Australian Journal of Earth Sciences (2003) **50**, 377–401

Stratigraphy, facies architecture and tectonic implications of the Upper Devonian to Lower Carboniferous Campwyn Volcanics of the northern New England Fold Belt*

S. E. BRYAN,[1†] C. R. FIELDING,[1‡] R. J. HOLCOMBE,[1] A. COOK[2] AND C. A. MOFFITT[1§]

[1]*Department of Earth Sciences, University of Queensland, Qld 4072, Australia.*
[2]*Queensland Museum, PO Box 3300, South Brisbane, Qld 4101, Australia.*

Upper Devonian to Lower Carboniferous strata of the Campwyn Volcanics of east central Queensland preserve a substantial sequence of first-cycle volcaniclastic sedimentary and coeval volcanic rocks that record prolonged volcanic activity along the northern New England Fold Belt. The style and scale of volcanism varied with time, producing an Upper Devonian sequence of mafic volcano-sedimentary rocks overlain by a rhyolitic ignimbrite-dominated sequence that passes upward into a Lower Carboniferous limestone-bearing sedimentary sequence. We define two facies associations for the Campwyn Volcanics. A lower facies association is dominated by mafic volcanic-derived sedimentary breccias with subordinate primary mafic volcanic rocks comprising predominantly hyaloclastite and peperite. Sedimentary breccias record episodic and high energy, subaqueous depositional events with clastic material sourced from a mafic lava-dominated terrain. Some breccias contain a high proportion of attenuated dense, glassy mafic juvenile clasts, suggesting a syn-eruptive origin. The lower facies association coarsens upwards from a lithic sand-dominated sequence through a thick interval of pebble- to boulder-grade polymict volcaniclastic breccias, culminating in facies that demonstrate subaerial exposure. The silicic upper facies association marks a significant change in eruptive style, magma composition and the nature of eruptive sources, as well as the widespread development of subaerial depositional conditions. Crystal-rich, high-grade, low- to high-silica rhyolite ignimbrites dominate the base of this facies association. Biostratigraphic age controls indicate that the ignimbrite-bearing sequences are Famennian to lower-mid Tournaisian in age. The ignimbrites represent extra-caldera facies with individual units up to 40 m thick and mostly lacking coarse lithic breccias. Thick deposits of pyroclastic material interbedded with fine-grained siliceous sandstone and mudstone (locally radiolarian-bearing) were deposited from pyroclastic flows that crossed palaeo-shorelines or represent syn-eruptive, resedimented pyroclastic material. Some block-bearing lithic-pumice-crystal breccias may also reflect more proximal subaqueous silicic explosive eruptions. Crystal-lithic sandstones interbedded with, and overlying the ignimbrites, contain abundant detrital volcanic quartz and feldspar derived from the pyroclastic deposits. Limestone is common in the upper part of the upper facies association, and several beds are oolitic (cf. Rockhampton Group of the Yarrol terrane). Overall, the upper facies association fines upward and is transgressive, recording a return to shallow-marine conditions. Palaeocurrent data from all stratigraphic levels in the Campwyn Volcanics indicate that the regional sediment-dispersal direction was to the northwest, and opposed to the generally accepted notion of easterly sediment dispersal from a volcanic arc source. The silicic upper facies association correlates in age and lithology to Early Carboniferous silicic volcanism in the Drummond (Cycle 1) and Burdekin Basins, Connors Arch, and in the Yarrol terranes of eastern Queensland. The widespread development of silicic volcanism in the Early Carboniferous indicates that silicic (rift-related) magmatism was not restricted to the Drummond Basin, but was part of a more substantial silicic igneous province.

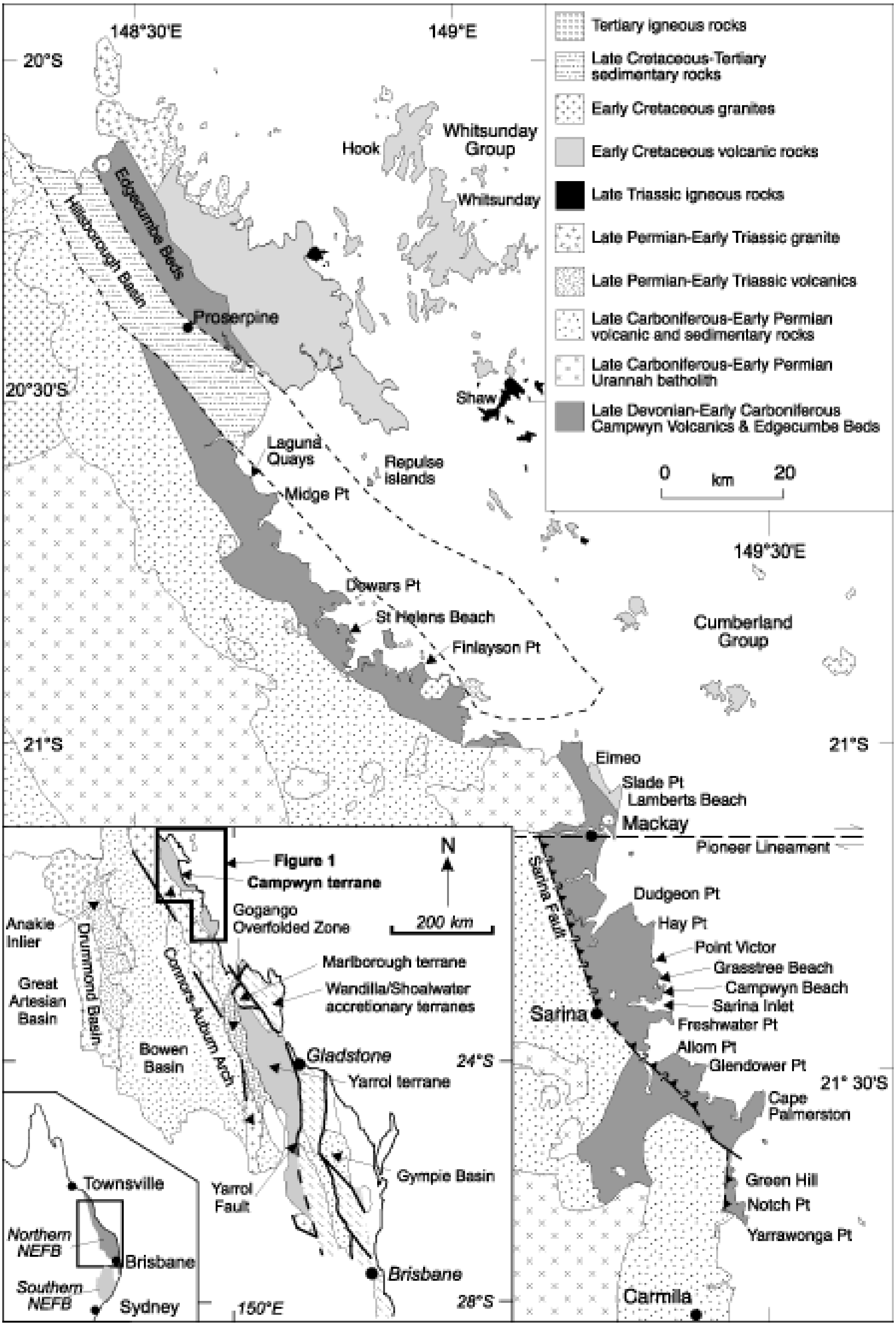
KEY WORDS: Campwyn Volcanics, Carboniferous, Devonian, facies associations, palaeogeography, Queensland, stratigraphy.

INTRODUCTION

Mafic to silicic magmatism was widespread across the New England Fold Belt during the Late Devonian and Early Carboniferous, with most products preserved as volcanogenic sedimentary rocks in the Yarrol–Tamworth sedimentary basin systems (Leitch 1974; Day *et al.* 1978). Magmatism and volcanogenic sedimentation have historically been linked to a supra-subduction zone magmatic arc developed to the west of this basin system. For the northern New England Fold Belt, the Connors–

*Tables 1–5 [indicated by an asterisk (*) in the text and listed at the end of the paper] are Supplementary Papers; copies may be obtained from the Geological Society of Australia's website (http://www.gsa.org.au) or from the National Library of Australia's Pandora archive (http://nla.gov.au/nla.arc-25194).

†Corresponding author: s.bryan@earth.uq.edu.au
‡Present address: Department of Geosciences, University of Nebraska, 214 Bessey Hall, Lincoln, NE 68588-0340, USA.
§Present address: BM Alliance Coal Operations Pty Ltd, Peak Downs Mine, Private Mail Bag, Moranbah, Qld 4744, Australia.


148°30'E
149°E
149°30'E
20°S
20°30'S
21°S
21° 30'S
Tertiary igneous rocks
Late Cretaceous-Tertiary sedimentary rocks
Early Cretaceous granites
Early Cretaceous volcanic rocks
Late Triassic igneous rocks
Late Permian-Early Triassic granite
Late Permian-Early Triassic volcanics
Late Carboniferous-Early Permian volcanic and sedimentary rocks
Late Carboniferous-Early Permian Urannah batholith
Late Devonian-Early Carboniferous Campwyn Volcanics & Edgecumbe Beds
0 km 20
Hook
Whitsunday Group
Whitsunday
Edgecumbe Beds
Hillsborough Basin
Proserpine
Shaw
Laguna Quays
Repulse islands
Midge Pt
Dewars Pt
St Helens Beach
Finlayson Pt
Cumberland Group
Eimeo
Slade Pt
Lamberts Beach
Mackay
Pioneer Lineament
Sarina Fault
Dudgeon Pt
Hay Pt
Point Victor
Grasstree Beach
Campwyn Beach
Sarina Inlet
Sarina
Freshwater Pt
Allom Pt
Glendower Pt
Cape Palmerston
Green Hill
Notch Pt
Yarrawonga Pt
Carmila
N
200 km
Figure 1
Campwyn terrane
Gogango Overfolded Zone
Anakie Inlier
Drummond Basin
Great Artesian Basin
Connors-Auburn Arch
Marlborough terrane
Wandilla/Shoalwater accretionary terranes
Bowen Basin
Gladstone
24°S
Yarrol terrane
Gympie Basin
Yarrol Fault
Brisbane
28°S
150°E
Townsville
Northern NEFB
Southern NEFB
Sydney

Auburn Arch has been interpreted as the site of the magmatic arc (Day *et al.* 1978; Murray *et al.* 1987) (Figure 1), whereas for the southern New England Fold Belt, postulated arc-related magmatic rocks are concealed by sedimentary rocks of the Gunnedah, Sydney and Great Artesian basin systems (Leitch 1974; Day *et al.* 1978). However, the igneous rocks of the Connors–Auburn Arch are now recognised as being part of a larger silicic igneous province formed mostly in the Late Carboniferous and Early Permian in response to extension and crustal melting preceding the opening of the Permian–Triassic Bowen Basin (Holcombe *et al.* 1997a; Fielding *et al.* 1997; Allen *et al.* 1998). The existence of a magmatic arc of Late Devonian – Early Carboniferous age in the New England Fold Belt consequently remains poorly defined.

The Upper Devonian – Lower Carboniferous Campwyn Volcanics, occurring to the east of the Connors Arch (Figure 1), have been interpreted as forming part of the forearc and arc assemblages, and include more proximal volcanic products than those preserved in the correlative Yarrol terrane to the south (Fergusson *et al.* 1994). The formation is described as being dominated by a recurring assemblage of mafic volcanic-dominated volcano-sedimentary facies associations (Fergusson *et al.* 1994). However, closer examination of previous descriptions (Jensen *et al.* 1966; Fergusson *et al.* 1994) reveals that the volcanic sequences are bimodal in composition (basalt–rhyolite). Bimodal volcanism is more characteristic of continental rift settings rather than supra-subduction zones. Palaeoflow directions from the sedimentary rocks were, in general, reported to the southeast and interpreted to be along-shelf (Fergusson *et al.* 1994 figure 12). The mafic volcanic-dominated character and palaeocurrent directions contrast with our own data from the Yarrol terrane to the south, where the volcano-sedimentary sequences changed with time from being mafic to silicic-dominated (i.e. the mafic and silicic volcanic rocks are stratigraphically separate), and palaeocurrent data indicated sediment transport toward the northwest (Bryan *et al.* 2001).

The aim of this study is to reassess the depositional environment, volcanic architecture and evolution of the Campwyn Volcanics to place constraints on the tectonic setting of volcanism. This is achieved through detailed stratigraphic and facies analyses of the sequences, supported by sedimentary petrofacies and palaeocurrent data. In this paper, we argue that the basis for interpreting the Campwyn Volcanics as preserving forearc and arc assemblage rocks to a western continental arc is invalid, and that palaeoflow directions are overwhelmingly toward the northwest rather than from the west. We show that the Campwyn Volcanics preserve a well-defined succession of Upper Devonian, mafic volcano-sedimentary rocks underlying a silicic volcanic sequence that passes upward into Lower Carboniferous limestone-bearing sedimentary rocks (Figure 2). This stratigraphy is correlative with that observed 150 km to the south, supporting the conclusions drawn in our earlier study (Bryan *et al.* 2001).

Figure 1 Location map and extent of the Upper Devonian – Lower Carboniferous Campwyn Volcanics in east central Queensland. Localities referred to in text are shown. The offshore extent of the Hillsborough Basin is marked by the dashed line. Granite ages based on Allen *et al.* (1998).

GEOLOGICAL OVERVIEW OF THE CAMPWYN VOLCANICS

The Campwyn Volcanics were first described by Jensen *et al.* (1966) as a relatively narrow belt of mafic to silicic volcanic and sedimentary rocks along the central Queensland coast, best exposed between Proserpine and Carmila (Figure 1). The unit is correlative with the Edgecumbe beds (Clarke *et al.* 1971) to the north and the better-known Upper Devonian and Lower Carboniferous sequences of the Yarrol terrane to the south (Yarrol Project Team 1997; Bryan *et al.* 2001). Fergusson *et al.* (1994) concluded that the Campwyn Volcanics represented a complex association of pyroclastic, hyaloclastic and resedimented, texturally immature volcaniclastic facies associated with shallow intrusions, lavas, minor ignimbrite, limestone and non-volcanic siliciclastic sedimentary rocks.

The mapped extent of the Campwyn Volcanics (Jensen *et al.* 1966; Fergusson *et al.* 1994) is now known to include some younger rock units that are not part of the Campwyn Volcanics of Late Devonian to Early Carboniferous age. Many intrusive rocks, primarily dykes and dyke swarms, cut the Campwyn Volcanics and probably range in age from Late Devonian to Early Cretaceous. Early Cretaceous volcanic and intrusive rocks dominate the Mackay area (forming several headland exposures) where exposure of the Campwyn Volcanics is limited.

Structure

In general, the Campwyn Volcanics occur as gently to moderately dipping (<30°), relatively undeformed and upward-facing sequences. North of Mackay, the sequence dips regionally to the west and passes up disconformably into the overlying Permian strata. Locally (e.g. Green Hill, Dudgeon Point), and particularly south of Sarina, beds in the Campwyn Volcanics are steeply dipping to moderately overturned, with moderately strong cleavage. Cleavage in the overturned sections generally dips shallowly to the east, indicating west-verging structures (Fergusson *et al.* 1994).

Boundaries between regions of gentle upright dips and steep to overturned dips in the southern part of the area are generally not exposed. However, the overall structure between the two areas is consistent with west-verging thrusts and thrust-propagation folds. Small-scale thrusts occur locally within the overturned sequences, as at Cape Palmerston, where a minor, very shallow east-dipping thrust fault occurs in some of the most strongly overturned beds observed in the Campwyn Volcanics. At this locality, overturned beds (as indicated by bedding-cleavage vergence and sedimentary structures) dip to the east at angles as low as 45° (Fergusson *et al.* 1994; Moffitt 2000). This overturned sequence persists for at least 10 km along strike along the coast between Green Hill and Cape Palmerston. Immediately to the west (≤2 km), these strongly overturned beds are juxtaposed against subhorizontal beds of Permian–Carboniferous conglomerate and sandstone. This

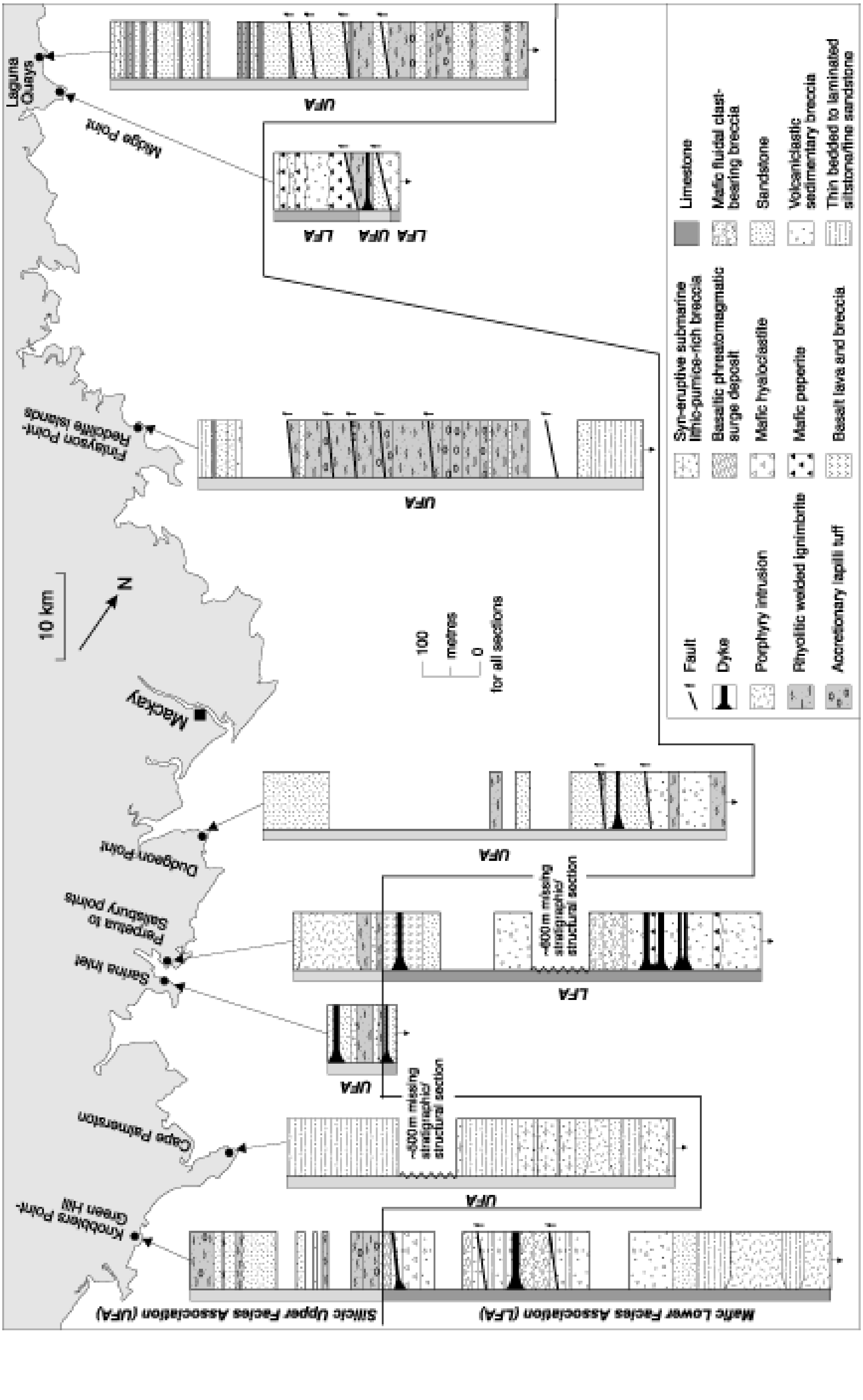


Figure 2 Generalised stratigraphic sections of the Campwyn Volcanics showing the distribution of the two facies associations identified in this study. LFA, lower facies association; UFA, upper facies association. Solid line marks the boundary between the two facies associations.

observed geometry is most consistent with the bounding structure between the two areas being either a major thrust ramp or a synclinal breakthrough fault associated with a major east-dipping blind thrust. The inferred major thrust may correspond to the Sarina Fault shown on the 1:250 000 Mackay map sheet (Jensen *et al.* 1966) and appears to be the only major thrust structure in the exposed Campwyn Volcanics. North of Dudgeon Point, the thrust probably steps out to the east (with the Pioneer Lineament acting as a tear fault: Figure 1). Therefore, the units of the Campwyn Volcanics along the coast south of the Pioneer Lineament probably lie entirely in the hangingwall of the thrust sheet, whereas all other exposures to the north and west lie in the footwall. The fault propagation antiform corresponds crudely to the 'Campwyn Anticline' of Jensen *et al.* (1966). Sparse outcrop precludes detailed mapping of these structures and subsidiary thrusts may also disrupt the succession. This is an important constraint in interpreting non-continuous stratigraphic transects in this part of the area.

Local exposures are commonly offset by complex systems of steep faults, with all possible fault slip senses observed. Such faults truncate and offset the cleavage-related thrust structures described above (e.g. at Cape Palmerston). Local folding of sedimentary strata (without cleavage) is fault-related and is evident between Midge Point and Laguna Quays (Figure 3). Strike-slip fault offsets vary from metres to hundreds of metres. Such faults, although occurring throughout the area, are most prominent to the north where the Campwyn Volcanics are overprinted by structures of the Late Cretaceous – Tertiary Hillsborough Basin.

The fold, cleavage and thrust structures are correlated with the Permo-Triassic Hunter–Bowen Orogeny. They are comparable with similar west-verging, thin-skinned fold-thrust systems described in the Yarrol Province and Gogango Overfolded Zone to the south (Fergusson 1991; Holcombe *et al.* 1997b). The overprinting dip-slip and strike-slip structures were most likely generated during a regional sinistral wrench event in the Late Cretaceous and during formation of Early Tertiary extensional basins.

STRATIGRAPHY

Homoclinal tilts characterise most exposures and allow insights into the stratigraphic evolution of the Campwyn Volcanics. However, the lack of exposure away from coastal platforms, and extensive and multiple generations of faulting, hinder stratigraphic correlation. Incorrect lithofacies recognition in previous studies has further hindered stratigraphic definition, and resulted in important vertical changes in lithofacies being overlooked.

We recognise two volcano–sedimentary facies associations: a mafic lower facies association and a silicic upper facies association (Figure 2). Facies association definition is based on the mafic or silicic composition of the volcanic rocks and volcaniclastic material. Although previous studies inferred that the spectrum of volcanic compositions were interbedded throughout, mafic and silicic volcanic rocks (and epiclastic derivatives) are clearly stratigraphically separate. Critical stratigraphic contacts

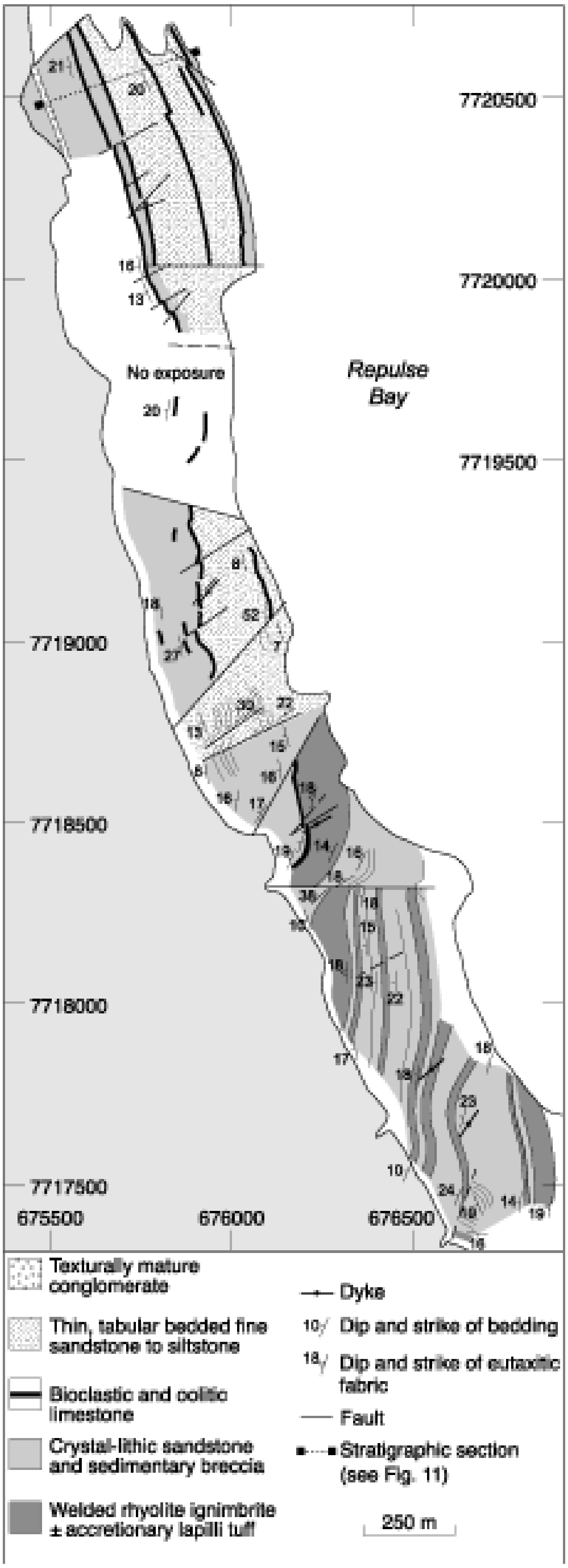


Figure 3 Geological map of the tidal platform at Laguna Quays, Repulse Bay, showing fault-related folding of strata and an up-sequence change from ignimbrite to limestone-dominated strata in the silicic upper facies association. See Figure 1 for location.

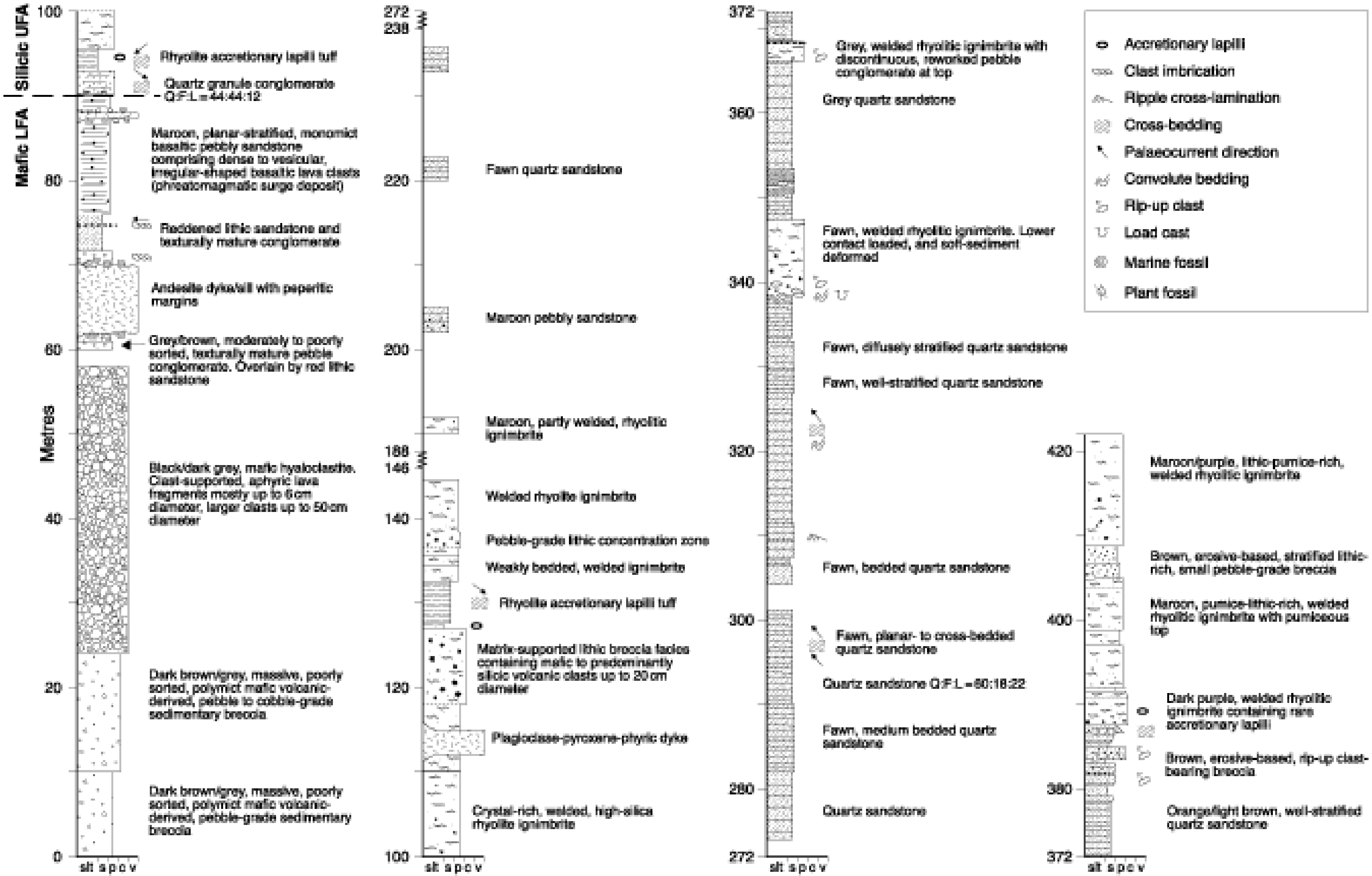


Figure 4 Stratigraphic section at Green Hill (GR 0754034E, 7600519N to 0753961E, 7599854N) illustrating the transition from a mafic volcanic and volcaniclastic breccia-dominated lower sequence to a rhyolite ignimbrite- and quartz sandstone-dominated upper sequence. This section represents the upper third of the generalised stratigraphic section for Green Hill – Knobblers Point shown in Figure 2. LFA, lower facies association; UFA, upper facies association; Q:F:L, quartz:feldspar:lithic ratio; slt, silt; s, sand; p, pebble; c, cobble and boulder; v, volcanic.

illustrating a mafic lower facies association overlain by a silicic upper facies association are exposed at Green Hill and Sarina Inlet (Figures 4, 5). Elsewhere, exposures tend to be of one facies association. Where there are alternations of facies, or mafic facies association rocks overlying silicic facies association rocks (e.g. Midge Point: Figure 2), the contacts are faulted.

Facies association definition is based on mapping and detailed stratigraphic logging of coastal exposure from Green Hill to Laguna Quays (Figures 1, 2). Field coordinates described in this paper are based on Zone 55 of the Map Grid of Australia (WG584).

Mafic lower facies association

Key sections through the lower facies association occur at Knobblers Point – Green Hill, Perpetua to Salisbury Points (Sarina Inlet), St Helens Beach and Midge Point (Figure 1) and, in general, the facies association is best exposed in coastal sections to the south of Mackay. The base of the association is not exposed, but upper contacts are observed at Green Hill and Sarina Inlet. A minimum thickness of 1 km is indicated based on exposures from Knobblers Point to Green Hill (Figure 2). This section comprises a lower, sandstone/siltstone-dominated sequence (Figure 6) that passes upward to the regionally predominant, coarse-grained mafic volcanic breccia-dominated sequence. The main lithofacies of the mafic lower facies association are described below.

HYALOCLASTITE

Quench fragmented lava facies are relatively widespread in the Campwyn Volcanics, but most of these exposures are of intrusive hyaloclastite (peperite). Most hyaloclastite units occur toward the upper parts of the mafic lower facies association. Clast-supported, but relatively poorly sorted, monomict mafic lava-fragment breccias, in units 20–50 m thick, characterise this facies (Table 1*). Fragments range in size from pebble to boulder grade, although clasts are predominantly 5–10 cm diameter. Clasts are non-vesicular and commonly equant and blocky, with curviplanar margins. Jigsaw-fit textures are observed, but dissociated clast fabrics predominate, reflecting the greater intensity of quench fragmentation producing abundant, interstitial finer grained matrix as well as some clast rotation. Cement void fill (quartz, chlorite, calcite, prehnite) is also common, especially at Green Hill and St Helens Beach. Representative chemical analyses are listed in Table 2*. Although there is some petrographic variation with porphyritic and aphyric varieties of breccia present (Table 1*), the hyaloclastite units range in composition from basalt to basaltic andesite.

Interpretation These monomict lava fragment breccias reflect the subaqueous extrusion of lava modified by quench fragmentation. The absence of resedimented facies

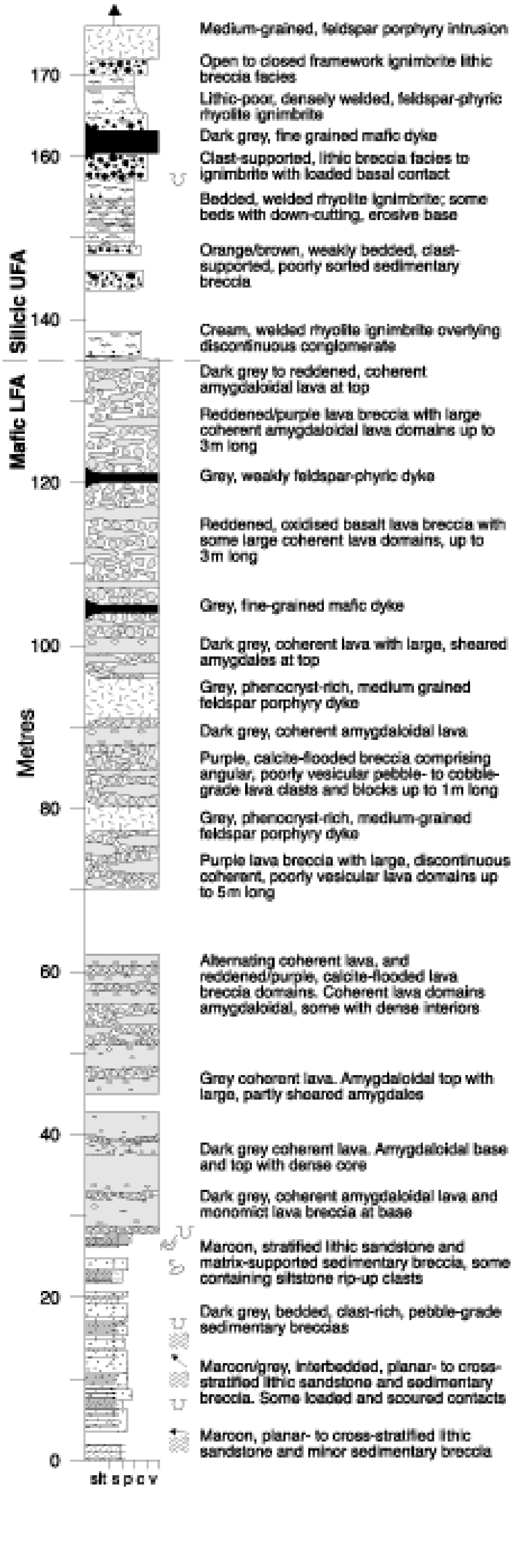


Figure 5 Stratigraphic section at Salisbury Point, Sarina Inlet (GR 0738657E, 7632058N to 0738650E, 7631850N) illustrating the contact between the mafic lower (LFA) and silicic upper (UFA) facies associations. Symbols as in Figure 4.

indicates that the hyaloclastite units represent subaqueously emplaced lavas proximal to their source with quench fragmentation occurring largely *in situ*. The petrographic variety of hyaloclastite indicates several widely scattered subaqueous eruptions of different mafic magma types.

PEPERITE

Syn-sedimentary intrusive rocks are common in the lower facies association and are basaltic to basaltic andesite in composition (Tables 2*, 3*) and, in general, cross-cut mafic volcanic-derived sedimentary breccias and sandstone. They range from relatively small intrusive bodies (~10 m thick) that are entirely fragmented to larger (~20 m thick) coherent sill-like intrusives with fragmentation restricted to the intrusive contacts (i.e. peperitic margins). Contact zones are typically irregular, comprising a mixture of igneous clasts and surrounding sediment as matrix. Baking and alteration of the sediment matrix occurs in some mixed contact zones (e.g. Midge Point). Examples of blocky or globular to rounded igneous clast shapes are observed in the mixed contact zones. Pillow lava reported at St Helens Beach by Fergusson *et al.* (1994) is a disaggregated mafic dyke cross-cutting mafic volcanic-derived, pebble-grade sedimentary breccias (GR 0691458E, 7695442N: Figure 7). In this example, most lava clasts are internally massive and lack thick chilled margins, vesicle zonation and radial joint development, which is characteristic of pillow lavas (Yamagishi 1991; Walker 1992; McPhie *et al.* 1993; and references therein).

Interpretation The contacts of the syn-sedimentary intrusions illustrate the varying effects of quenching and of interaction with unlithified, water-saturated sediment and are interpreted as peperite (White *et al.* 2000), with both blocky and fluidal peperite varieties occurring (Figure 8). The similarity in composition indicates that the peperites are intrusive equivalents of the hyaloclastite

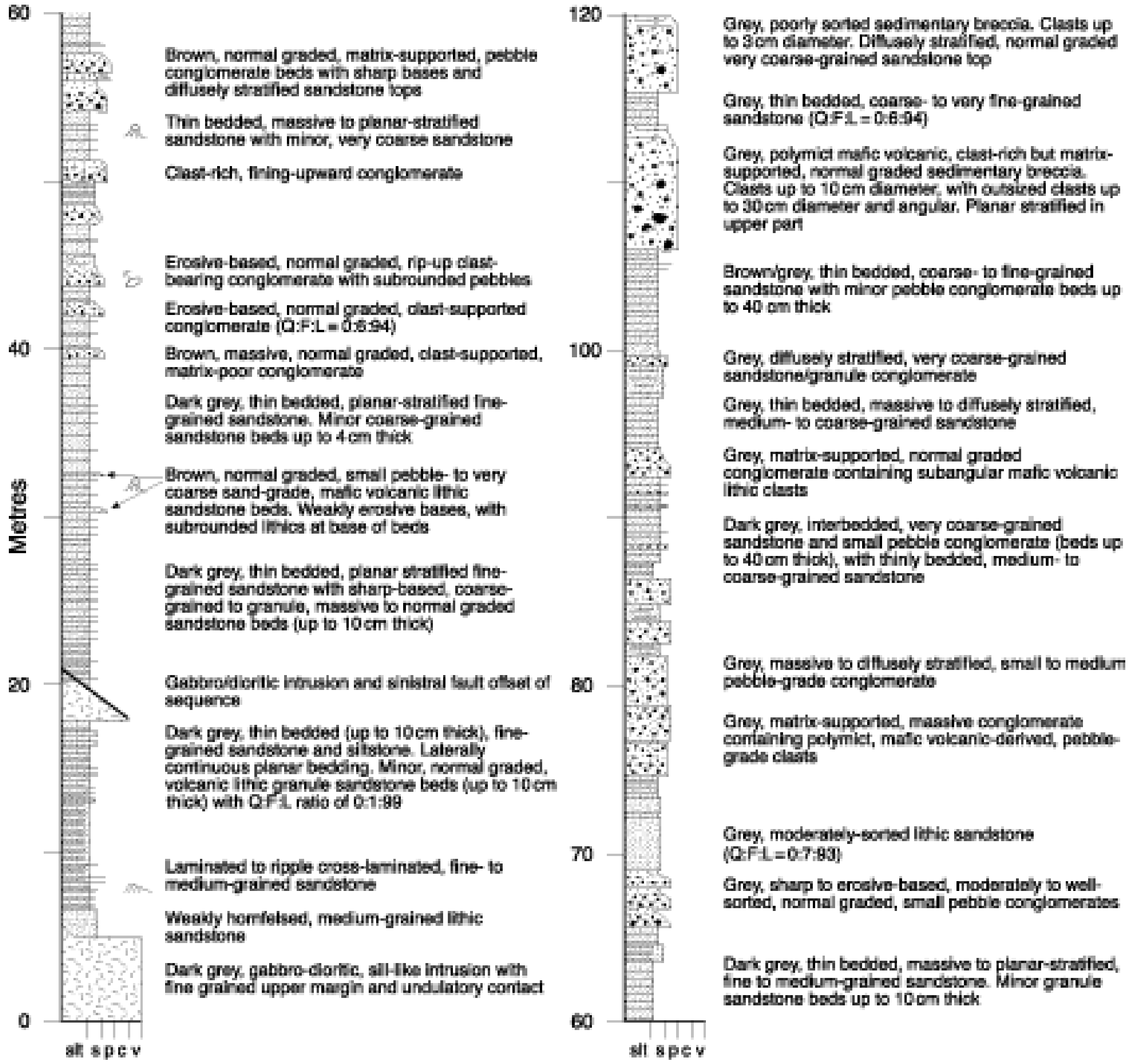


Figure 6 Stratigraphic section at Knobblers Point (GR 0753381E, 7602607N) illustrating the sand-dominated character of the stratigraphically lowest exposed parts of the mafic lower facies association. This section forms the base of the generalised stratigraphic section for Green Hill – Knobblers Point in Figure 2. Symbols as in Figure 4.

facies. Widely scattered yet small volume intrusions of mafic magma are indicated from petrographic variations of the peperitic units (Table 3*).

BASALTIC LAVA AND AA LAVA BRECCIA

A thick section (50–100 m) of amygdaloidal basaltic lava and breccia is exposed at Salisbury Point, Sarina Inlet (Figure 5). The lower contact is partly loaded with basaltic lava and breccia downcutting into dark-coloured, mafic volcanic-derived, bedded sandstone and sedimentary breccia. The top contact of the lava sequence is reddened and overlain by a thin (≤20 cm thick) pebble conglomerate bed and welded rhyolite ignimbrite; welded rhyolite ignimbrite also directly overlies the strongly reddened basaltic lava/breccia sequence on the south side of Sarina Inlet (GR 0739916mE, 7630600mN).

Coherent amygdaloidal lava occurs as laterally continuous sheets (1–6 m thick) and as discontinuous bodies or domains up to 3–5 m long within breccia zones. Coherent lava sheets show some internal stratigraphy with vesicular (commonly sheared) tops and bases, and dense, less-vesicular interiors. Vesicles are mostly up to 3 cm long and infilled with calcite and lesser chlorite. Upper and lower contacts with breccia zones are sharp, but irregular, and commonly reddened. The breccias are clast-supported monomict aggregates of reddened, ragged angular clasts of variably vesicular basaltic lava.

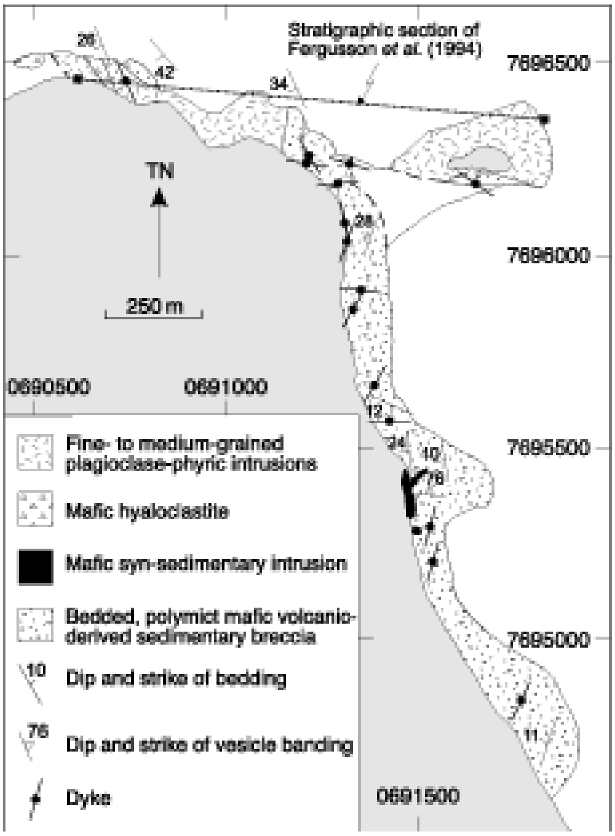


Figure 7 Geological map of coastal exposures at St Helens Beach. A >400 m thick, coherent lava sequence was described from these exposures by Fergusson *et al*. (1994) and pillow lava reported by these authors is a mafic syn-sedimentary intrusion. See Figure 1 for location.

Interpretation The lack of pillow structures and jigsaw-fit textures rule out a pillow lava/hyaloclastite origin. The reddened character of the breccia zones and nature of the overlying lithofacies are consistent with subaerial emplacement of the lava and breccia. However, soft-sediment deformation at the lower contact indicates emplacement across an unconsolidated substrate. The dominance of lava breccia over coherent facies suggests an emplacement style analogous to aa-type lava flows rather than pahoehoe (MacDonald 1953; Walker 1971). The substantial thickness of lava and breccia indicates proximity to vent and/or lava has ponded in a topographic depression.

MAFIC VOLCANIC-DERIVED SEDIMENTARY BRECCIA

Massive, poorly sorted, mafic volcanic-derived sedimentary breccia represents the predominant and most widespread lithofacies of the mafic lower facies association. General characteristics of the sedimentary breccias are illustrated in Figure 8. Grain fabric is poorly developed and beds are otherwise massive, with only limited development of coarse-tail normal grading. Clasts are generally pebble grade, although maximum sized clasts are up to 2 m diameter, and erosional bases characterise several breccia beds. Lithic clasts are mostly angular to subangular and a population of rounded clasts is generally present. Breccia beds vary from matrix- to clast-supported, with some being open framework and well sorted (e.g. Perpetua Point). The breccias represent a heterogeneous mixture of mafic to intermediate volcanic rocks that vary from being dense to amygdaloidal or scoriaceous, devitrified to formerly glassy (chlorite-replaced glass), aphyric to plagioclase ± pyroxene-phyric, and phenocryst-poor to phenocryst-rich. Detrital mineral grains are mostly absent.

Interpretation The breccias represent a spectrum of subaqueous flow-styles ranging from dilute tractional currents (in the case of size-sorted and stratified varieties) to density-modified grain flows or high-density turbidity flows for the more internally homogeneous and massive beds. The distinctive bedded breccias at Perpetua Point (Figure 8) may represent the products of surging, dilute aqueous flows in the upper plane-bed bedform stability field, the open framework intervals recording periods of low sediment delivery and relatively clear water flow, allowing removal of fines from the sediment by winnowing.

TEXTURALLY MATURE MAFIC VOLCANIC-DERIVED CONGLOMERATE

Minor occurrences of texturally mature conglomerate occur in the mafic lower facies association (Figure 4), whereas conglomerate/sedimentary breccia of more variable textural maturity is relatively common (e.g. Perpetua Point: Figure 8). Conglomerate beds are tabular and typically clast-supported (in some cases are partly openwork). Graded and graded–stratified units are rare, and alternations between conglomerate and sandstone are more characteristic. Intervening sandstone units commonly show planar- and cross-stratification. Scoured, erosional contacts are occasionally observed for the con-

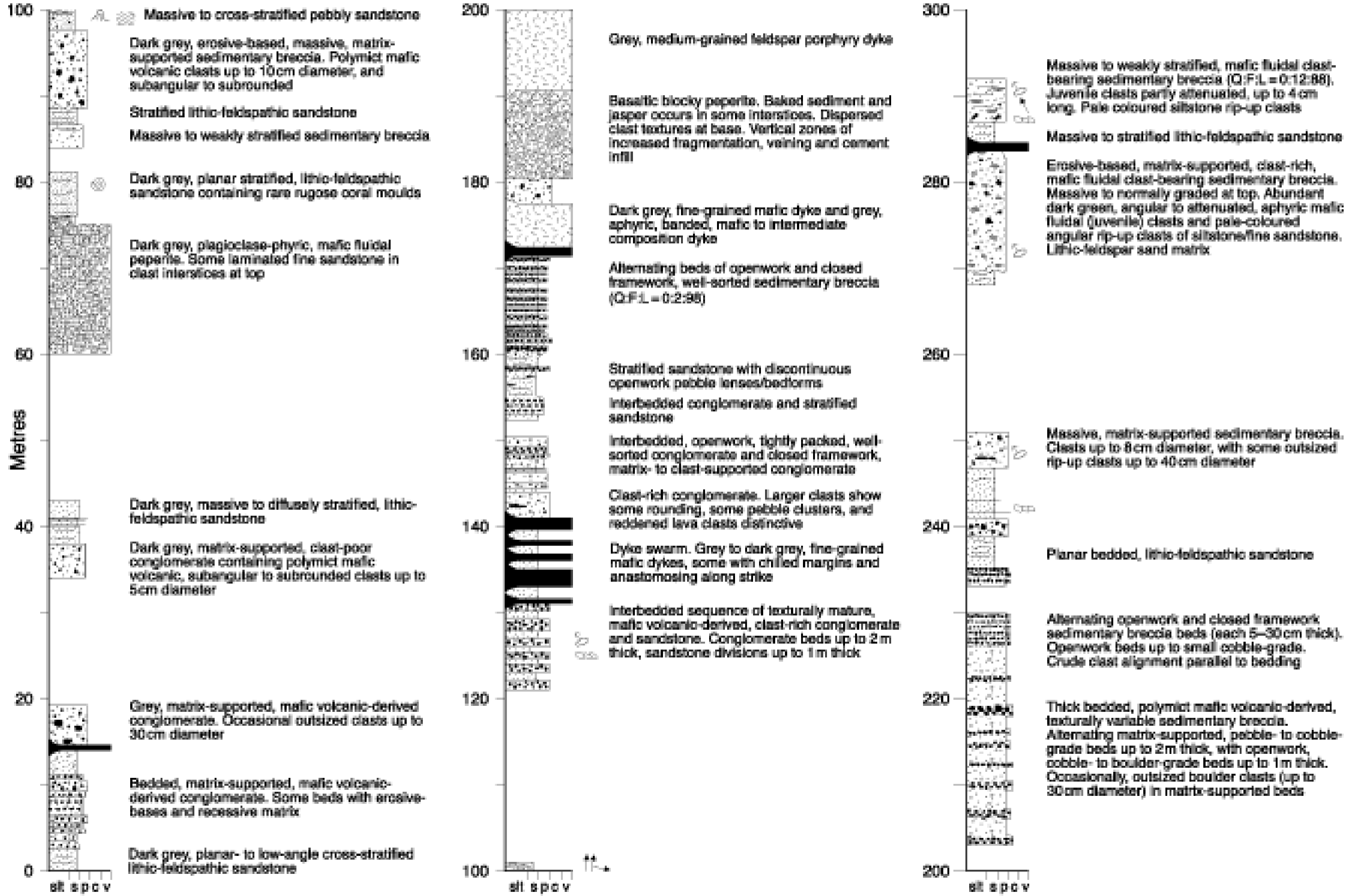


Figure 8 Stratigraphic section at Perpetua Point, Sarina Inlet (GR 0740085E, 7632546N to 0739769E, 7632231N) illustrating an overall coarsening-upward succession of mafic volcanic lithic-derived sandstone to sedimentary breccia. Symbols as in Figure 4.

glomerate beds as are siltstone rip-up clasts. Organised clast fabrics, such as imbrication and pebble clusters, are poorly developed. The clast population consists of a variety of fine-grained, mostly plagioclase-phyric mafic-intermediate volcanics with reddened volcanic clasts distinctive in some beds.

Interpretation Textural maturity of the sediment indicates prior working at either shoreface or in fluvial environments. Textures and fabrics indicate aqueous flows of varying strength and sediment concentration, but generally of sufficiently high sediment concentration as to impede the development of bedforms. Water depths for these facies cannot be confidently determined, but general coarsening-upward patterns indicate shallowing trends and shallow shelfal to coastal water depths are considered most likely from deposit characteristics and the nature of enclosing facies.

MAFIC FLUIDAL CLAST-BEARING BRECCIA

This enigmatic lithofacies occurs in the middle to upper parts of the lower facies association, with type exposures occurring at Green Hill (GR 0753739E, 7601124N; 0754025E, 7600759N). Fluidal clast-bearing breccia also overlies fossiliferous lithic sandstone at Campwyn Beach (GR 0740170E, 7634549N) and finer grained beds are exposed at Perpetua Point (Figure 8). Based on the descriptions of Fergusson *et al.* (1994), this lithofacies may also occur at Dewars Point.

The breccias comprise predominantly matrix-poor and clast-supported mixtures of abundant, attenuated to fluidal-shaped clasts and angular, polymict mafic volcanic clasts. Individual breccia beds (up to 20 m thick) are typically massive, but can show layering defined by alternating fluidal clast-rich and lithic clast-rich layers, or coarse-tail normal grading of the volcanic rock fragments with both rounded and angular lithic debris up to 40 cm diameter occurring at the base of beds. Volcanic rock fragments are commonly subordinate to juvenile clastic material and detrital crystal grains (feldspar) form a minor clastic component of the breccia beds. Bed bases are downcutting and erosional, and rip-up clasts of siltstone are observed in finer grained breccia units at Perpetua Point.

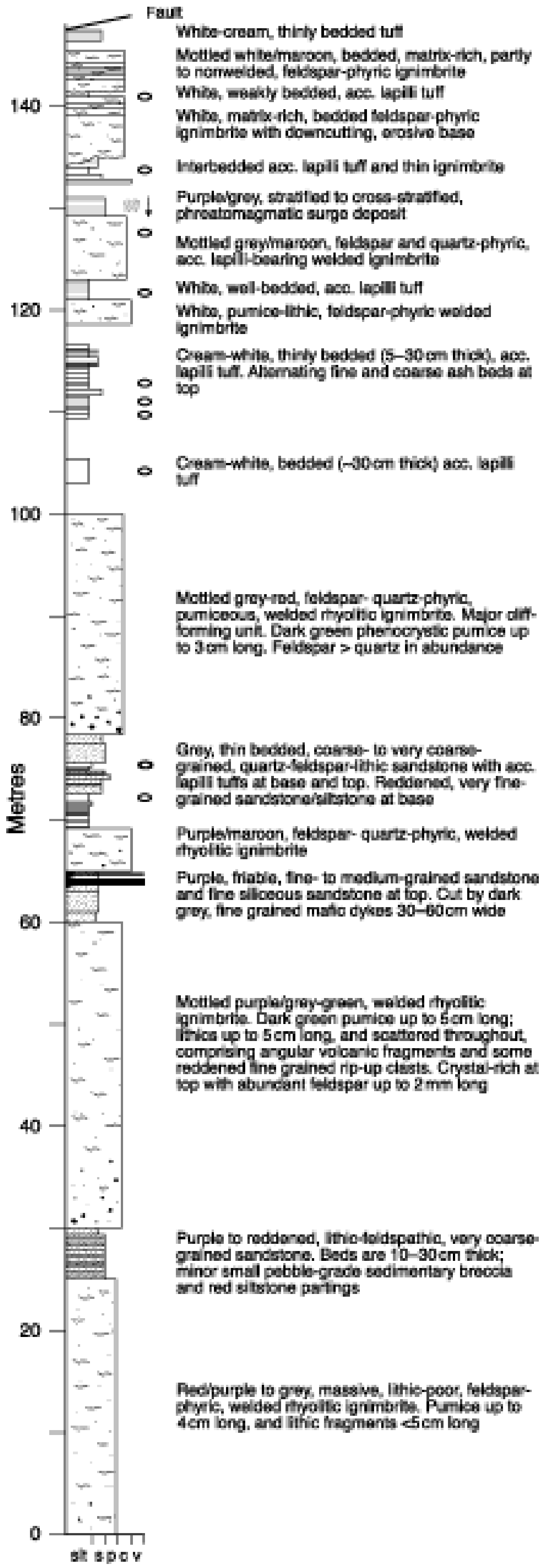
The distinctive fluidal clasts are variably glassy and mafic in composition. Flattening is variable between clasts; larger clasts (>10 cm long) can form thin fluidal rags or are equant and only weakly attenuated, whereas adjacent smaller clasts often show high compaction ratios. Clast attenuation is not always parallel to bedding or layering. Lithic fragments often indent the fluidal clasts and in some cases occur as inclusions. The fluidal clasts are mostly dense and poorly vesiculated. However, moderately vesicular clasts and larger clasts with vesiculated cores and dense margins are also observed.

Interpretation The contorted to folded and highly attenuated or ductile appearance and non-bedding-parallel flattening suggest that the fluidal clasts were hot and plastic during deposition, and coupled with the lack of clay alteration and poor vesicularity of fluidal clasts, argue against clast attenuation resulting from cold-state diagenetic compaction (Branney & Sparks 1990). A syn-eruptive origin is indicated by the abundance of glassy juvenile material and the episodic and catastrophic nature of these breccia-forming events is reinforced by one breccia underlain and overlain by ripple cross-laminated fine sandstone. The depositional environment is poorly constrained, but the association with hyaloclastite and the interbedded nature with a thick sequence of sedimentary rocks support a subaqueous setting. Although the fluidal clast breccias show some similarities to subaqueous fire-fountain deposits (Cas *et al.* 1996; Simpson & McPhie 2001), they differ by: (i) lacking relatively thick glassy, quenched rims to fluidal clasts; (ii) lacking abundant quench-fragmented (hyaloclastite) matrix; and (iii) comprising abundant accessory (polymict) volcanic lithic material. In general, the poor vesicularity of the juvenile clasts suggests that volatile expansion was not a driving force for magma fragmentation. The generation of highly competent and erosive, syn-eruptive flows to emplace the mafic juvenile clast-bearing breccias may alternatively have been triggered by phreatomagmatic eruptions. The deposit characteristics show more affinity to mafic spatter-bearing agglomerates occurring at phreatomagmatic calderas [e.g. Santorini (Mellors & Sparks 1991); Taal (Torres *et al.* 1995 and references therein)].

MAFIC VOLCANIC-SOURCED LITHIC SANDSTONE/SILTSTONE

Epiclastic sandstone and siltstone represent a minor component, being best developed in the lower to middle parts of the mafic lower facies association, and occur interbedded with mafic volcanic-derived sedimentary breccias and the mafic fluidal clast-bearing breccias (e.g. Perpetua Point: Figure 8). A significant thickness (≥100 m) of thin to rhythmically bedded, laminated siltstone and fine sandstone to small pebble conglomerate occurs at Knobblers Point (Figure 6), and forms part of a coarsening-upward trend through an interbedded sequence of silicified siltstone/fine sandstone and mafic volcanic-derived sedimentary breccias to the mixed volcanic and sedimentary breccia sequence at Green Hill (Figure 4). The siltstone packages exhibit well-developed planar lamination, and include minor, thin, medium- to coarse-grained lithic sandstone beds. Detrital sandstone compositions are dominated by fine-grained mafic volcanic rock fragments with an average Q:F:L ratio of 0:5:95. Sandstone containing bioclasts (mostly brachiopod shell and rugose coral fragments) has only been observed at Campwyn Beach (GR 0740170E, 7634549N), and occurs as an isolated sequence of flat to low-angle cross-stratified, very coarse-grained lithic sandstone and pebbly sandstone.

Interpretation Low energy, suspension to weakly tractive sedimentation conditions are indicated by the rhythmic bedded, sandstone/siltstone packages. Episodic and slightly more energetic, but decelerating, aqueous currents deposited beds of coarser sandstone and pebble-grade conglomerate with erosive bases, normal grading and gradations from massive to overlying stratified divisions (Figure 6). The overall low-energy depositional conditions were repeatedly interrupted by high-energy, competent flows depositing the thicker beds of pebble- to boulder-grade, mafic volcanic-derived sedimentary breccias as typified by the sequences at Green Hill.



Silicic upper facies association

The silicic upper facies association is extensively exposed, and dominates coastal exposures north of Grasstree Beach. Key sections occur between Midge Point and Laguna Quays, Redcliffe Islands – Finlayson Point, Dudgeon Point and Cape Palmerston (Figure 2), and indicate a minimum thickness of 1 km for the upper facies association. Sections exposed at Dudgeon Point, Laguna Quays and, to a lesser extent, Green Hill illustrate the vertical transition from basal ignimbrite-dominated to sandstone-dominated sequences. The contact with the lower facies association is sharp and defined by abrupt lithological and compositional changes in volcanic lithofacies, and detrital grain compositions of sedimentary rocks.

IGNIMBRITE

Previous work indicated that ignimbrite in the Campwyn Volcanics was restricted to a few individual units having limited lateral continuity and small thicknesses (≤5 m thick). However, in this study ignimbrite was found to be a more widespread, abundant and, thus, important lithofacies, with many ignimbrite exposures previously misinterpreted as either mafic sedimentary, hyaloclastic breccias or tuff cone deposits (e.g. Dudgeon Point, Slade Point, Laguna Quays, Sarina Inlet, Inner Redcliffe Island). Many ignimbrites are crystal-rich, containing quartz and feldspar phenocrysts up to 1 cm diameter, and eutaxitic textures defined by attenuated pumice clasts are well preserved in most exposures. Note that ignimbrite at Slade Point is Early Cretaceous in age (SHRIMP zircon date, 138 ± 1.5 Ma: I. Withnall pers. comm. 2001), and should not be included in the Campwyn Volcanics.

Ignimbrite occurs toward the base of the upper facies association, in places defining the contact between the two facies associations (e.g. Sarina Inlet: GR 0739916E, 7630600N). Individual eruptive units vary from 5 to ~30 m thick, but can form stacked sequences in excess of 200 m thickness (Figure 9). Both crystal-rich and crystal-poor varieties (8–35 modal% crystals) of ignimbrite occur, with the phenocryst assemblage dominated by alkali feldspar, plagioclase and quartz. Subtle differences occur based on the relative proportions of quartz and feldspar, with the quartz-predominant ignimbrites (≥10 modal% quartz) typically coarser grained (quartz phenocrysts up to 1 cm diameter). Mafic minerals are almost entirely absent, contrasting with ignimbrites of the Early Cretaceous Whitsunday Volcanic Province to the east (Ewart *et al.* 1992) and the Upper Carboniferous – Lower Permian ignimbrites exposed to the west (e.g. Bulgonunna Volcanics: Oversby *et al.* 1994; Hutton *et al.* 1998). Whole-rock analyses (Table 2*) reveal that the ignimbrite compositions range from dacite to high-silica rhyolite (68% to >75% SiO_2), with the more quartz-rich ignimbrites being high-silica rhyolite.

Figure 9 Rhyolite ignimbrite-dominated stratigraphic section at Inner Redcliffe Island (GR 0704227E, 7691037N to 0704035E, 7690764N). Symbols as in Figure 4; acc. lapilli; accretionary lapilli.

Ignimbrite eruptive units are commonly interbedded with volcaniclastic sedimentary rocks (Figures 3, 5), although fossiliferous limestone directly overlies ignimbrite at Notch Point Road (GR 0753987E, 7596048N) and Laguna Quays (GR 0676198E, 7718676N). At Midge Point (GR 0680328E, 7716295N), several *Lepidodendron* trunks in growth position, preserved in an altered, fine-grained, bedded pumice-fall deposit, are truncated by overlying crystal-rich rhyolite welded ignimbrite. Elsewhere, ignimbrite units are intimately interbedded with accretionary lapilli tuffs (Figure 9).

Most ignimbrite units are typically massive, exhibiting a relatively simple internal stratigraphy possessing weakly developed basal lithic (lithic clasts mostly <5 cm diameter) and upper pumice (pumice clasts <10 cm long) concentration zones. Matrix- to clast-supported lithic breccia facies occur in the upper parts of some ignimbrite units, best observed at Green Hill (Figure 4) and Salisbury Point (Figure 5). The lithic breccia horizons (up to 10 m thick) are defined by sharp increases in clast size (up to 40 cm diameter) and abundance (up to 50%), with the lithic clast assemblage comprising a variety of mafic to silicic volcanic rock fragments. Ignimbrite units are moderately to densely welded, or medium to high grade (terminology of Walker 1983) and occasionally lava-like (e.g. Midge Point: GR 0679781E, 7715908N). In general, vitriclastic or shard textures are poorly preserved because of pervasive low-grade alteration and local cleavage deformation.

Interpretation The generally small maximum lithic clast size, limited development of lithic breccia facies and relative thinness (≤30 m thick) of individual welded ignimbrite units are features resembling outflow (extracaldera) ignimbrite sheets. The coarser lithic breccias occurring in the upper parts of some ignimbrites may reflect ignimbrite emplacement more proximal to the vent, and also most likely record caldera collapse events during the final stages of the ignimbrite-forming eruptions (Bryan *et al.* 1998). In general, a subaerial depositional environment is indicated for the ignimbrites and is supported by *in situ Lepidodendron* trunks beneath welded rhyolite ignimbrite at Midge Point. However, a loaded lower contact to one welded ignimbrite unit at Green Hill (Figure 4) indicates emplacement, in this case, across a wet unconsolidated sedimentary substrate (Kokelaar & Koniger 2000). Of note is that accretionary lapilli occasionally occur in some ignimbrite units (Figure 9), suggesting a phreatomagmatic component to these ignimbrite-forming eruptions.

ACCRETIONARY LAPILLI TUFF

Associated with several ignimbrites are accretionary lapilli tuffs, with the best exposures occurring at Green Hill (Figure 4), Inner Redcliffe Island (Figure 9) and Laguna Quays (GR 0676537E, 7717792N). Accretionary lapilli tuff units commonly occur at the base of ignimbrite eruptive units and are of limited thickness (≤4 m), but alternations of ignimbrite and accretionary lapilli tuffs are also observed. In this study, no accretionary lapilli-bearing deposits were found to be associated with mafic sandstone or phreatomagmatic deposits of mafic composition, nor was any evidence found for thicker successions

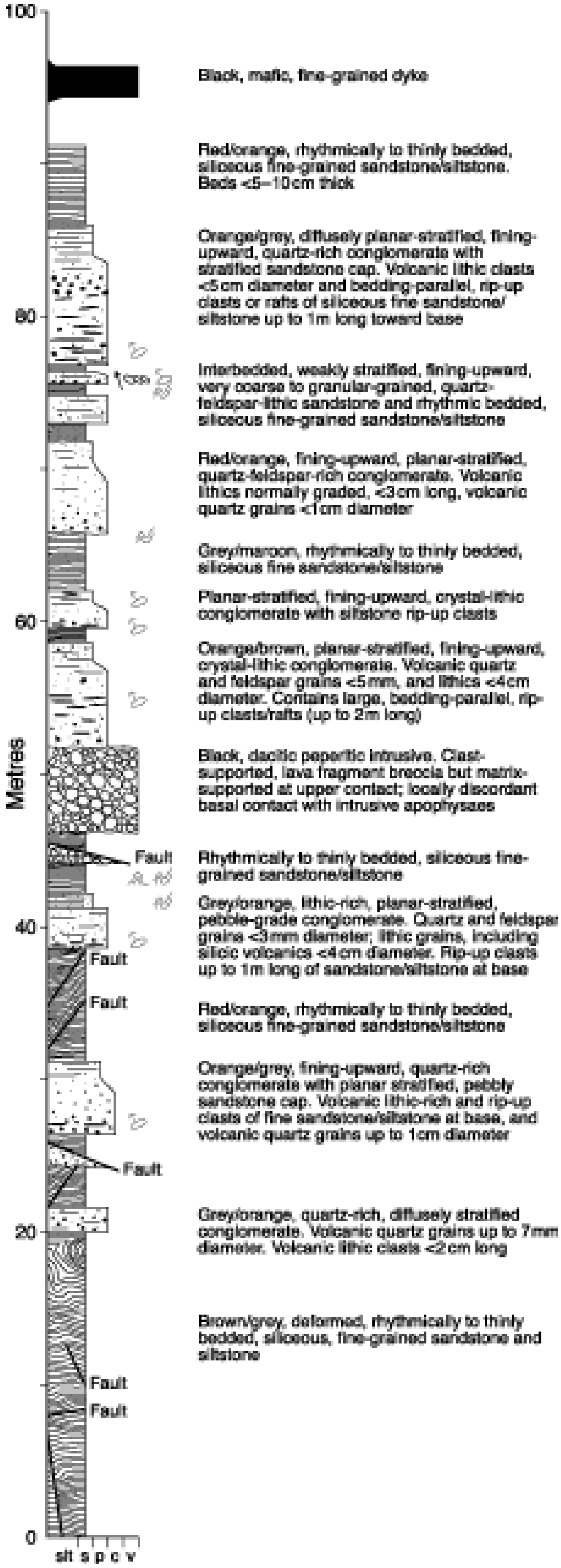


Figure 10 Cape Palmerston stratigraphic section (GR 0756765E, 7616676N to 0756950E, 7616718N), silicic upper facies association. Symbols as in Figure 4.

(e.g. Inner Redcliffe Island) being sourced from basaltic tuff cone vents (cf. Fergusson *et al.* 1994).

Two types of accretionary lapilli-bearing units occur. Type 1 units exhibit laterally continuous planar bedding (≤50 cm thick), with beds defined by alternations and gradations from accretionary lapilli-rich to lapilli-poor (massive ash) horizons. Type 2 units exhibit thinner bedding, cross-stratification, lateral variations in bed thickness and pinch and swell of bedding. The tuffs contain angular, fine-grained fragments of quartz and feldspar, and minor intermediate to silicic volcanic rock fragments. However, all units are notably lithic-poor and ash-rich.

Interpretation The lateral continuity and thickness of type 1 units indicate that deposition was dominated by fallout processes, whereas type 2 beds are interpreted to be phreatomagmatic surge deposits. The lithic-poor and ash-rich composition suggests magma interaction with surface water rather than groundwater where greater explosive fragmentation at the depth of wall rock increases the proportion of lithic material in the deposits (Barberi *et al.* 1989). The formation of accretionary lapilli tuffs at the base of ignimbrite eruptive units indicates frequent, but limited, water–magma interaction at the onset of silicic explosive eruptions, followed by the reversion to ‘dry’ magmatic explosive conditions producing welded ignimbrite. Alternations between ignimbrite and accretionary lapilli tuffs and emplacement of accretionary lapilli-bearing ignimbrite indicate more complex and repeated water–magma interactions during eruptions.

SUBAQUEOUSLY EMPLACED PYROCLASTIC BRECCIA

A variety of subaqueously emplaced breccia units containing pumice, lithic and crystal material occur in the upper facies association, and their deposit characteristics are summarised in Table 4*. Weakly graded, matrix-supported breccias over 40 m thick are the most striking examples, occurring at Cape Palmerston (GR 0757320E, 7616770N) and Point Victor (GR 0738399E, 7639407N). In general, the breccias are often interbedded with thin to rhythmically bedded sandstone or siliceous sandstone/siltstone, and most have downcutting/erosional bases with rip-up clasts characteristic of stratified conglomerates at Cape Palmerston (Table 4*; Figure 10). Grain fabrics, grading, sorting and stratification are best developed in the thinner (≤10 m thick) breccia beds (Table 4*). Abundant, volcanic quartz and feldspar crystal grains and quartz–feldspar-phyric pumice clasts characterise most units, although the stratified, quartz-rich conglomerates (Table 4*) lack pumiceous material. Lithic clast compositions include silicic ignimbrite and lava as well as sedimentary clasts, and blocks ≥1 m diameter occur in the thickest breccia units at Cape Palmerston and Point Victor.

Interpretation Erosive bases to the breccias and the fine-grained nature of interbedded sedimentary lithofacies are consistent with the breccias recording high-energy, catastrophic events. Gradations into crystal-rich sandstone tops indicate emplacement from decelerating high-density sediment gravity flows. The occurrence of abundant pumice/juvenile material and the large deposit thickness suggests that these deposits are syn-eruptive, emplaced from high-concentration sediment gravity flows triggered by ignimbrite-forming eruptions. Detrital grain compositions and phenocryst mineralogy of the pumice clasts confirm a rhyolite composition for the source explosive eruptions. Many breccia units may be subaqueous equivalents of subaerial welded rhyolite ignimbrites observed elsewhere in the sequence. The stratified and normally graded conglomerates (Table 4*) that lack pumiceous material most likely represent deposits of syn-eruptive, high-concentration flows (i.e. subaerial pyroclastic flows that entered water), where increased water mixing and fluidisation has resulted in hydraulic separation and elutriation of pumice and ash from the current (Cas & Wright 1987; Jagodzinski 2000). However, the breccia units at Cape Palmerston and Point Victor appear unlikely to represent the subaqueous equivalents to ignimbrite. At those localities, the greater deposit thickness, maximum lithic clast size (≥1 m diameter) and higher lithic contents indicate that they are not simply lateral equivalents of relatively thinner, finer grained and lithic-poor subaerial welded ignimbrites exposed elsewhere in the Campwyn Volcanics. These breccias may represent the products of more proximal subaqueous silicic explosive eruptions.

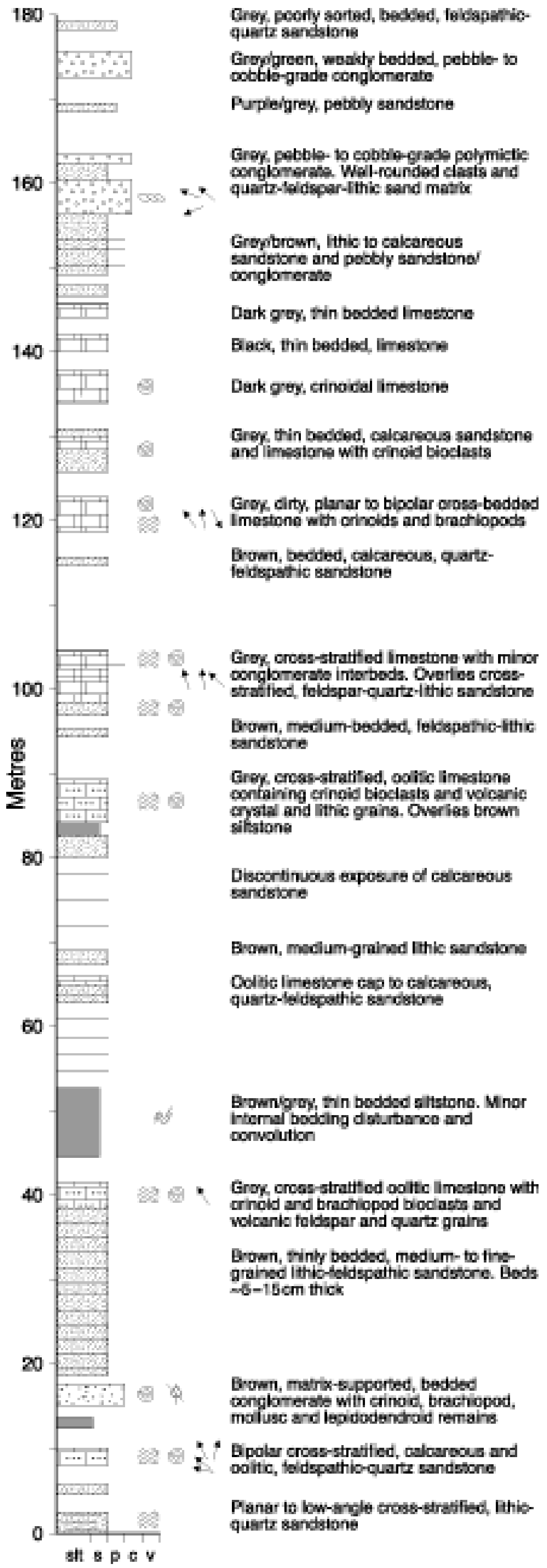
LITHIC–CRYSTAL SEDIMENTARY BRECCIA AND CONGLOMERATE

Thinner sedimentary breccia units and subordinate conglomerate occur in the upper facies association, and deposit characteristics are summarised in Table 5*. All are characterised by a polymict volcanic clast assemblage with silicic volcanic clasts predominating, and a sand-sized matrix comprising relatively abundant, detrital volcanic quartz and feldspar. Interbedded with welded ignimbrites at the base of the upper facies association (Figure 5) are distinctive sedimentary breccias that are poorly sorted, clast-supported, stratified and exhibit a poorly developed clast fabric (Table 5*). Texturally mature conglomerate is restricted to the uppermost part of the sequence, occurring above bioclastic and oolitic limestones at Laguna Quays (Figure 11) (‘basaltic beach’ conglomerate of Fergusson *et al.* 1994).

Interpretation The range of textures, fabrics and bedding features of this lithofacies (Table 5*) are comparable to the sedimentary breccias and conglomerates described from the lower facies association, and a similar range of depositional processes and environments is envisaged. However, the sedimentary breccias interbedded with ignimbrites at Sarina Inlet (Figure 5) show structures indicative of being emplaced from hyperconcentrated flood flows (Smith 1986). The texturally mature conglomerates, associated with limestones (Figure 11), are interpreted as shoreface or nearshore deposits.

CRYSTAL-RICH SANDSTONE

Epiclastic crystal-rich sandstone occurs throughout the upper facies association. Sandstone forms considerable thicknesses at Dudgeon Point, Green Hill and Laguna Quays (up to 100 m thickness: Figures 2, 4, 11). Abundant detrital volcanic quartz (with resorbed and embayed faces) and feldspar grains, which are commonly greater than



sand grade, are characteristic and distinguish the sandstones from those occurring in the mafic lower facies association (Figure 12). The sandstones have an average Q:F:L ratio of 58:26:16. Cross-stratified quartz arenite (terminology of Folk *et al.* 1970) at Lamberts Beach (GR 0731532E, 7667542N) is compositionally distinct from all other sandstones in the Campwyn Volcanics having a Q:F:L ratio of 99.5:0:0.5 (Figure 12) and is dominated by angular quartz grains with undulose extinction.

Sandstones interbedded with ignimbrites are typically coarse-grained to pebbly, but usually become finer grained up-sequence in the facies association (as typified by Green Hill/Laguna Quays sequences). Tabular to trough cross-stratification is observed in the coarser sandstone beds, whereas planar stratification and ripple cross-laminations characterise the fine- to medium-grained sandstones (e.g. Green Hill: Figure 4). Hummocky cross-stratification is relatively common and is best developed in sandstone sequences at Halliday Bay (GR 0676750E, 7669000N). Rarely, *Lepidodendron* moulds and imprints (e.g. Midge Point: GR 0680349E, 7716724N) occur in some fine sandstone intervals.

Interpretation The crystal-rich character of the sandstones and coarse grainsizes of quartz and feldspar reflect the coarsely phenocrystic nature of the interbedded ignimbrites from which they have been derived. In contrast, the quartz arenite at Lamberts Beach is the only sandstone in the Campwyn Volcanics to have such a distinct non-volcanic grain composition, and has previously been interpreted to be craton-derived (Fergusson *et al.* 1994). Such quartz-rich petrofacies are more commonly associated with the Permian sedimentary sequences of the Bowen Basin (Baker *et al.* 1993), raising the possibility that the Lamberts Beach sandstones are not part of the Upper Devonian – Lower Carboniferous Campwyn Volcanics. Fluvial sandstones are commonly associated with ignimbrites, whereas the development of hummocky cross-stratification indicates moderately extensive depositional environments above storm wave-base for the upper parts of the facies association.

SILICEOUS VERY FINE-GRAINED SANDSTONE/SILTSTONE

Thin bedded, siliceous, very fine-grained sandstone and siltstone locally form sequences up to 30–35 m thick and are best exposed at Cape Palmerston (Figure 10), Outer Redcliffe Island (GR 0703937E, 7691570N) and Finlayson Point (GR 0703463E, 7690021N). Laterally continuous, tabular, massive to weakly planar stratified beds between 5 and 50 cm thick are characteristic. Soft-sediment deformation structures (convolute bedding, loading and dewatering structures) are locally developed and locally intense folding and faulting is common, as typified by exposures at Cape Palmerston and Outer Redcliffe Island. Petrographically, abundant fine quartz and rare feldspar grains up to 0.5 mm diameter occur in a

◄

Figure 11 Stratigraphic section at Laguna Quays (GR 0675908E, 7720593N to 0675430E, 7720440N) illustrating the sand- and limestone-dominated character of the upper part of the silicic upper facies association. Symbols as in Figure 4.

microcrystalline siliceous matrix. Radiolarians have been reported from this lithofacies at Cape Palmerston and Outer Redcliffe Island (Fergusson *et al.* 1994), and interbedded fossiliferous sandstones containing crinoid, brachiopod and gastropod bioclasts also occur at Finlayson Point.

Interpretation Sedimentary structures and fine grainsize suggest low-energy, suspension-dominated sedimentation conditions. Some interbeds have erosive bases and grade from massive to stratified sandstone and, rarely, have ripple cross-laminated sandstone tops, consistent with deposition from relatively dilute, aqueous currents. Embayed faces to some of the larger quartz grains indicate a silicic volcanic origin, and much of the fine material may be resedimented pyroclastic ash. Little evidence exists to indicate that the siliceous sandstone and siltstone formed by biogenic accumulations of radiolarians with growth promoted by submarine mafic–intermediate volcanism (Fergusson *et al.* 1994).

LIMESTONE

Limestone is mostly restricted to the upper parts of the Campwyn Volcanic stratigraphy, with Midge Point – Laguna Quays (Figures 3, 11) and Allom–Glendower Points the two main areas of limestone exposure. Bioclastic and oolitic varieties are present, with oolith-bearing limestone present at Laguna Quays (Figure 11), and in the correlative Edgecumbe beds to the north (Brown 1963). Most limestone units are fossiliferous with a diverse faunal assemblage dominated by crinoids and brachiopods, indicating early to late Tournaisian ages (Jensen *et al.* 1966; Clarke *et al.* 1971).

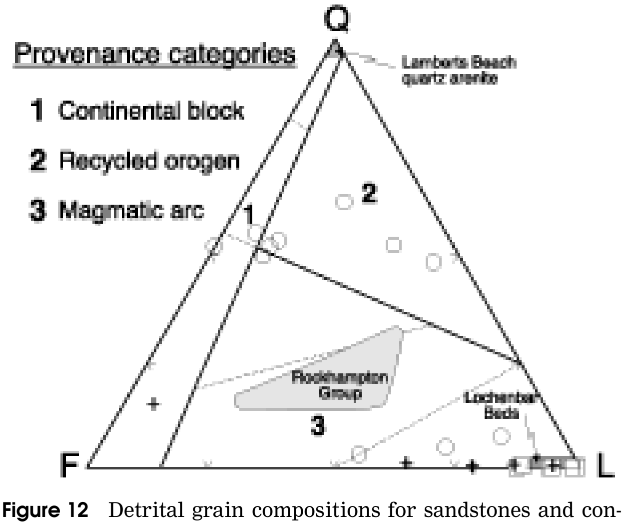


Figure 12 Detrital grain compositions for sandstones and conglomerates from the Campwyn Volcanics. The three apices of the diagram are: total quartzose grains (Q), which are all monocrystalline volcanic quartz grains; total monocrystalline feldspar grains (F) and total lithic fragments (L). Provenance boundaries after Dickenson *et al.* (1983). Shown for comparison are detrital grain compositions from the Upper Devonian, mafic volcanic-sourced Lochenbar beds, and Upper Devonian to Lower Carboniferous, ignimbrite-sourced sandstones of the Three Moon Conglomerate and Rockhampton Group from the Yarrol terrane (Bryan *et al.* 2001). Point-count data based on counts of at least 500 points per thin-section and a step length of 0.5 mm. n is the number of samples. ○, Silicic Upper Facies Association ($n = 12$); □, Mafic Lower Facies Association ($n = 8$); +, Three Moon Conglomerate (Yarrol terrane).

Most limestone beds are <5 m thick and commonly exhibit flat to cross-stratification or bipolar cross-stratification (Figure 11). The limestones contain varying proportions of detrital volcanic lithic and crystal material, with volcanic lithic fragments predominantly intermediate to silicic in composition (feldspar- and feldspar–quartz-phyric), and with feldspar and quartz dominating the detrital crystal population.

Interpretation The cyclic development of oolitic limestone and ooid-bearing sandstone is a characteristic of the Lower Carboniferous formations (Rockhampton Group) of the Yarrol terrane to the south (Yarrol Project Team 1997). Collectively, a region of ≥600 km length dominated by high-energy to tidal-dominated, shallow-marine conditions with areas of restricted terrigenous sediment input is indicated for the Early Carboniferous. Embayment textures observed in some detrital quartz grains are consistent with a volcanic origin for the siliciclastic material.

SYN-SEDIMENTARY INTRUSIONS

Evidence for shallow-level intrusion of magma coeval with aggradation of the silicic upper facies association is restricted to small irregular bodies cross-cutting siltstone at Half-Tide Beach (Figure 13), peperitic sills at Cape Palmerston (Figure 11) and Freshwater Point, and a series of irregular intrusive bodies at Grasstree Beach. The characteristics and phenocryst assemblage of the intrusions are summarised in Table 3*. The intrusions at Half-Tide and Cape Palmerston are dacitic and at Grasstree Beach rhyolitic in composition (Table 2*).

Subvolcanic intrusions

Shallow-level, typically fine-grained intrusive rocks are common in exposures of the Campwyn Volcanics. Intrusive bodies range from thin (≤50 cm), anastomosing, discontinuous dykes (e.g. Finlaysons Point) to thick (~150 m) massive intrusive bodies (e.g. Freshwater Point), with sills also occurring locally (e.g. Point Victor). Dykes have a dominant northeast to east-northeast strike that is characteristic along the length of exposure of the Campwyn Volcanics (Figure 14). This strike orientation contrasts with the predominant northwest to north-northeast orientations for Early Cretaceous dykes of the Whitsunday Volcanic Province (Ewart *et al.* 1992; Bryan *et al.* 2000) and as observed in the Mackay area, and the dominant north-northwest strike for Permo-Carboniferous mafic and felsic dykes of the Urannah Batholith (Paine *et al.* 1974; Stephenson 1990; Allen 2000). The presence of a distinct suite of Late Devonian to Early Carboniferous dykes is distinguished on the basis of contact relationships (e.g. peperitic margins), petrographic similarities to host volcanic sequences, degree of alteration and, less precisely, by structural relationships (e.g. dykes cross-cut by thrust faults: Half-Tide Beach: Figure 13). Thus, taken together this region of the northern New England Fold Belt has been the site of repeated extension and dyke-forming events.

The northeast strike is characteristic of both mafic and silicic dyke compositions. Fine-grained, grey to dark-grey, variably plagioclase-phyric or doleritic-textured dykes are dominant in the Campwyn Volcanics. However, some dyke compositions are geographically distinctive. A suite of medium-grained quartz diorite dykes (≤15 m thick) comprising brown-green hornblende, plagioclase and intercumulate quartz, cross-cuts sequences from Freshwater Point to Half-Tide Beach (Jensen *et al.* 1966). Flow-banded, coarsely phenocrystic quartz + feldspar ± biotite dykes (e.g. GR 0742207E, 7628800N) are also relatively widespread in the Campwyn Volcanics, and show petrographic similarities to the rhyolite ignimbrites occurring in the upper facies association. Rhyolite dykes have been noted to cut mafic dykes in the rare dyke intersections observed (Jensen *et al.* 1966).

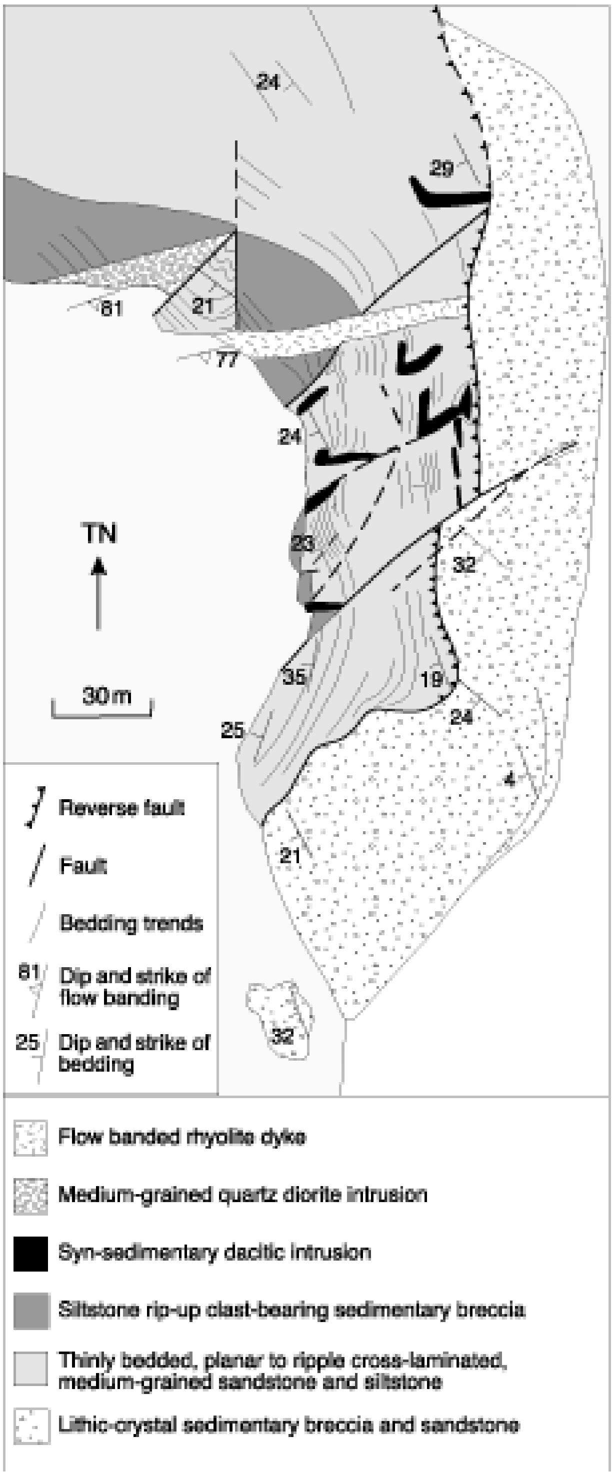


Figure 13 Geological map of Half-Tide Beach (GR 0738105E, 7642920N) showing several different intrusions cross-cut by faults and a shallow west-dipping reverse fault. Note that some northeast-trending faults control the emplacement of the syn-sedimentary intrusions.

Biostratigraphy

Biostratigraphic age control is mostly restricted to the upper facies association. A variety of fossils occurs in the limestone-rich units, including crinoids, brachiopods, rugose corals and gastropods (Jensen *et al.* 1966), as well as *Lepidodendron* sp. in sandstone units. Gastropod species *Straparollus subdionysii*, *Stegocoelia* sp. and *Meekospira* sp. have been identified, with *S. subdionysii* also occurring

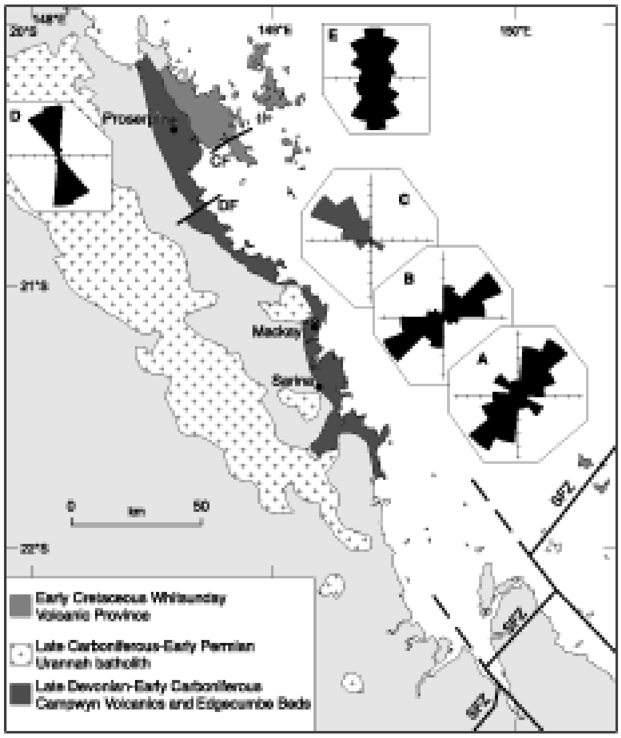


Figure 14 Dyke orientations in the Campwyn Volcanics, compared to other dyke-forming events in the northern New England Fold Belt. (a) rose diagram for all dykes intruding the Campwyn Volcanics (number of dyke measurements is 174); (b) dykes of inferred Late Devonian to Early Carboniferous age (number of dyke measurements is 41); (c) palaeocurrent data for the Campwyn Volcanics (number of measurements is 153; see Figure 15a: note the orthogonal relationship between dyke orientations and palaeocurrent directions); (d) Late Carboniferous to Early Permian dyke orientations from the Urannah Batholith (number of dykes is 602: data from Paine *et al.* 1974); (e) Early Cretaceous dykes of the Whitsunday Volcanic Province (number of dykes is 320: data from A. Ewart, R. W. Schön, C. J. Stephens & S. E. Bryan unpubl. data; Bryan 1991; Downes 1991; Ewart *et al.* 1992; ;). SFZ, Stanage Fault Zone; DF, Dempster Fault; CF, Conway Fault.

in the Tellebang Formation (correlative of the Three Moon Conglomerate: Dear *et al.* 1971) of the Yarrol terrane (Maxwell 1961), as well as the Tournaisian to Visean of the Bonaparte Basin (A. Cook unpubl. data). The taxa largely confirm an Early Carboniferous age for the limestone-bearing sections of the Campwyn Volcanics. Fossil assemblages from limestones of the correlative Edgecumbe beds to the north are middle to upper Tournaisian in age (Clarke *et al.* 1971).

The age of the boundary between the lower and upper facies associations is older than the Devonian–Carboniferous boundary based on: (i) the early to middle Tournaisian ages of limestones interbedded with ignimbrite at Notch Point Road and Midge Point – Laguna Quays (Jensen *et al.* 1966); and (ii) marine fossils indicating a Late Devonian age reported from other sections of the upper silicic facies association (Clarke *et al.* 1971).

Middle Devonian fossils have been reported from three localities in the Campwyn Volcanics. The crinoid *Melonocrinites tempestus*, known from the Middle Devonian (Givetian) of the Broken River Province to the north, has been described from Lower Carboniferous limestones at Laguna Quays (Jell 1999). The interpreted crinoid age contradicts the ages of associated gastropod fauna, and the nature of the echinoderm precludes reworking of the fossil from another older unit. A coral fauna at Campwyn Beach (GR 0740170E, 7634549N) considered to be Middle Devonian in age by Fergusson *et al.* (1994) occurs as detrital clasts that have been reworked into stratified to cross-stratified mafic volcanic-derived coarse-grained sandstones. It provides only a maximum depositional age for the unit, and the coral fauna is not diagnostic of either the Middle or Upper Devonian. A large slab of allochthonous limestone (>150 m long and 15 m thick) containing the Late Devonian corals *Alveolites* sp. and *Macgeea* sp. (but designated as Middle Devonian by Fergusson *et al.* 1994), occurs in megabreccia exposed on East Repulse Island (Simmonds & Tucker 1960). The origin of the breccia has been controversial, with the limestone interpreted to occur in coeval volcaniclastic rocks (Simmonds & Tucker 1960; Fergusson *et al.* 1994) or in Early Cretaceous volcanics (Clarke *et al.* 1971; Parianos 1993). The breccia occurs adjacent to altered and sheared rocks on South Repulse Island that represent the Repulse Fault Zone and the north-eastern boundary of the Late Cretaceous – Early Tertiary Hillsborough Basin (Parianos 1993). Thus, evidence for the age of the Campwyn Volcanics extending into the Middle Devonian remains equivocal.

Petrostratigraphy

Modal data for 22 sandstone and pebble-grade breccia/conglomerate samples from the two facies associations are shown graphically in Figure 12. All lithic grains are volcanic in composition and those containing quartz phenocrysts and/or a microcrystalline siliceous groundmass, confirming a silicic composition, are only observed in sandstones from the upper facies association. Most volcanic lithic clasts are hypocrystalline to fine-grained, weakly feldspar-phyric lavas, with trachytic or felted textures common. Formerly glassy juvenile clasts are now replaced by chlorite. Alteration of feldspar detrital grains preclude the distinction of alkali feldspar and plagioclase. Quartz grains show straight extinction and embayed/resorbed faces, indicating a volcanic origin. Quartz grains with undulatory extinction occur only in the Lamberts Beach quartz arenite.

Sandstone units from the mafic lower facies association have an average composition of $Qt_0F_6L_{94}$. Detrital mineral grains are almost entirely absent, a feature also observed in the conglomerates and sedimentary breccia units. Detrital grain compositions overlap those from sedimentary rocks of the lower Frasnian Lochenbar beds of the correlative Yarrol terrane to the south (Bryan *et al.* 2001), which are also derived from mafic lava-dominated volcanic sequences.

In contrast, framework modes for sandstones from the silicic upper facies association have mean values of $Qt_{53}F_{29}L_{18}$. Interbedded sedimentary breccias and conglomerate contain a higher proportion of volcanic lithic fragments, having a mean value of $Qt_4F_{19}L_{77}$, but are distinguishable from similar coarse-grained sedimentary facies of the lower facies association by their higher proportion of detrital crystal grains, the presence of quartz and the variety of mafic to silicic volcanic fragments. Quartz and feldspar grains in both sandstones and breccias are typically angular to subrounded, with many quartz grains showing embayed faces. Textural inversion occurs in some conglomerate beds where sand-grade crystal grains are more angular than coexisting pebble- to cobble-grade rock fragments (e.g. texturally mature conglomerate lithofacies at Laguna Quays: Figure 11). Increased rounding to crystal grains is observed in the oolitic limestones at Laguna Quays where they form nuclei to ooliths. Heavy minerals are more abundant than in lower facies association sandstones and are dominated by Fe–Ti oxides. The crystal forms (e.g. embayed faces), grainsize, angularity and presence of pumice in some sedimentary units are consistent with the detrital crystal grain population being sourced from rhyolite pyroclastic deposits, which occur interbedded with the sedimentary rocks. Detrital grain compositions of sandstones are notably more quartz-rich than similar-aged, quartz-bearing volcanogenic sandstones of the Rockhampton Group further south in the Yarrol terrane (Figure 12). The higher volcanic quartz content reflects the quartz-rich nature of the source pyroclastic material and interbedded ignimbrites contain up to 18 modal% quartz. Volcanic clast compositions are more varied than those observed in the lower facies association. Quartz–feldspar porphyry, flow-banded rhyolite, ignimbrite and minor vitric (pumice) clasts are present as are trachytic-textured, fine-grained feldspar-phyric lava clasts texturally similar to those observed in sandstones and breccias of the lower facies association.

Palaeocurrent data

The palaeocurrent data shown in Figure 15 were taken from cross-bedding, ripple cross-lamination and to a lesser extent clast imbrication, all of which are clear indicators of unidirectional current flow. Facies that showed evidence of deposition under oscillatory water waves or combined (wave–current) flow were excluded from the analysis to avoid the risk of collecting spurious data. Some facies were possibly deposited in shallow subtidal or intertidal water depths in the coastal realm, and data from these facies contribute both to the principal mode and to a minor mode at 180° to the principal mode in some rose diagrams. The palaeocurrent directions evident from these sediments are nonetheless consistent with those from other facies, so that including data from tidal facies does not confuse the overall pattern. Given the large number of data collected from localities throughout the outcrop belt, the overall strong principal mode to the northwest (Figure 15a) is considered to be a reliable proxy for the regional sediment dispersal direction in the Campwyn Volcanics.

DISCUSSION

Volcano-sedimentary evolution of the Campwyn Volcanics

The Campwyn Volcanics preserve a wide variety of volcanic and sedimentary rocks, and an intimate relationship exists between volcanism and sedimentation. Stratigraphic data presented here reveal that the Campwyn Volcanics consist of two contrasting sequences or facies associations with marked differences in terms of eruptive styles, compositions and sources. Mafic and silicic volcanic facies are stratigraphically separate. This has also resulted in contrasting sedimentation styles between the two facies associations.

MAFIC LOWER FACIES ASSOCIATION

An overall coarsening-upward trend is evident for the lower facies association. Sedimentation conditions dominated by suspension and lower flow regime/low concentration currents characterised the lowermost exposed sections of the facies association (Knobblers Point: Figure 6). However, coarse-grained sedimentary breccias dominate the lower facies association and the transition to sedimentation from flows with high sediment concentrations appears to be abrupt (Figure 6). The sedimentary breccias reflect episodic high-energy events remobilising mafic lava material and the presence of some reddened to well-rounded clasts suggest derivation in part from subaerially exposed and worked volcanic sources. Palaeocurrent data for the lower facies association are limited because of coarse grainsize and high concentration sedimentation conditions, but cross-strata from sandstone intervals and clast imbrication in the breccias consistently indicate sediment transport directions to the west and northwest (Figure 15b).

Mafic fluidal clast-bearing breccias, predominating in the middle to upper parts of the facies association, provide a more direct record of syn-eruptive sedimentation from

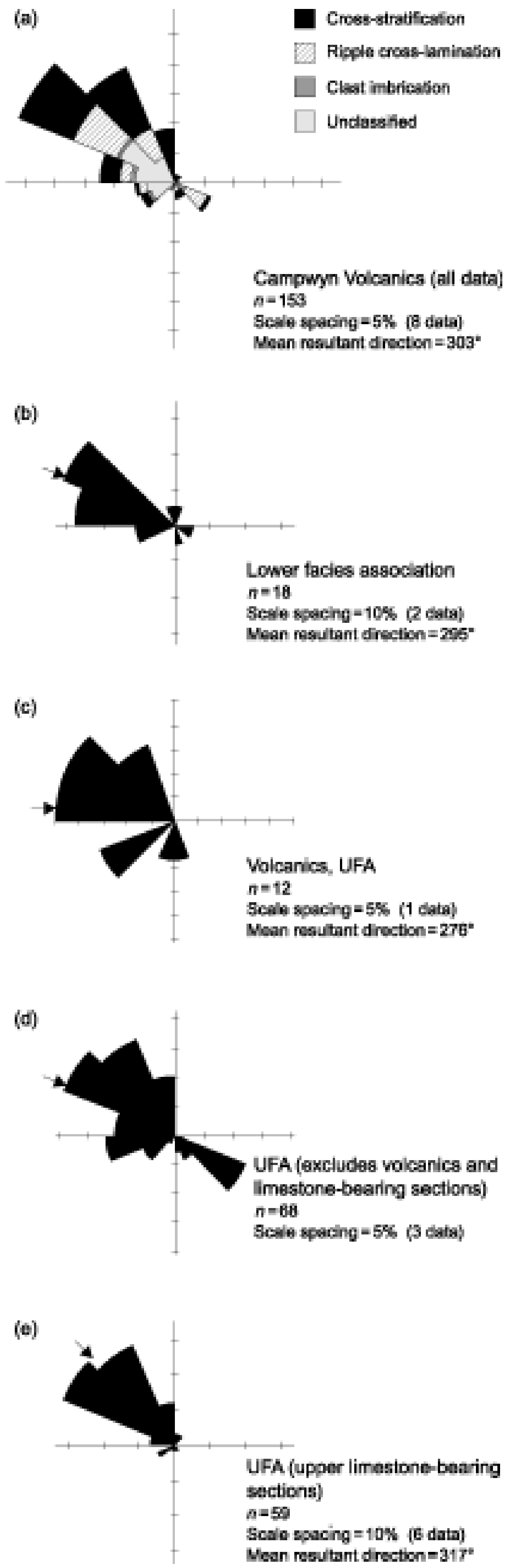


Figure 15 Palaeocurrent data for the Campwyn Volcanics. (a) All data, subdivided on the basis of bedform-type. (b) Mafic lower facies association. (c) Measurements from bedforms in pyroclastic and phreatomagmatic deposits, upper facies association (UFA). (d) UFA, but excluding data in (c) and (e). (e) Upper, limestone-bearing sequences of the UFA. *n* is number of measurements.

eruptions of mafic magma. The interpreted phreatomagmatic origin for these breccias implies that eruptions occurred in shallow-water depths or where significant volumes of water could access the vent/conduit (e.g. coastal, lacustrine environments). Primary volcanics that are basaltic to basaltic andesite in composition (e.g. hyaloclastite, lava) occur toward the upper part of the facies association and peperitic intrusions are relatively widespread. Basaltic lava and aa lava breccia (Figure 5) indicate partial emergence and the establishment of subaerial environments at the end of aggradation of the lower facies association.

LOWER TO UPPER FACIES ASSOCIATION CONTACT

The contacts between the two facies associations define a transition from predominantly subaqueously emplaced, mafic effusive volcanism and breccia-dominated sedimentation to widespread subaerial depositional conditions with silicic explosive volcanism, accompanied by sand-dominated sedimentation. Exposed contacts between the two facies associations are conformable. Basal conglomerates of the upper facies association contain some rip-up clasts and indicate only minor incision and erosion of the topmost units of the mafic lower facies association.

At Green Hill, tabular to trough-cross stratified quartz granule conglomerate (Q:F:L ratio of 49:40:11) overlying stratified monomict basaltic pebbly sandstone define the contact (Figure 4). A fine-grained, massive and indurated top to the basaltic pebbly sandstone is interpreted to represent a palaeosol, and suggests some exposure prior to emplacement of the upper facies association. Two thick welded rhyolite ignimbrite units above the contact indicate subaerial depositional environments during the early stages of the upper facies association. At Sarina Inlet, the transition is defined by basaltic lava overlain by a discontinuous and thin ($\leq$30 cm thick), silicic volcanic-dominated pebble conglomerate (Figure 5) and welded rhyolite ignimbrite.

UPPER SILICIC FACIES ASSOCIATION

Rhyolite and high-silica rhyolite welded ignimbrite dominate the lower sections of the upper facies association (Figures 4, 5). At least nine different ignimbrite-forming eruptions have been recognised in one stratigraphic section at Laguna Quays, and some ignimbrite sequences are >200 m thick (Figure 9), indicating that explosive silicic volcanism was at a maximum at this time. Phreatomagmatic eruptive phases during the silicic explosive eruptions were also commonplace as indicated by accretionary lapilli-bearing facies (base surge and/or fallout deposits) associated with many ignimbrite eruptive units. Other sections comprise subaqueously emplaced pyroclastic breccias that appear to be the deposits from pyroclastic flows that entered the sea, or from more proximal subaqueous/shallow-marine silicic explosive eruptions (e.g. Cape Palmerston, Point Victor).

Limited palaeocurrent information from phreatomagmatic units associated with the ignimbrites show more widely dispersed flow directions (south to northwest), suggesting eruptive points both within and outside the basin/depocentre (Figure 15c). However, palaeocurrent measurements from sedimentary units interbedded with the ignimbrite units show that northwest-directed sediment dispersal was re-established following silicic explosive eruptions (Figures 4, 15d). A change in detrital grain composition of associated sedimentary rocks accompanies the abrupt change in volcanic composition between the lower and upper facies associations. Clasts become dominated by silicic volcanic compositions and there is a marked increase in detrital quartz and feldspar content (Figure 12).

The upper sections of the upper facies association record the cessation of volcanism and define a transgressive sequence with the re-establishment of shallow-marine depositional environments (as indicated by presence of fossiliferous and oolitic limestone and hummocky cross-stratified sandstones). Although bipolar cross-stratification in the limestone units indicates strong tidal influences, northwest palaeocurrent directions are dominant (Figure 15e).

In contrast to the lower facies association, syn-sedimentary intrusions are less abundant and mostly silicic in composition (Table 2*). The petrographic similarity of some quartz–feldspar-phyric dykes to the pyroclastic rocks suggests that dyke intrusion may have been more widespread and coeval with silicic explosive volcanism. However, the overprint by Permo-Carboniferous and Early Cretaceous dykes makes distinguishing any Early Carboniferous dykes difficult.

Facies architecture

PROBLEMS WITH THE PREVIOUS MODEL

Key elements of the volcanic architecture interpreted by Fergusson *et al.* (1994) are that: (i) basaltic to andesitic magmatism was dominant, occurring throughout the Campwyn sedimentary basin both in space and time; (ii) proximal, multi-vent mafic volcanism was always the major contributor to sedimentation in the basin; (iii) the depositional environment was primarily a broad shallow-marine shelf, but that mafic magmatism led to the development of emergent tuff and scoria cones and larger, lava shield volcanoes comprising subaerially emplaced lava sequences and hyaloclastite-dominated ‘pedestals’; (iv) silicic volcanism was minor, but that silicic volcanics did occur interbedded throughout; (v) silicic volcanic-bearing sedimentary breccias and rhyolite ignimbrites were sourced from an interpreted supra-subduction zone arc to the west (Connors Arch); and (vi) there was restricted input of craton-derived (quartz-rich) sandstone from the west as a result of the relatively high-standing Connors volcanic arc. Consequently, the Campwyn Volcanics represented a collage of volcano-sedimentary facies with no well-defined volcanic compositional trends through the formation.

The mapping and recognition of mafic breccia and/or volcanics at *all* localities were the basis for interpreting mafic–intermediate volcanism persisting throughout aggradation of the Campwyn Volcanics. Many exposures of mafic breccia are in fact rhyolite ignimbrite (e.g. Inner

Redcliffe Island, Laguna Quays, Dudgeon Point, Slade Point), and a thick lava sequence at St Helens Beach interpreted to record the development of emergent lava shield volcanoes is a dyke/intrusive swarm (Figure 7). Accretionary lapilli-bearing units are rhyolitic in composition and interbedded with rhyolitic ignimbrites (Figure 9); they are not associated with thick sequences of mafic sandstone that can be interpreted as the remnants of tuff cone vents. Thus, the regional extent of mafic volcano-sedimentary rocks is far less than indicated previously. The recognition of two stratigraphically separate mafic and silicic facies associations in this study demonstrates that mafic magmatism was restricted in time and did not continue into the Early Carboniferous.

The Lamberts Beach quartz arenite with palaeoflow indicators to the southeast represents the only example of cratonic-derived quartz sedimentary rocks in the Campwyn Volcanics. Sandstones of this type, however, are more characteristic of Permian sandstones from the Bowen Basin. The association of the Lamberts Beach sequence with the Campwyn Volcanics must be considered suspect until the depositional age can be constrained. Sediment grain compositions of both facies associations are entirely volcanic and, in conjunction with palaeocurrent data (Figure 15), indicate that cratonic-derived material, if present, is volumetrically overwhelmed by first-cycle volcanic material being shed predominantly toward the craton.

REVISED FACIES ARCHITECTURE

The Campwyn Volcanics comprise two fundamentally distinct facies associations that record temporal changes in eruptive sources, styles and compositions, and differences in palaeogeography. These aspects are summarised below.

Water depth and depositional setting

The general lack of sedimentary structures and fossils in the lower facies association provides few constraints on water depth and depositional environment. However, shallow-marine conditions are interpreted to have prevailed for the most part. Partially emergent conditions existed during the closing stages of the lower facies association with the emplacement of basaltic lava and aa-type lava breccia.

Low-relief terrestrial tracts existed widely during the early stages of the upper facies association, when explosive silicic volcanism was at a maximum. Phases of phreatomagmatic activity characterised many silicic explosive eruptions, indicating that vents were not completely isolated from surface water. Fossiliferous limestone overlying some ignimbrites implies proximity to shallow-marine environments and phreatomagmatic activity may have been in response to explosive magma interaction with lake water (e.g. caldera lakes) or sea water. Many crystal-rich volcaniclastic breccias interbedded with finer grained, sand-dominated shallow-marine sequences record the deposits of pyroclastic flows that entered the sea. The coexistence of both subaerial and shallow-marine depositional environments during silicic explosive volcanism is thus indicated. However, the widespread re-establishment of shallow-marine environments is recorded by the limestone-dominated sections in the upper part of the facies association.

Character and environment of volcanic centres

Mostly submarine, mafic shallow intrusions and extrusive volcanism are recorded by lithofacies of the lower facies association. Mafic volcanism became localised in the Campwyn depocentre during the middle to later stages of aggradation of the lower facies association. Widely scattered hyaloclastite and peperitic intrusions indicate that no large volcanic edifices were constructed. In general, mafic volcanism was effusive, producing hyaloclastite, and at the top of the lower facies association subaerial basaltic lavas were produced. However, some mafic phreatomagmatic activity is interpreted for the generation of the fluidal clast-bearing breccias.

In contrast, magmatic explosive eruptions from large silicic vents (calderas) produced numerous densely welded, dacite to high-silica rhyolite ignimbrites at the base of the upper facies association. Petrographic and compositional differences and extensive emplacement of ignimbrite indicate derivation from multiple caldera-type vents, which are not preserved in current exposures of the Campwyn Volcanics. The moderately coarse lithic breccia facies in a few ignimbrite eruptive units most likely record a culminating phase of vent/caldera-collapse to the explosive eruptions. Some subaqueous silicic explosive eruptions are also indicated, with deposit characteristics implying a more proximal relationship to their source than for the subaerial welded ignimbrites. The Taupo Volcanic Zone (Wilson *et al.* 1984, 1995) and Santorini (Druitt *et al.* 1989) provide modern analogues to the inferred setting of calderas active during the early stages of the upper facies association. Intrusive activity persisted during aggradation of the upper facies association as recorded by minor dacitic to rhyolitic peperitic intrusions and dykes cross-cutting the sequences.

Sedimentation styles

Coarse-grained sedimentation of mafic volcanic-derived material dominated the lower facies association. The presence of both texturally immature and mature clastic material in the sedimentary breccias indicate that moderately to well-worked sediment sourced from emergent to shoreline environments was resedimented with first-cycle volcanic material. The first-cycle, coarse-grained mafic volcanic material was sourced from proximal subaerial and subaqueous lava eruptions. The occurrence of relatively abundant, mafic fluidal clasts in several breccia units suggests that some high-energy depositional events were triggered by mafic eruptions.

Sedimentation was more sand-prone during aggradation of the upper facies association and reflects the large volumes of sand-grade material (particularly feldspar and quartz) generated by numerous and widespread, silicic pyroclastic eruptions, and a low-relief subaerial depositional environment. Both fluvial and hyperconcentrated flood-flow lithofacies occur interbedded with the ignimbrites. Storm-influenced sedimentation is recorded by hummocky cross-stratified sandstones, whereas bipolar cross-stratification in several oolitic limestone beds indicate tidal-influenced sedimentation in shallow ooid shoals for the upper parts of the facies association.

TECTONIC IMPLICATIONS AND BASIN ARCHITECTURE SPECULATION

Evidence that the Campwyn Volcanics represent part of the arc and forearc assemblages (Murray *et al.* 1987; Fergusson *et al.* 1994) hinges on: (i) palaeocurrent data indicating sediment derivation from the continental arc (and craton) to the west; and (ii) the volcanic rocks representing products of the supra-subduction zone continental volcanic arc.

Palaeocurrent data along the length of exposure of the Campwyn Volcanics, and at all stratigraphic levels, indicate sediment dispersal overwhelmingly to the northwest and toward the craton (Figure 15a). Furthermore, palaeocurrent directions measured from bedforms in silicic volcanic units show no preferred dispersal from the west (Figure 15c). These observations are consistent with palaeocurrent data from the correlative Yarrol terrane, which also indicated sediment transport to the northwest (Bryan *et al.* 2001).

The facies associations reflect two contrasting volcanic architectures for the Campwyn Volcanics. The mafic lower facies association contains many lithofacies that can occur in (submerged) arc (Cas & Wright 1987) or in rifted arc and backarc settings (phase II of Fackler-Adams & Busby 1998). However, several features point to mafic volcanism and sedimentation occurring in a backarc environment. Primary volcanics form a minor component of the facies association, are widely scattered and indicate that no large volcanic edifices (e.g. stratovolcanoes) were constructed. Geochemical data (Table 2*) also reveal that andesitic compositions are lacking. Palaeocurrent data indicate that sediment was shed largely from mafic volcanic sources to the east (Figure 15b).

In contrast, the volcanic architecture for the upper facies association is most consistent with a low-relief, continental caldera system. Many of the ignimbrite eruptive units in the Campwyn Volcanics are high-silica rhyolites (>75% wt SiO_2: Table 2*), and it is seldom appreciated that high-silica rhyolites, although common in intracontinental settings, are uncommon in island and continental margin arcs (Hildreth & Fierstein 2000). For most arc volcanoes, the most important evolved product is dacite (63–68 %wt SiO_2) or rhyodacite (68–72 %wt SiO_2), which tends to be volumetrically minor, except during summit caldera-forming eruptions [e.g. 1991 Pinatubo eruption (Pallister *et al.* 1996); Mt Mazama (Bacon 1983)].

Silicic volcanics of the upper facies association correlate in age and lithology with silicic volcanism occurring elsewhere in the northern New England Fold Belt – Drummond Basin, Broken River Province, Connors Arch and Yarrol terrane (Withnall & Lang 1993; Henderson *et al.* 1998; Hutton *et al.* 1999; Bryan *et al.* 2001). Thus, a more widespread and volumetrically substantial silicic igneous province is indicated for the northern New England Fold Belt during the Late Devonian and Early Carboniferous, which was emplaced across terranes variably interpreted as backarc (Drummond Basin), foreland (Broken River Province), arc (Connors Arch) and forearc (Campwyn). The change from mafic to widespread silicic volcanism implies decreasing proximity with time to any magmatic arc occurring to the east.

The dominant northeast-strike of the inferred Late Devonian – Early Carboniferous dykes (Figure 14) is anomalous in the northern New England Fold Belt. However, this trend is parallel to a system of major lineaments that cross this part of the New England Fold Belt. These include the Stanage Fault Zone (Henderson *et al.* 1993), a major northeast-trending cross-orogen structure that controls a number of younger New England Fold Belt features (Holcombe *et al.* 1997b; Harbort 2002), and crosses the coast approximately 100 km south of the area investigated in this paper. One possibility is that the Stanage Fault Zone and other northeast-trending lineaments reflect a Late Devonian – Early Carboniferous rift architecture (Johnson & Henderson 1991).

The dyke trends are normal to the mean orientation of the low variance, northwest-trending palaeoflow data (Figure 15). One possibility is that this volcano-sedimentary system reflects a northeast-trending rift or half-graben system with an uplifted block to the southeast (as the cause for a northwest-trending palaeogradient and palaeoflow directions). The orientation of such a structure is at odds with all previously suggested basin architectures, and such a palaeogeographical reconstruction would impact on palaeogeographical interpretations of the coeval Yarrol Basin to the south. We speculate that the Yarrol (Bryan *et al.* 2001) and Campwyn successions represent separate sub-basins in a broader extensional or backarc terrane/environment. These results reinforce similar conclusions for the Yarrol terrane (Bryan *et al.* 2001), which indicate that the accretionary terranes of southern Queensland may be largely allochthonous and have been juxtaposed against backarc elements during the Hunter–Bowen Orogeny.

CONCLUSIONS

The Campwyn Volcanics are divided into lower mafic and upper silicic facies associations that record contrasting periods of volcanism and volcaniclastic sedimentation. Mafic and silicic volcanics were emplaced by different processes. Mafic magmas were emplaced widely across the Campwyn depocentre from predominantly effusive eruptions, and affected by quench fragmented processes producing proximal facies of hyaloclastite and peperitic intrusions. Some phreatomagmatic explosivity is indicated by juvenile, fluidal clast-bearing breccias. In contrast, silicic magmas were emplaced almost entirely by explosive processes involving ‘wet’ phreatomagmatic and ‘dry’ magmatic eruptions from caldera-type vents producing accretionary lapilli tuffs and welded ignimbrite. Several coarse-grained, crystal-rich volcaniclastic units are interpreted to be subaqueously emplaced, syn-eruptive deposits from pyroclastic eruptions. The Campwyn Volcanics are cut extensively by intrusions including both syn-sedimentary varieties (e.g. peperite) as well as younger suites, most likely Permo-Carboniferous (Allen 2000) and Early Cretaceous (Ewart *et al.* 1992) in age.

Associated sedimentary rocks reflect remobilisation of coeval volcanic material, and sedimentation characteristics of the two facies associations are strongly controlled by the nature of the associated volcanic deposits. Sedimentation during the lower facies association was breccia-dominated, reflecting episodic, high-energy events that remobilised coarse lava debris generated by subaerial and subaqueous eruptions. In contrast, sedimentation during the upper facies association was sand-prone and sourced largely from pyroclastic deposits, as recorded by high abundances of detrital quartz and feldspar grains that are characteristic of the interbedded ignimbrite sheets.

Shallow-marine conditions persisted throughout the majority of the period of aggradation. Emergent tracts and subaerial conditions developed at the transition between the two facies associations, but shallow-marine to coastal environments were re-established toward the end of silicic explosive eruptions. The occurrence of oolitic limestones of Early Carboniferous age indicates an extension of ooid shoal environments ~350 km to the north of the main ooid-forming areas in the Yarrol Basin (Yarrol Project Team 1997). A bipartite stratigraphy of a lower mafic-dominated volcanic and volcaniclastic sequence, and an upper, silicic volcanic and volcaniclastic sequence (including oolitic limestones) has also been recognised for the correlative Yarrol Basin to the south (Bryan *et al.* 2001). Coupled with palaeocurrent data, a shallow-marine-dominated basin system extending for >400 km along the northern New England Fold Belt is indicated, with volcaniclastic material shed overwhelmingly westwards. Volcaniclastic sedimentation was apparently due to the exclusion of cratonic sediment derived from the west. We see no evidence to support the Campwyn Volcanics having formed on the eastern forearc flank of a major supra-subduction zone magmatic arc during the Late Devonian and Early Carboniferous.

ACKNOWLEDGEMENTS

We thank Chris Stephens, John Jell and Paul Blake for constructive discussions on aspects of the manuscript. Financial support for this project was provided by an ARC Large Grant A10027005 to R. J. Holcombe and C. R. Fielding. Discussions with Gillian Adshade, who completed her honours thesis in the region, are acknowledged. Sharon Price (Queensland University of Technology), Kim Baublys and Alan Greig (University of Queensland) are thanked for major and trace-element analyses, respectively. Peter Cawood and Mark Doyle are thanked for constructive reviews that greatly improved the manuscript.

REFERENCES

Allen C. M. 2000. Evolution of a post-batholith dike swarm in central coastal Queensland, Australia: arc-front or back-arc? *Lithos* **51**, 331–349.

Allen C. M., Williams I. S., Stephens C. J. & Fielding C. R. 1998. Granite genesis and basin formation in an extensional setting: the magmatic history of the northernmost New England Orogen. *Australian Journal of Earth Sciences* **45**, 875–888.

Bacon C. R. 1983. Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, U.S.A. *In*: Aramaki S. & Kushiro I. eds. *Arc Volcanism*, pp. 57–115. Journal of Volcanology and Geothermal Research **18**.

Baker J. C., Fielding C. R., De Caritat P. & Wilkinson M. M. 1993. Permian evolution of sandstone composition in a complex back-arc extensional to foreland basin: the Bowen Basin, eastern Australia. *Journal of Sedimentary Petrology* **63**, 881–893.

Barberi F., Cioni R., Rosi M., Santacroce R., Sbrana A. & Vecci R. 1989. Magmatic and phreatomagmatic phases in explosive eruptions of Vesuvius as deduced by grain-size and component analysis of the pyroclastic deposits. *Journal of Volcanology and Geothermal Research* **38**, 287–307.

Branney M. J. & Sparks R. S. J. 1990. Fiamme formed by diagenesis and burial-compaction in soils and subaqueous sediments. *Journal of the Geological Society of London* **147**, 919–922.

Brown G. A. 1963. Progress report on the geology of the Proserpine area, Qld, ATP 94P (surface geology). *Geological Survey of Queensland Authority Report* **1295** (unpubl.).

Bryan S. E. 1991. Geology and geochemistry of the southern Molle Group, the Whitsundays, northeast Queensland. BSc (Hons) thesis, University of Queensland, Brisbane (unpubl.).

Bryan S. E., Cas R. A. F. & Martí J. 1998. Lithic breccias in intermediate volume phonolitic ignimbrites, Tenerife (Canary Islands): constraints on pyroclastic flow depositional processes. *Journal of Volcanology and Geothermal Research* **81**, 269–296.

Bryan S. E., Ewart A., Stephens C. J., Parianos J. & Downes P. J. 2000. The Whitsunday Volcanic Province, central Queensland, Australia: lithological and stratigraphic investigations of a silicic-dominated large igneous province. *Journal of Volcanology and Geothermal Research* **99**, 55–78.

Bryan S. E., Holcombe R. J. & Fielding C. R. 2001. The Yarrol terrane of the northern New England Fold Belt: forearc or backarc? *Australian Journal of Earth Sciences* **48**, 293–316.

Cas R., Moore C. & Scutter C. 1996. Fragmentation processes and water depth significance of Miocene submarine fire fountain deposits, Ryugazaki, Hokkaido, Japan. Western Pacific Geophysics Meeting. *EOS* **77**, W126.

Cas R. A. F. & Wright J. V. 1987. *Volcanic Successions, Modern and Ancient*. Unwin-Hyman, London.

Clarke D. E., Paine A. G. L. & Jensen A. R. 1971. Geology of the Proserpine 1:250 000 Sheet area, Queensland. *Bureau of Mineral Resources Report* **144**.

Day R. W., Murray C. G. & Whitaker W. G. 1978. The eastern part of the Tasman Orogenic Zone. *Tectonophysics* **48**, 327–364.

Dear J. F., McKellar R. G. & Tucker R. M. 1971. Geology of the Monto 1:250 000 sheet area. *Geological Survey of Queensland Report* **46**.

Dickenson W. R., Beard L. S., Brakenridge G. R., Erjavec J. L., Ferguson R. C., Inman K. F., Knepp R. A., Lindberg F. A. & Ryberg P. T. 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin* **94**, 222–235.

Downes P. J. 1991. Geology and geochemistry of Lindeman and Little Lindeman Islands, northeast Queensland. BSc (Hons) thesis, University of Queensland, Brisbane (unpubl.).

Druitt T. H., Mellors R. A., Pyle D. A. & Sparks R. S. J. 1989. Explosive volcanism on Santorini, Greece. *Geological Magazine* **126**, 95–126.

Ewart A., Schön R. W. & Chappell B. W. 1992. The Cretaceous volcanic–plutonic province of the central Queensland (Australia) coast—a rift related 'calc-alkaline' province. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 327–345.

Fackler-Adams B. N. & Busby C. J. 1998. Structural and stratigraphic evolution of extensional oceanic arcs. *Geology* **26**, 735–738.

Fergusson C. L. 1991. Thin-skinned thrusting in the northern New England Orogen, central Queensland, Australia. *Tectonics* **10**, 797–806.

Fergusson C. L., Henderson R. A. & Wright J. V. 1994. Facies in a Devonian–Carboniferous volcanic forearc succession, Campwyn Volcanics, Mackay district, central Queensland. *Australian Journal of Earth Sciences* **41**, 287–300.

Fielding C. R., Stephens C. J. & Holcombe R. J. 1997. Permian stratigraphy and palaeogeography of the eastern Bowen Basin, Gogango Overfolded Zone and Strathmuir Synclinorium in the Rockhampton–Mackay region of Central Queensland. *Geological Society of Australia Special Publication* **19**, 80–95.

Folk R. L., Andrews P. B. & Lewis D. W. 1970. Detrital sedimentary rock classification and nomenclature for use in New Zealand. *New Zealand Journal of Geology and Geophysics* **13**, 947–968.

Harbort T. A. 2002. Structure and tectonic synthesis of the Marlborough Block, northern New England Fold Belt, Australia. PhD thesis, University of Queensland, Brisbane (unpubl.).

Henderson R. A., Davis B. K. & Fanning C. M. 1998. Stratigraphy, age relationships and tectonic setting of rift-phase infill in the Drummond Basin, central Queensland. *Australian Journal of Earth Sciences* **45**, 579–595.

Henderson R. A., Fergusson C. L., Leitch E. C., Morand V. J., Reinhart J. J. & Carr P. F. 1993. Tectonics of the Northern New England Fold Belt. *In*: Flood P. G. & Aitchison J. C. eds. *New England Orogen, eastern Australia*, pp. 505–515. Department of Geology and Geophysics, University of New England, Armidale.

Hildreth W. & Fierstein J. 2000. Katmai volcanic cluster and the great eruption of 1912. *Geological Society of America Bulletin* **112**, 1594–1620.

Holcombe R. J., Stephens C. J., Fielding C. R., Gust D. A., Little T. A., Sliwa R., Kassan J., McPhie J. & Ewart A. 1997b. Tectonic evolution of the Northern New England Fold Belt: the Permian–Triassic Hunter–Bowen event. *Geological Society of Australia Special Publication* **19**, 52–65.

Holcombe R. J., Stephens C. J., Fielding C. R., Gust D. A., Little T. A., Sliwa R., McPhie J. & Ewart A. 1997a. Tectonic evolution of the northern New England Fold Belt: Carboniferous to Early Permian transition from accretion to extension. *Geological Society of Australia Special Publication* **19**, 66–79.

Hutton L. J., Grimes K. G. & Law S. R. & McLennan T. P. T. 1998. *Queensland 1:250 000 Geological Series, Explanatory Notes: Mount Coolon.* Geological Survey of Queensland, Brisbane.

Hutton L. J., Withnall I. W., Rienks I. P., Bultitude R. J., Hayward M. A., Von Gneilinski F. E., Fordham B. G. & Simpson G. A. 1999. A preliminary Carboniferous to Permian magmatic framework for the Auburn–Connors Arches, central Queensland. *In*: Flood P. G. eds. *New England Orogen*, pp. 223–232. Division of Earth Sciences, University of New England, Armidale.

Jagodzinski E. A. 2000. The Turondale formation, Hill End Trough, NSW: facies interpretation and palaeogeography. *Geological Society of Australia Abstracts* **59**, 249.

Jell P. A. 1999. The crinoid *Melanocrinites tempestus* in the Devonian Campwyn Beds on the shore of Repulse Bay, south of Proserpine. *Memoirs of the Queensland Museum* **43**, 352.

Jensen A. R., Gregory C. M. & Forbes V. R. 1966. Geology of the Mackay 1:250 000 sheet area. *Bureau of Mineral Resources Report* **104**.

Johnson S. E. & Henderson R. A. 1991. Tectonic development of the Drummond Basin, eastern Australia: back-arc extension and inversion in a Late Palaeozoic active margin setting. *Basin Research* **3**, 197–213.

Kokelaar P. & Koniger S. 2000. Marine emplacement of welded ignimbrite; the Ordovician Pitts Head Tuff, North Wales. *Journal of the Geological Society of London* **157**, 517–536.

Leitch E. C. 1974. The geological development of the southern part of the New England Fold Belt. *Journal of the Geological Society of Australia* **21**, 133–156.

MacDonald G. A. 1953. Pahoehoe, aa, and block lava. *American Journal of Science* **251**, 169–191.

McPhie J., Doyle M. & Allen R. 1993. *Volcanic Textures: a Guide to the Interpretation of Textures in Volcanic Rocks*. Centre for Ore Deposit and Exploration Studies. University of Tasmania, Hobart.

Maxwell W. G. H. 1961. Lower Carboniferous brachiopod faunas from Old Cannindah, Queensland. *Journal of Paleontology* **35**, 82–103.

Mellors R. A. & Sparks R. S. J. 1991. Spatter-rich pyroclastic flow deposits on Santorini, Greece. *Bulletin of Volcanology* **53**, 327–342.

Moffitt C. A. 2000. The volcano-sedimentary stratigraphy of the Campwyn Volcanics at Green Hill and Cape Palmerston. BSc (Hons) thesis, University of Queensland, Brisbane (unpubl.).

Murray C. G., Fergusson C. L., Flood P. G., Whitaker W. G. & Korsch R. J. 1987. Plate tectonic model for the Carboniferous evolution of the New England Fold Belt. *Australian Journal of Earth Sciences* **34**, 213–236.

Oversby B. S., Mackenzie D. E., McPhie J., Law S. R. & Wyborn D. 1994. The Geology of Palaeozoic volcanic and associated rocks in the Burdekin Falls Dam – 'Conway' area, northeastern Queensland. *Australian Geological Survey Organisation Record* **1994/21**.

Paine A. G. L., Clarke D. E. & Gregory C. M. 1974. Geology of the northern half of the Bowen 1:250 000 sheet area, Queensland (with additions to the geology of the southern half). *Bureau of Mineral Resources Report* **145**.

Pallister J. S., Hoblitt R. P., Meeker G. P., Knight R. J. & Siems D. F. 1996. Magma mixing at Mount Pinatubo: petrographic and chemical evidence from the 1991 deposits. *In*: Newhall C. G. & Punongbayan R. S. eds. *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*, pp. 687–731. University of Washington Press, Seattle.

Parianos J. 1993. Carboniferous to Tertiary Geology of the Airlie Block. MSc thesis, University of Queensland, Brisbane (unpubl.).

Simmonds N. A. H. & Tucker R. M. 1960. Limestone inspection—Repulse Islands. *Queensland Government Mining Journal* **61**, 23–25.

Simpson K. & McPhie J. 2001. Fluidal-clast breccia generated by submarine fire fountaining, Trooper Creek Formation, Queensland, Australia. *Journal of Volcanology and Geothermal Research* **109**, 339–355.

Smith G. A. 1986. Coarse-grained nonmarine volcaniclastic sediment: terminology and depositional process. *Geological Society of America Bulletin* **97**, 1–10.

Stephenson P. J. 1990. Some aspects of dyke emplacement and characteristics in the Townsville–Ingham District, North Queensland, Australia. *In*: Parker A. J., Rickwood P. C. & Tucker D. H. eds. *Mafic Dykes and Emplacement Mechanisms: Proceedings of the 2nd International Dyke Conference*, pp. 421–430. A. A. Balkema, Rotterdam.

Torres R. C., Self S. & Punongbayan R. S. 1995. Attention focuses on Taal; Decade volcano of the Philippines. *EOS* **76**, 246–248.

Walker G. P. L. 1971. Compound and simple lava flows and flood basalts. *Bulletin of Volcanology* **35**, 579–590.

Walker G. P. L. 1983. Ignimbrite types and ignimbrite problems. *Journal of Volcanology and Geothermal Research* **17**, 65–88.

Walker G. P. L. 1992. Morphometric study of pillow-size spectrum among pillow lavas. *Bulletin of Volcanology* **54**, 459–474.

White J. D. L., McPhie J. & Skilling I. 2000. Peperite: a useful genetic term. *Bulletin of Volcanology* **62**, 65–66.

Wilson C. J. N., Houghton B. F., McWilliams M. O., Lanphere M. A., Weaver S. D. & Briggs R. D. 1995. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. *Journal of Volcanology and Geothermal Research* **68**, 1–28.

Wilson C. J. N., Rogan A. M., Smith I. E. M., Northey D. J., Nairn I. A. & Houghton B. F. 1984. Caldera volcanoes of the Taupo Volcanic Zone, New Zealand. *Journal of Geophysical Research* **89**, 8463–8484.

Withnall I. W. & Lang S. C. (Editors) 1993. Geology of the Broken River Province, North Queensland. *Queensland Geology* **4**.

Yamagishi H. 1991. Morphological features of Miocene submarine coherent lavas from the 'Green Tuff' basins: examples from basaltic and andesitic rocks from the Shimokita Peninsula, northern Japan. *Bulletin of Volcanology* **53**, 173–181.

Yarrol Project Team 1997. New insights into the geology of the northern New England Orogen in the Rockhampton–Monto region, central coastal Queensland: progress report on the Yarrol Project. *Queensland Government Mining Journal* **98**, 11–26.

Received 15 April 2002; accepted 23 January 2003

SUPPLEMENTARY PAPERS

Table 1 Textural and petrographic characteristics of hyaloclastite units in the Campwyn Volcanics.

Table 2 Selected whole-rock chemical analyses of volcanic rocks from the Campwyn Volcanics. Major element oxides have been normalised to 100% on an LOI-free basis with all Fe as Fe_2O_3. Major element oxides were determined by the atomic absorption method of silicate rock analysis using Inductively Coupled Plasma – Atomic Emission Spectroscopy (ICP-AES), and trace and rare-earth elements were analysed by Inductively Coupled Plasma – Mass Spectrometry (ICP-MS).

Table 3 Textural and petrographic characteristics of syn-sedimentary intrusions of the Campwyn Volcanics.

Table 4 Deposit characteristics of syn-eruptive sedimentary lithofacies from the silicic upper facies associatin.

Table 5 Deposit characteristics of epiclastic sedimentary lithofacies from the silicic upper facies association.