magma interaction occurring with surface water. This is because magma interaction with subsurface water (e.g. aquifers, hydrothermal systems) will involve fragmentation of the country rock producing more wall rock material than interaction with abundant surface water (e.g. Hatepe and Rotongaio ashes, where the lithic content is $<5\%$; Smith and Houghton, 1995; cf. Barberi et al., 1989).

4.3.1. Base surge deposits

Thin bedding, planar to wavy lamination/bedding (Fig. 9B) and soft-sediment deformation (e.g. dewatering structures) are characteristic of the base surge deposits discontinuously exposed for up to 150 m thickness at South Molle (Fig. 10). Cross-stratification, coupled with asymmetric wavy lamination/bedding indicates an overall progradation downcurrent (to the south). The undulatory waveforms typically have small wavelengths ($\sim$30 cm) and amplitude (a few cm). They are characterised by gently dipping stoss and lee-sides, although the slope of the lee-side is larger than that of the stoss-side in the asymmetric waveforms (Fig. 9C). Clastic components are dominated by angular to subangular crystal (plagioclase, augite and Fe–Ti oxide) and juvenile basaltic lithic fragments $\leq$0.5 cm diameter. The lithic grain composition and types of crystal grains are consistent with a basaltic source.

Two peperitic intrusions occur within the base surge deposits at South Molle. A basaltic fluidal peperite occurs in the lower part of the sequence, which is characterised by large, rounded domains of coherent lava. Bedding is disturbed around pillows of the fluidal peperite (Fig. 9D), and detached domains of coherent lava also occur. Towards the top of the base surge sequence is a prominent doleritic sill (10 m thick) showing a curviplanar to blocky (hackly)

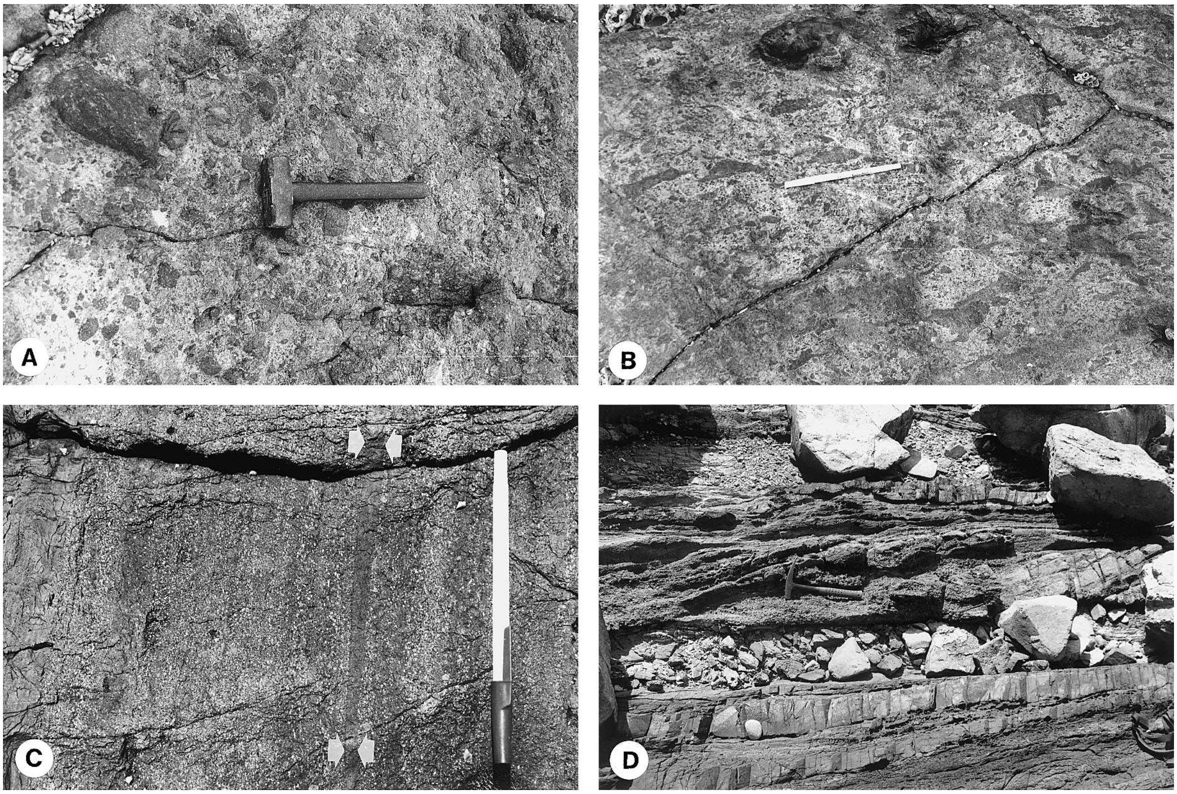

Fig. 8. Nature of dacitic massive and stratified ignimbrite lithofacies. (A) Lithic concentration zone to dacitic ignimbrite at Daydream Island ($^{6}89^{400}$, $^{77}58^{800}$). Hammer is 35 cm long. (B) Upper part of dacitic ignimbrite exhibiting a well-developed eutaxitic texture ($^{6}91^{600}$, $^{77}56^{100}$). Pen is 15 cm long. (C) Stratified ignimbrite lithofacies (vertically dipping), showing well-developed planar bedding and stratification ($^{6}91^{110}$, $^{77}59^{000}$). Note the "pinch and swell" of individual beds, indicated by arrows. Pen is 15 cm long. (D) Stratified ignimbrite lithofacies at Mid Molle Island ($^{6}91^{310}$, $^{77}59^{420}$) showing cross-bedding and low-angle bedding at the base of photo, which also shows lateral changes in bed thickness. Hammer is 35 cm long.

jointing, and an upper margin with intrusive hyaloclastite (blocky peperite) textures. Dispersed clasts of the doleritic sill grade inwards to jig-saw fit textures close to the contact with the coherent dolerite. Collectively, these peperitic textures indicate intrusion of magma into unconsolidated and wet base surge deposits, and may indicate some proximity to source for the base surge deposits.

4.3.2. Basaltic ashfall deposits

Interbedded with massive and stratified dacitic ignimbrite on South Molle and the mainland are thin ($\leq$1 m thick) but distinctive, maroon-coloured, planar bedded, ash-dominated deposits (Table 4). Grain size bedding and grading is apparent in some exposures, and bedding is laterally persistent over the length of the exposure. Coarser grained, clast-supported layers ($<$10 cm thick) of dense to highly vesicular or scoriaceous lava clasts ($\leq$2 cm diameter) also occur. These clasts range from aphyric to plagioclase-phyric varieties, and are inferred to be basaltic in composition. Accretionary lapilli, often broken and with numerous generations of concentric growth rings, are characteristic of the ash-rich beds.

The planar and laterally persistent bedding are consistent with fallout from an eruption plume. The ash-rich nature and presence of accretionary lapilli suggest a phreatomagmatic origin. These ashfall deposits are interpreted to be the distal products of basaltic phreatomagmatic eruptions from tuff cone/tuff ring or maar-type vents (e.g. Cas and Wright, 1987).

Table 5
Averaged X-ray fluorescence (XRF) major and trace element analyses of the major chemical groupings of dykes, lavas and ignimbrites. *N* is number of analyses. Major elements normalised to 100% loss on ignition (LOI) free. Trace element abundances LOI-free normalised; b.d., below detection limit. XRF analyses were performed on a Philips PW1400 spectrometer at the University of Queensland. Major elements were analysed on fused glass discs and trace elements on pressed powder pellets

Composition Lithology *N*	Dolerite Dykes 18	Basaltic andesite Dykes 7	Andesite Dykes 27	Dacite Dykes 13	Rhyolite Dykes 30	Basalt Lavas 6	Andesite Lavas 10	Dactite Lavas 5	Rhyolite Lavas 20	Rhyolite Mesa lavas 9	Dactite Ignimbrites 25	Rhyolite Ignimbrites 15
Major elements (wt%)												
SiO_2	51.79	56.29	62.04	69.31	74.25	51.16	61.13	67.01	74.66	73.78	68.73	74.34
TiO_2	1.68	1.23	1.12	0.58	0.30	1.68	1.00	0.95	0.26	0.29	0.66	0.28
Al_2O_3	17.39	16.82	16.65	15.45	14.07	17.91	16.54	15.37	14.14	13.95	15.47	14.05
Fe_2O_3	1.59	1.31	1.06	0.57	0.33	1.69	1.05	0.80	0.26	0.39	0.65	0.31
FeO	7.96	6.54	5.29	2.83	1.65	7.53	5.25	4.02	1.31	1.53	3.26	1.57
MnO	0.18	0.14	0.14	0.08	0.05	0.16	0.13	0.12	0.03	0.03	0.10	0.05
MgO	5.39	4.65	2.40	0.94	0.38	5.77	2.56	1.17	0.19	0.40	1.10	0.40
CaO	8.49	7.00	3.88	1.96	0.64	8.65	6.01	2.72	0.33	0.75	2.33	0.99
Na_2O	3.33	3.98	4.43	4.58	4.34	4.20	3.85	4.29	4.20	4.87	4.43	3.84
K_2O	1.53	1.66	2.61	3.49	3.90	0.75	2.11	3.23	4.54	3.82	3.06	4.07
P_2O_5	0.46	0.36	0.40	0.21	0.11	0.41	0.37	0.32	0.09	0.06	0.21	0.10
H_2O	4.28	3.91	3.38	2.33	1.64	2.25	3.14	2.97	1.78	–	2.63	1.94
LOI	3.01	2.32	2.05	1.94	2.55	3.34	3.04	2.77	1.97	1.46	2.66	2.68
Trace elements (ppm)												
Nb	11	8	10	10	10	11	9	10	12	14	10	10
Zr	220	170	262	308	279	196	201	286	279	308	287	250
Y	32	25	35	33	38	34	28	35	37	35	35	36
Sr	538	554	426	263	187	502	498	270	113	101	287	249
Rb	49	46	66	101	115	15	62	89	127	109	84	127
U	b.d.	b.d.	1	3	2	b.d.	3	1	3	3	2	2
Th	b.d.	b.d.	6	11	12	2	7	10	15	14	9	11
Pb	4	5	10	10	18	5	10	10	15	15	12	21
Cu	50	46	21	10	9	31	33	13	8	b.d.	11	13
Ni	63	40	11	14	10	78	10	5	10	8	11	10
Zn	112	106	112	74	67	106	93	92	45	45	88	71
Cr	123	107	30	11	9	147	100	25	9	7	27	12
V	205	194	119	41	13	216	155	94	6	10	51	17
Ba	322	294	474	560	641	205	370	540	647	535	534	699
Sc	22	23	18	10	8	25	19	17	7	6	13	10
La	18	16	27	28	31	11	21	27	37	36	26	29
Ce	44	39	60	62	70	37	48	67	81	70	59	64
Nd	27	22	37	35	39	23	29	40	42	32	35	36

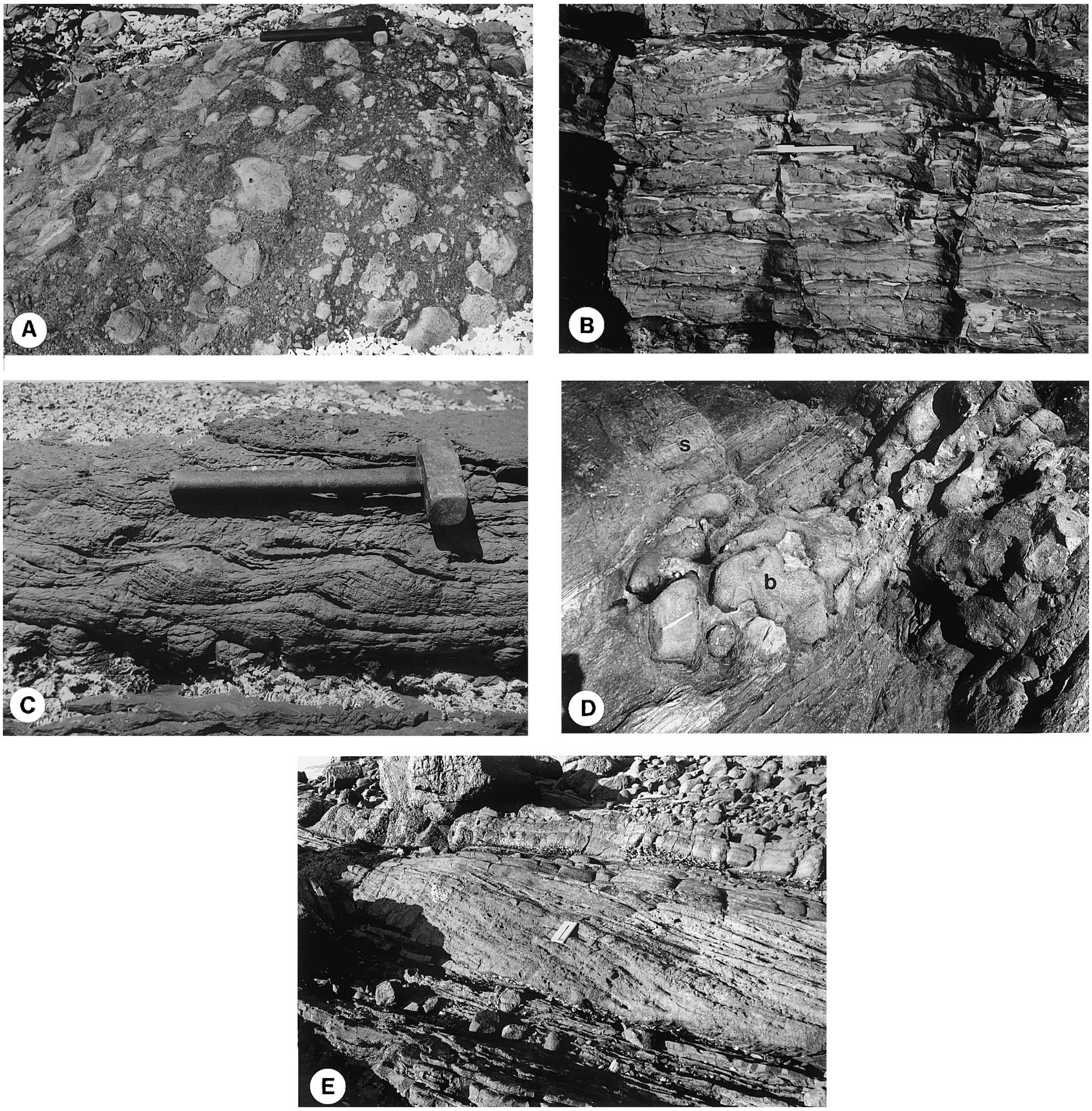

Fig. 9. (A) Resedimented basaltic hyaloclastite ($^{6}92^{315}$, $^{77}58^{350}$). Note clast-rotated textures, diffuse grading and bedding. Hammer is 35 cm long. (B) Typical nature of base surge deposits ($^{6}92^{600}$, $^{77}58^{600}$). Note thin, normally graded packages, with wavy lamination best developed in the finer grained (dark) tops to beds. Flow direction is from left to right. (C) Progressive bedforms in basaltic base surge deposits ($^{6}92^{600}$, $^{77}58^{650}$). Hammer is 35 cm long and flow direction is from left to right. (D) Fluidal basalt peperite (b) intruding base surge deposits (s). Note the bulbous or pillowy form of the basalt and the disruption of bedding around pillows ($^{6}92^{625}$, $^{77}58^{650}$). Pen is 15 cm long. (E) Transitional bedform in very coarse-grained sandstone ($^{6}92^{750}$, $^{77}58^{800}$). Note convex-upward bedding, passing into planar bedding at upper contact, and along strike to left.

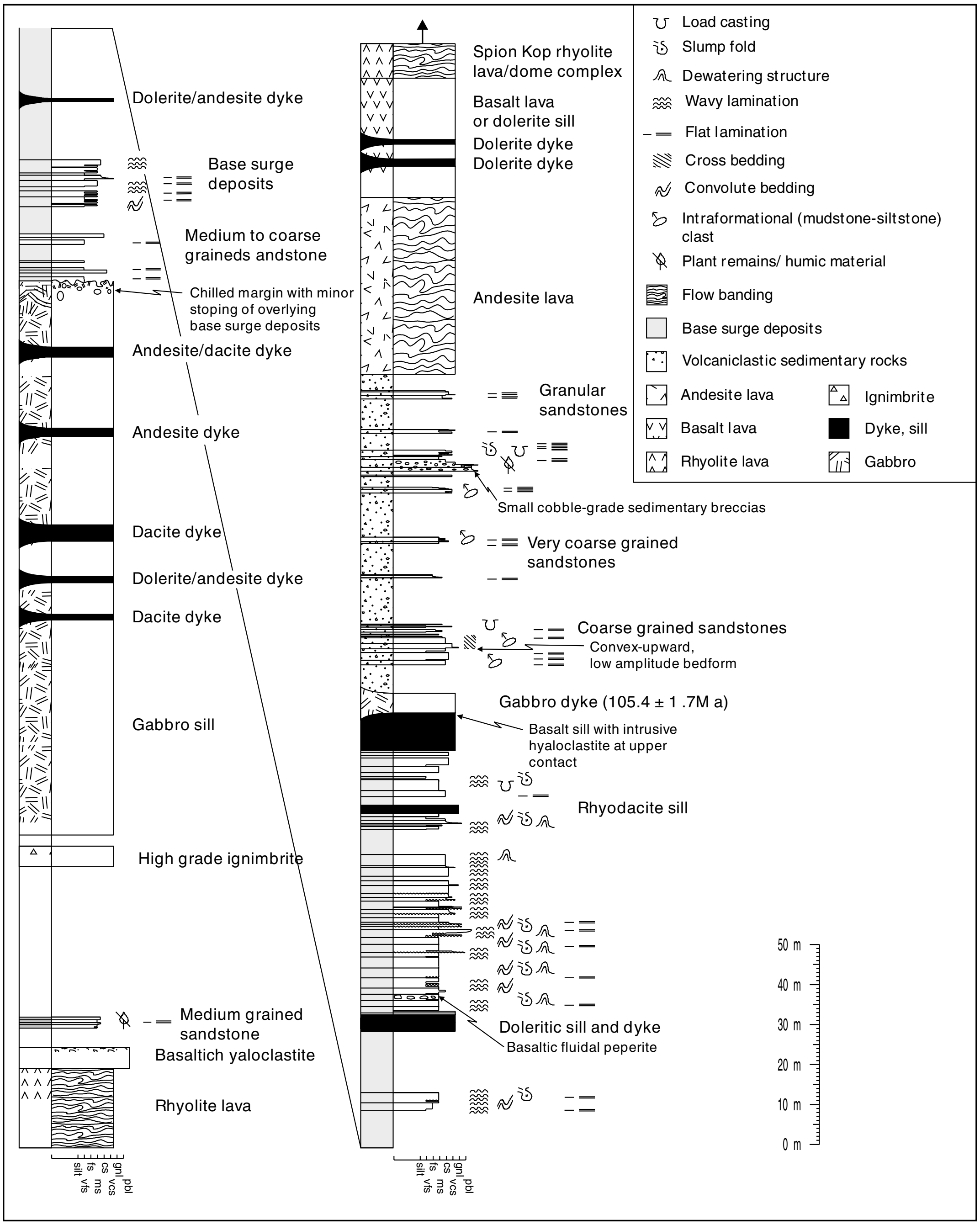

Fig. 10. Measured section along the eastern coastline of Bauer Bay, South Molle.

4.4. Basaltic agglomerate

Coarse-grained basaltic agglomerate is exposed on Daydream Island (Fig. 3), which is underlain by a dacitic lava, and overlain by a thick dacitic ignimbrite sequence (Fig. 5). The agglomerate is up to 60 m thick and mostly massive, although bedding, defined by finer grained layers, becomes more pervasive in the upper parts as the unit fines upwards. Abundant clasts of the underlying dacitic lava occur within the basal few metres of the agglomerate. Clasts are otherwise monomictic, typically aphyric and highly vesiculated or scoriaceous. Most highly vesiculated clasts are ≤10 cm diameter, and form a clast-supported breccia. Large, dense (poorly vesicular), rounded bombs up to 50 cm diameter are prominent in the middle part of the unit. Some bombs show significant attenuation and contrast with the non-welded character of the bulk of the agglomerate.

The agglomerate is interpreted as proximal fallout deposits of a basaltic scoria cone. The large, fluidal-shaped bombs are consistent with a near-vent setting.

4.5. Volcaniclastic sedimentary rocks

Coarse-grained epiclastic sedimentary rocks have been observed at Cape Conway (Cape Conway clastic succession of Clarke et al., 1971) and at South Molle (Table 4), with the most impressive sequence occurring at Cape Conway (up to 750 m thickness). Thinner sequences (≤50 m thick) of finer grained, typically planar laminated, fine- to coarse-grained sandstone and siltstone also occur interbedded with thick ignimbrite sequences exposed on Whitsunday and Esk islands.

4.5.1. Volcanic sandstone and breccia

At South Molle, the sedimentary sequence coarsens upward from medium-coarse sandstones to granular sandstone and pebbly conglomerate, but is interrupted at one interval by a sudden influx of graded small cobble breccia (Fig. 10). Petrographic studies reveal the sandstones are quartz-poor with quartz:feldspar:lithic fragments (Q:F:L) ratios ranging between 2:24:74 and 11:32:56 (see Bryan et al., 1997, fig. 10). Lithic and crystal grains are mostly angular to subangular, reflecting the local provenance. Organic/humic material is preserved in some horizons consistent with a terrestrial setting. In places, the sandstones contain flattened, black and fine grained (siltstone or mudstone) 'intraformational' clasts up to ~5 cm long. Planar bedding is characteristic, and minor truncation and scouring of beds also occur. A convex-upward, low amplitude bedform is observed within the South Molle sequence ($^{6}92^{750}$, $^{71}58^{800}$), with foreset inclination gradually decreasing upwards to plane bedding at the top (Fig. 9E). This structure is interpreted as a transitional lower to upper flow regime bedform, and contrasts with the plane bedded characteristics of most of the sequences. Toward the top of the sequence at South Molle are normally graded, small cobble breccias (Fig. 10) in which cobbles exhibit a bedding parallel stratification. Clast imbrication, reverse grading or cross-bedding are not observed in any of the sequences. The volcanic conglomerates at Cape Conway are notable for containing boulders (≤1.5 m diameter) of inferred basement-derived granite and coal clasts, the latter suggesting erosion of exposed coal measures (Parianos, 1993).

The coarse grain-size, planar bedding and absence of cross-bedding are consistent with deposition from hyperconcentrated flood flows (e.g. Smith, 1986). Deposition is concluded to have occurred in a poorly confined alluvial environment in which upper flow regime conditions dominated. Variations in discharge rate are evident (e.g. transitional bedform, small cobble breccia beds, Fig. 10). Two possible interpretations of the depositional environment for the sedimentary sequence at South Molle are: (1) a stacked sheetflood succession recording an upward increase in flow energy, with occasional, very high energy events (sedimentary breccias); or (2) a prograding toe of sand-dominated alluvial fans formed adjacent to fault scarps (e.g. the Whitsunday Fault).

4.5.2. Debris-flow deposit

Debris-flow deposits and other coarse-grained mass wastage products are extremely rare within the WVP, and the only deposit that has been recognised so far is exposed on South Molle (Figs. 3 and 4). Here, the debris-flow deposit is interbedded with basalt lavas ($^{6}91^{850}$, $^{77}56^{240}$). The deposit is between 20 and 30 m thick, massive, poorly sorted and matrix-supported (Table 4). Some reverse coarse-tail grading is observed in the basal metre (where it is also partly clast-supported), but overall, the deposit is normally coarse-tail graded. Clast sizes range from pebble to boulder (≤50 cm diameter). Petrography of the clasts confirms their unimodal and mafic lava composition.

4.6. Intrusions

Dykes are a common feature of the WVP volcanic sequences. Dykes range in thickness from 0.5 to 50 m, and some of the larger dykes are composite, consisting of at least two intrusive phases. A dacitic welded pyroclastic dyke (≥40 m wide) occurs on Whitsunday Island (Finnis, 1999), and confirms the very proximal setting of this ignimbrite-dominated sequence interpreted by Ewart et al. (1992). Abundant sills occur in the upper parts of the MGI stratigraphy, with a 136 m thick gabbro sill being the most prominent. Multiple episodes of dyke intrusion are apparent as the gabbro sill is itself intruded by several dykes. Mineralogy of the gabbro consists of plagioclase, orthopyroxene (pseudomorphed by uralite) and ophitic augite. Plagioclase compositions are continuously zoned from labradorite through to oligoclase, due to in situ crystallisation (Ewart et al., 1992). This gabbro sill is especially significant as it is geochemically one of the most primitive compositions from the WVP, showing E-MORB affinities (a chemical analysis has been published by Ewart et al., 1992).

Dyke and sill compositions are mostly dolerite with minor andesite and dacite in the MGI and mainland sequences (≤60 wt% SiO_2; Parianos, 1993); rhyolite dykes are absent. This differs from the eastern islands (e.g. Hook, Whitsunday) where intense concentrations of silicic dykes have been reported (Ewart et al., 1992). There thus appears to be a regional variation in dyke composition across the province. Representative analyses of dykes are given in Table 5. For all compositional types, dyke trends are dominantly northerly (Fig. 3; Ewart et al., 1992). Where cross-cutting relationships are observed, dolerite dykes cross-cut the rhyolitic dykes, and E–W dykes cross-cut the dominant N–S oriented dykes. E–W extension nonetheless, appears to be the primary extensional direction for the province based on the approximately N–S-oriented regional dyke swarm.

5. Volcanic architecture and evolution

The essential characteristics of the WVP sequences can be summarised as follows: (1) The dominance of ignimbrites of dacitic to rhyolitic composition; (2) the paucity of mass-wastage products such as debris-flow deposits; and (3) the interstratification of near-vent/proximal and medial to distal facies deposits.

For the MGI volcanic sequences, the vertical arrangement and distribution of the lithologies described above define two facies assemblages: (1) a Lower Facies Assemblage dominated by dacitic massive welded, and stratified ignimbrite; and (2) an Upper Facies Assemblage that is dominated by rhyolite lavas and ignimbrites and basalt lavas. Similar distributions or vertical associations of lithofacies are also observed in the mainland and Lindeman Island sequences (Figs. 6 and 7).

5.1. Lower facies assemblage

The minimum thickness of the Lower Facies Assemblage (LFA) is 1 km, based on the exposed section at South Molle (Fig. 4). Dacitic ignimbrite (both massive and stratified lithofacies) comprises >90% by thickness of the assemblage, indicating an early and sustained period of explosive volcanism. The relatively small maximum lithic clast sizes of ignimbrites contrasts with those of the very coarse lithic lag breccias and lithic concentration zones of ignimbrites on the eastern islands (Fig. 7). The dacitic ignimbrites (both massive and stratified facies) of the LFA therefore are interpreted to represent medial (outflow) facies sourced from caldera-type vents not exposed in the MGI or mainland sequences.

An intracaldera facies association was interpreted by Ewart et al. (1992) for the Hook–Whitsunday–Hamilton–Lindeman Island sequences based on the following: (1) the preservation of >1 km thick ignimbrite sequences; (2) the occurrences of very coarse lithic lag breccias; (3) the abundance of intermediate-silicic dykes, with the thicker dykes interpreted to be volcanic feeders; and (4) a pervasive low grade hydrothermal alteration. The presence of multiple, coarse (up to 2 m diameter), thick (≤30 m) lithic lag breccias (Table 2) confirms a proximal setting for the ignimbrite sequences of Lindeman Island (Fig. 7), whereas the occurrence of a welded pyroclastic dyke at Whitsunday Island indicates this was a vent region for explosive volcanism.

Although the LFA is dominated by ignimbrite, the intercalation of basaltic ashfall deposits, agglomerate, and rare dacitic lava within the MGI, as well as basaltic to andesitic lavas at Lindeman Island and in the mainland sequences, collectively indicate the coeval activity of local monogenetic vents. In particular, the proximal basaltic agglomerate on Daydream Island (Fig. 5) records the eruption of a monogenetic scoria cone, and basaltic ashfall deposits record phreatomagmatic eruptions from similar monogenetic maar-type vents between major dacitic explosive eruptions. Burial of the near-vent basaltic agglomerate by medial facies dacitic ignimbrite at Daydream Island (Fig. 5) is consistent with this early phase of volcanism occurring in a low-relief multiple vent environment. The Cape Conway stratigraphy (Fig. 6) suggests that eruption of mafic to intermediate lavas and volcanogenic sedimentation also occurred during this early phase of volcanism.

5.2. Upper Facies assemblage

The Upper Facies Assemblage (UFA) similarly preserves a >1-km-thick volcanic sequence. On South Molle, basalt lavas mark the boundary between the Lower and Upper facies assemblages (see Fig. 4), whereas a more regional signature may be the first appearance of rhyolitic ignimbrite (see Figs. 6 and 7). Although thick rhyolitic ignimbrites volumetrically dominate the UFA, abundant lavas, especially in the MGI sequences, indicate a significant contribution from effusive eruptions. Explosive eruptions, therefore, may have been less frequent during aggradation of the UFA. However, the less frequent explosive eruptions tapped not only more fractionated rhyolite magma, but also larger magma volumes as indicated by the greater individual thicknesses of rhyolite ignimbrites. Dacitic ignimbrites notably represent a small proportion of the facies assemblage. Similarly small maximum lithic clast sizes of the rhyolitic ignimbrites in the MGI and mainland sequences are also consistent with them being medial or outflow facies.

Lava compositions are mostly bimodal (basalt–rhyolite), and there is an up sequence change from basaltic to predominantly rhyolitic lavas in the MGI (see Figs. 3 and 4). The young, extensive, mesa-like rhyolite lavas on the mainland are interpreted to be the latest expression of volcanism (Parianos, 1993). Lavas are interpreted as proximal deposits to monogenetic vents, and the repetition and abundance of lavas in the MGI sequences suggest several vents were active locally during this interval. The thick dolerite dykes intruding the MGI and mainland sequences may be feeders for the proximal basaltic monogenetic vents. The predominance of basaltic and rhyolitic lavas and rhyolitic ignimbrites thus records a change to bimodal volcanism.

Evidence for erosion and reworking of the volcanic deposits is recorded by the high energy sheetflood volcanic sandstones and conglomerates/breccias at South Molle. Substantial water–magma interaction is also recorded by the 150 m thick base surge deposits on South Molle. Basaltic hyaloclastite associated with the base surge sequence (Figs. 9A and 10), which passes laterally into coherent lava, is interpreted to reflect the existence of a body of standing water (e.g. a small lake).

5.3. Volcanic evolution

Based on stratigraphic relationships (Figs. 4–7), volcanism is interpreted to have evolved in the following manner:

(1) Blanketing of the region by large volumes of dacitic pyroclastic material, emplaced primarily as ignimbrite, with coeval, locally derived (extracaldera) mafic-intermediate volcanism (e.g. basaltic agglomerate and phreatomagmatic ashfall deposits, basaltic to dacitic lava). Burial of vents is indicated by proximal basaltic agglomerate overlain by a thick sequence of medial facies dacitic ignimbrites on Daydream Island (Fig. 5). Explosive volcanism was at a maximum during accumulation of the LFA.

(2) The transition from the LFA to UFA records an increase in effusive eruptions from multiple extracaldera vents. The UFA reflects lava eruptions from both these monogenetic vents as well as large ignimbrite eruptions from caldera-type vents. Ignimbrites sourced from these large explosive eruptions also buried effusive vents within the MGI and on the mainland. Phreatomagmatic deposits (e.g. base surge deposits, accretionary lapilli tuffs) are more commonplace in the UFA, suggesting that standing bodies of

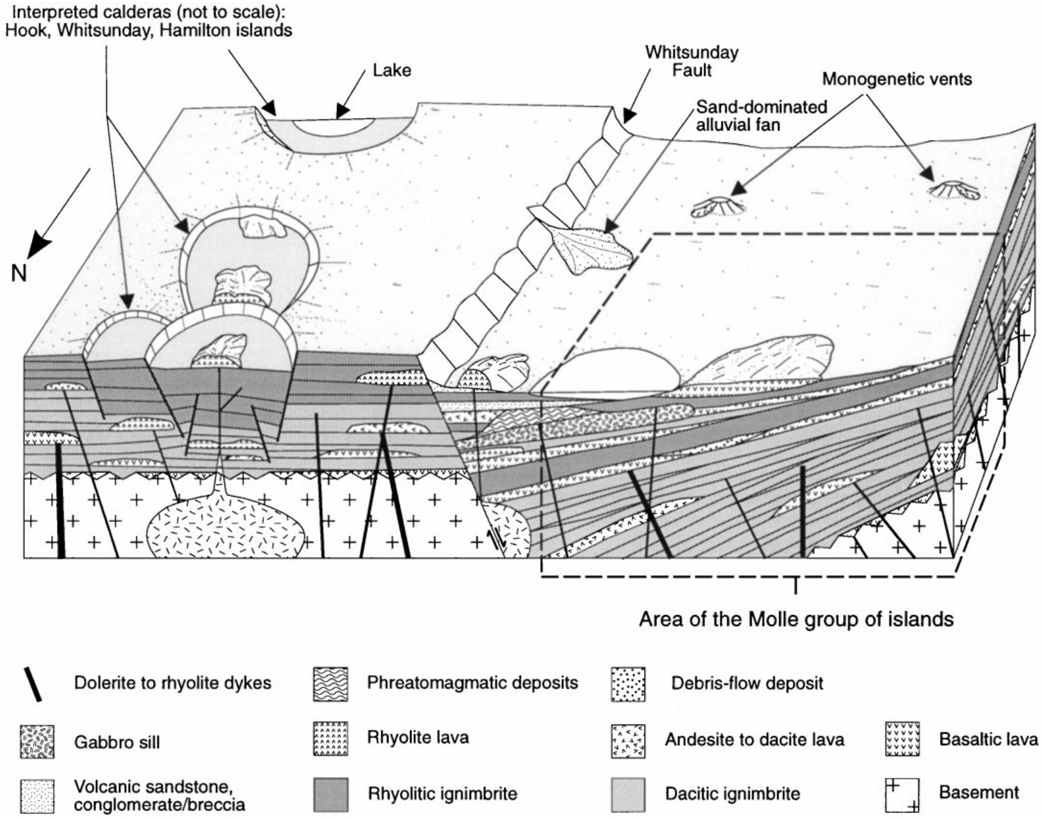

Fig. 11. Proposed facies model illustrating the palaeogeography for the WVP, based on the volcanic sequences of the MGI. The left-hand side of the diagram shows the caldera sources for ignimbrite.

water (e.g. small lakes) began to occupy the land surface.

(3) The change in eruptive style with time is paralleled by a change in magma composition from primarily dacitic (LFA) to basalt and rhyolite (UFA) compositions. Large explosive eruptions began tapping relatively crystal-rich rhyolite magma chambers, whereas effusive eruptions tapped both basaltic and rhyolitic magma. Intrusive activity was fundamentally basaltic, and some of the youngest intrusions show the most primitive geochemical signatures (e.g. gabbro sill at South Molle).

5.4. Volcanic architecture

A palaeogeographic reconstruction, based primarily on the MGI sequences (Fig. 11) illustrates the activity of several local vents, as well as contributions from calderas not preserved in the MGI. The lack of debris-flow deposits and other mass-wastage products, coupled with the burial of near-vent deposits by ignimbrites, are consistent with volcanism occurring in an overall low-relief terrain. The interstratification of proximal/near-vent (e.g. basaltic agglomerate, lavas) and medial (e.g. ignimbrite) deposits indicates that volcanism occurred from multiple vents. The overwhelming dominance of thick ignimbrites in the volcanic stratigraphy suggests that caldera-type complexes were the main eruptive sources, whereas effusive eruptions occurred from many extracaldera monogenetic vents. The preservation of rare carbonised tree logs in ignimbrite, and plant/humic material in the volcanic sandstones, supports a terrestrial volcanic environment (cf. Clarke et al., 1971). However, relatively abundant, and occasionally thick, sequences of phreatomagmatic deposits (e.g. South Molle, Whitsunday islands) and volcaniclastic deposits (e.g. Whitsunday, Esk islands; Cape Conway) suggest lacustrine environments were periodically developed during volcanism. As large explosive eruptions became less frequent with time, erosion and reworking of the volcanic pile occurred primarily by high-energy sheetflood processes. The volcanic sequences clearly record the interplay of multiple-vent volcanism, resulting in the complex stratigraphy now observed.

6. Conclusions

Silicic-dominated large igneous provinces (LIPs) are a new class of LIPs, and feature during the Jurassic-Cretaceous break-up of Gondwana. Emerging descriptions indicate they are: (1) volumetrically dominated by ignimbrite; (2) emplaced over relatively long time intervals (up to 50 m.y.) compared with better known continental flood basalt volcanic provinces; and (3) spatially/temporally associated with plate break-up and other basaltic LIPs. The Whitsunday Volcanic Province and the coeval $>1.4 \times 10^6$ km^3 volume of volcaniclastic sediment in sedimentary basins of eastern Australia (Bryan et al., 1997) preserve the products of the largest known silicic-dominated volcanic province in the world.

We conclude that volcanism in the Whitsunday Volcanic Province occurred in a low-relief, multiple volcanic vent environment, dominated by several large caldera-type centres. Changes in: (1) eruptive styles; (2) the nature of the source vents; and (3) erupted compositions, occurred with time as volcanism progressed from an early explosive dacitic pyroclastic phase to a later mixed pyroclastic-effusive phase producing an essentially bimodal suite of lavas and rhyolitic ignimbrite. The ignimbrite-dominated character of the volcanic sequences is considered critical in generating the large volumes of fine-grained volcanogenic sediment preserved in sedimentary basins of eastern Australia. Voluminous pyroclastic eruptions, in particular, the pyroclastic mode of fragmentation and dispersal as high eruption columns and widespread pyroclastic flows, permitted large volumes of relatively fine-grained and easily erodible pyroclastic material to be rapidly delivered in to these sedimentary basins (Bryan et al., 1997).

Although volcanic and intrusive compositions for the Whitsunday Volcanic Province show a broad spectrum from basalt to high-silica rhyolite (Ewart et al., 1992), stratigraphic analysis has highlighted distinct chemical groupings with time, in particular, the change to an essentially bimodal volcanic suite. Some of the youngest mafic intrusive compositions show the most primitive geochemical signatures (see Ewart et al., 1992; Bryan et al., 1997). The E-MORB affinities of the gabbro and some dolerite dykes approach those of the younger Late Cretaceous-Tertiary ($\leq$80 Ma) within-plate alkaline basalts of eastern Australia (see Johnson, 1989; Ewart et al., 1992). This indicates a ‘geochemical connection’ between pre-break-up magmatism represented by this silicic-dominated LIP and syn- to post-break-up intraplate volcanism that was coincident with sea-floor-spreading in the Tasman Basin system.

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