(4) Whether arc or backarc, the closest modern analogues of the Monal volcanic facies association are volcanics from intra-oceanic arcs and backarc basins, not from continental settings.

(5) The Bindawalla Stratigraphic Assemblage was deposited in a basin that deepened to the east everywhere, making transport of volcanic detritus across this basin from an eastern source impossible.

(6) Similarities between the Yarrol terrane and the Tamworth Belt support a common tectonic model based on the existence of an Early Carboniferous volcanic chain to the west shedding detritus eastwards.

(7) Upper Carboniferous to Lower Permian mafic volcanics of the Connors–Auburn Arch have strong subduction-related signatures, indicating that an arc was definitely developed at this time.

(8) A forearc basin setting for the Rockhampton Group is confirmed by the direct provenance linkage across the Yarrol Fault for dispersed ooids in sandstones of the accretionary wedge.

Acknowledgements

The accretionary wedge – forearc basin – arc model for the New England Orogen is based on the work of many geologists, some of whom are referenced in this discussion. We thank Tony Crawford for discussions on the complexities of arc versus backarc volcanics, but emphasise that any errors or misconceptions are our responsibility alone. Useful comments were provided by reviewer Peter Cawood. The figures were drawn by Lesley Blight and Tom Moore. Chemical analyses were carried out by the Government Chemical Laboratory, Queensland Health, under the supervision of Henry Olszowy. This discussion is published with the approval of the Director General, Department of Natural Resources and Mines, Queensland.

REPLY

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Introduction

We questioned the 'classical' forearc model for the Yarrol Basin of the northern New England Fold Belt in Bryan *et al.* (2001) on the basis of geochemical, stratigraphic and sedimentological data. Murray *et al.* dismiss the possibility of the Yarrol Basin developing initially as a backarc basin in the Middle to Late Devonian. This dismissal is not supported by significant new information and largely reiterates old concepts and work, with the belief that the previous model was built on such a strong database that it is unassailable (a 'cornerstone').

We address four key issues raised in their discussion: (i) the 'classic' convergent continental margin model for the New England Fold Belt; (ii) the interpretation of calc-alkaline/'arc' signatures and tectonic affinities of Middle Devonian to Early Permian magmatism; (iii) volcanogenic sedimentation sourced from a volcanic arc to the west of the basin; and (iv) palaeogeography and an apparent deepening of the basin from west to east.

Convergent continental margin model

We have no disagreement with aspects of the model and currently accept that a westwardly convergent accretionary complex of Late Devonian to Early Carboniferous age existed. However, the model should be questioned for the following reasons: (i) data for the Late Devonian – Early Carboniferous arc, forearc basin, backarc basin tectonic elements are sparse; (ii) modern geochronological and geochemical analyses have eliminated the original candidates for the nominated arc rocks entrenched within the model; (iii) there is limited understanding of which basinal and tectonic elements are related to westward convergence, and which may be far-field responses (e.g. to a central Australian orogeny); and (iv) its basis has never been properly documented in peer-reviewed literature.

The references cited by Murray *et al.* are a fair sample of the available database on which the previous New England Fold Belt model is based. Of the 48 references related to the New England Fold Belt cited by Murray *et al.*, 22 are pre-1975 and only eight (including the paper being discussed) are peer-reviewed publications on the northern New England Fold Belt. Of those 22 pre-1975 publications, not one is from a peer-reviewed source and nine are pre-1965. Eleven citations are of data from Honours theses. Our experience has shown that Honours theses do not necessarily provide reliable data (for example, one of the palaeoflow citations used by Murray *et al.* was found on subsequent field checking to be 180° in error). In the past quarter century, earth science has undergone major changes in virtually all fields, particularly those of sedimentology, structural geology, volcanology/igneous geology and geochronology on which the 'cornerstone' was built. In addition, there have been major advances in the understanding of both the neighbouring Lachlan Fold Belt and central Australian orogens. Consequently, the model, and Murray *et al.*, over rely on field data collected and interpreted either by Honours students or by professionals constrained by the limitations of an earlier era.

Mid-Devonian magmatism

The older Calliope terrane was not the focus of our paper, although there are interpretations raised by Murray *et al.* that we believe to be false (e.g. the Mt Morgan sequences formed in a volcanic arc), and will continue to cloud northern New England Fold Belt literature. We re-state here, the key conclusions of Messenger (1996) and reconfirmed by him (P. R. Messenger pers. comm. 2002).

(1) The Mt Morgan volcano-plutonic suite is weakly bimodal, being dominated by low-Al + K trondhjemite and rhyolitic volcanics. Mafic compositions (basalt, basaltic andesite, quartz gabbro) are subordinate and andesite is rare (all restricted to minor cross-cutting intrusives). The suite differs from geochemically similar southwest Pacific island arc suites by being silicic dominated (Figure 4a).

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(2) The trace-element geochemistry, petrography and mineralogy are similar to suites from immature continental margin (e.g. western Peninsular Ranges Batholith) and oceanic island arc (e.g. Tonga–Kermadec, Izu–Bonin) settings, as well as felsic volcanism in backarc basins (e.g. Manus Basin). The geochemistry cannot be unambiguously interpreted as reflecting supra-subduction zone arc volcanism.

(3) Isotopic data and geochemical modelling are most consistent with silicic magmas formed by a two-stage process involving low-pressure partial melting of depleted mafic meta-igneous crust with superimposed fractional crystallisation.

TECTONIC SETTING OF MIDDLE DEVONIAN SILICIC MAGMATISM

Messenger (1996 p. 228–232) never concluded that Mid-Devonian volcanism at Mt Morgan occurred at an island arc floored by oceanic crust detached from, and exotic to, the continental margin. The silicic-dominated, Middle Devonian magmatism of Mt Morgan and correlative units are extension-related (Messenger 1996). By drawing analogy to the modern Izu–Bonin arc, where rifting began at 2 Ma (Taylor 1992), Murray *et al.* reinforce this interpretation, which is consistent with Phase 1 of the Fackler-Adams and Busby (1998) model. However, the geochemical data of Messenger (1996) cannot distinguish between extension and rifting of the arc (analogous to Izu–Bonin) or magmatism occurring more inboard, in a backarc environment.

Middle Devonian magmatism in the northern New England Fold Belt must be placed in a regional context, which Murray *et al.* have not done. Intermediate to silicic magmatism of the same age is also preserved ~350 km to the west in the Anakie Inlier (Retreat Batholith—most compositions are ≥60 wt% SiO_2 anhydrous basis: see Withnall *et al.* 1995). Recent studies by Murray *et al.* do not support a subduction-related origin for the Retreat Batholith, and instead interpret it as the product of crustal melting in a setting similar to the Tertiary Basin and Range Province of western USA (Withnall *et al.* 1995 p. 93).

The assertion that the model of Fackler-Adams and Busby (1998) refers only to extensional 'oceanic arcs' is false; the paper is based on the Early Cretaceous 'Alisitos arc' of the Baja California Peninsula that formed at the continental margin ('fringing island arc' of phase two of Busby *et al.* 1998). Extension and rifting of volcanic arcs sited either at continental margins or on oceanic crust will tend to show a two-phase evolution of: (i) an intermediate to silicic composition, explosive volcanic phase resulting in caldera-forming eruptions; followed by (ii) a mafic-dominated, effusive volcanic phase recording rifting of the arc and inception of the backarc basin (C. J. Busby pers. comm. 2002 has confirmed this statement). Murray *et al.* miss the point here: the first stage of intermediate to silicic composition, predominantly explosive volcanism, reflects partial melting during extension of continental crust (that may vary from basaltic to silicic in composition), or more primitive (basalt to andesite) arc igneous basement in the case of oceanic island arcs (Tamura & Tatsumi 2002). As an example of the first phase of this model, the Taupo Volcanic

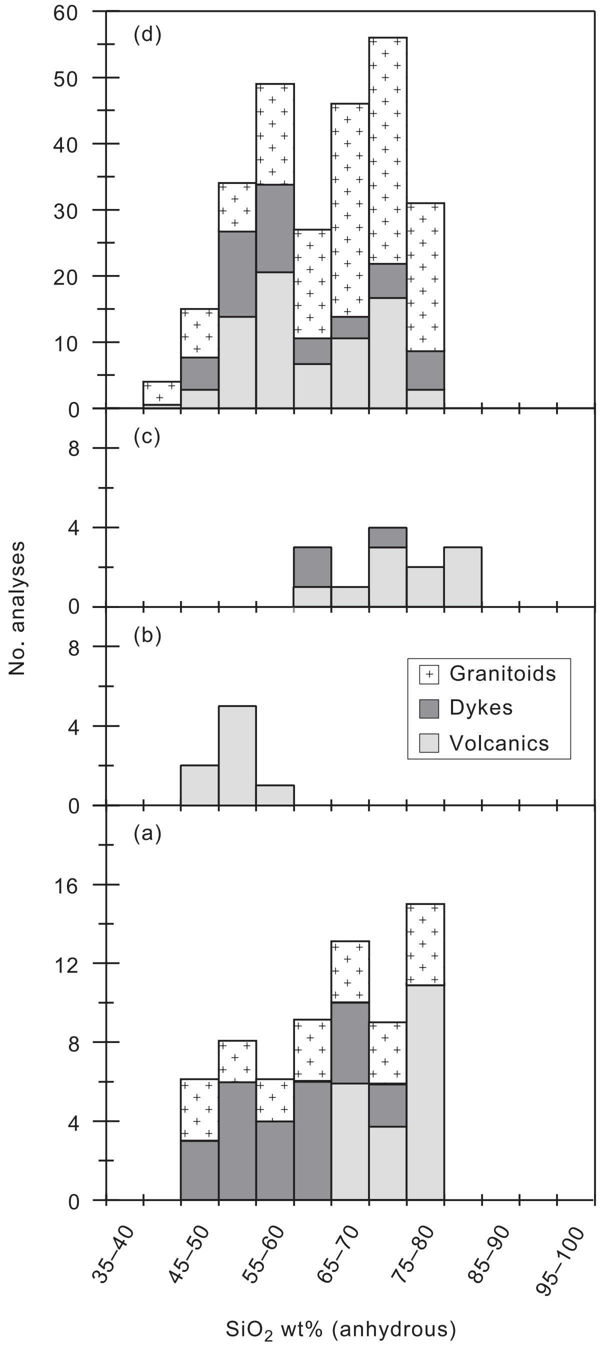

Figure 4 SiO_2 histograms of Devonian to Permian volcano-plutonic rocks of the northern New England Fold Belt. (a) Middle Devonian Capella Creek Group volcanic rocks associated with sedimentation and hosting mineralisation are silicic-dominated, whereas cross-cutting dykes and the Mt Morgan Trondhjemite suite are mafic to silicic in composition (data from Messenger 1996). (b) The early Late Devonian and overwhelmingly basaltic/basaltic andesite Monal volcanic facies association (data from Bryan *et al.* 2001). (c) Late Devonian to Early Carboniferous Campwyn Volcanics (upper facies association of Bryan *et al.* in press), with high-silica rhyolite (ignimbrite) compositions predominant (data from Moffitt 2000; Bryan *et al.* in press). (d) Permo-Carboniferous igneous compositions from the Connors–Auburn Arch showing bimodal volcanic and silicic-dominated granitoid compositions (data from Jones 2002; Allen 2000; C. M. Allen unpubl. data).

Zone represents the youngest (≤1.6 Ma) and most southward expression of backarc to arc rifting in the Taupo–Hikurangi arc–trench system (Cole 1990; Wilson *et al.* 1995). It is an exceptionally active area of young volcanism (≥90% is rhyolitic), heat flow and tectonism accompanying rapid extension of continental crust (Stern 1985; Wilson *et al.* 1995).

NATURE OF CRUSTAL BASEMENT TO MT MORGAN/CALLIOPE TERRANE

Murray *et al.* argue that Mt Morgan magmatism was sited on exotic oceanic crust of unknown age and affinity, and formed above a subduction zone to form an island arc. They disagree with many authors who interpret Mt Morgan and the Calliope terrane to have formed at the continental margin (Henderson *et al.* 1993; Morand 1993a, b; Messenger 1996; Bryan *et al.* 2001; Ulrich *et al.* 2001). Implications of their discussion are that crustal maturity reflects crustal thickness, and that low-K magma compositions are restricted to oceanic settings.

Increasing evidence exists for the basement to Mt Morgan to include continental material: (i) Messenger (1996) reported 450 Ma inherited zircons in the Mt Morgan tonalite (minimum emplacement age is 372.1 ± 1 Ma, Ar–Ar hornblende: Golding *et al.* 1994); and (ii) recently acquired Pb isotope data for the Mt Morgan igneous suite indicate contamination of a MORB-like mantle source component with material that has a substantially higher $^{207}Pb/^{206}Pb$ ratio, with contamination being most significant for the associated rhyolite volcanics (Capella Creek Group: Ulrich *et al.* 2001, 2002). The elevated Pb ratio of the contaminant requires isolation for at least one billion years, only possible in continental crust. Such data are not consistent with the Calliope terrane forming in an intra-oceanic setting and exotic to the eastern Australian continent in the Devonian. At the very least, the data imply some continental basement and involvement of continental crust in rhyolite petrogenesis.

PETROGENESIS OF MIDDLE DEVONIAN MAGMAS

A key point is why silicic magmatism was so volumetrically dominant during the Middle Devonian (Figure 4a). Murray *et al.* ignore the results of Messenger (1996) who showed that the data are most consistent with the silicic magmas forming mostly by partial melting of meta-igneous, depleted MORB-like crust with superimposed fractional crystallisation and crustal assimilation in light of the Pb isotope data (Ulrich *et al.* 2002). This was central to the thesis of Messenger (1996) and his petrogenetic model for the genesis of Cu–Au VMS deposits in which the source rocks for magmas were mafic in character.

Supporting the case for Mt Morgan magmatism to be largely derived from basement composed mostly of basaltic crust is the recent isotopic and geochemical study of the nearby Marlborough Ophiolite (Bruce *et al.* 2000). The Marlborough Ophiolite is a thrust-emplaced section of *ca* 560 Ma MORB crust, and suggests that the eastern portions of the New England Fold Belt formed on old relict oceanic crust (Bruce *et al.* 2000).

The reference to the paper of Roberts and Clemens (1993) by Bryan *et al.* (2001) has been misunderstood and taken out of context. We went to considerable length to illustrate the high-SiO_2 and low-K_2O nature of the Mt Morgan Trondhjemite suite and a granitic clast from the Lochenbar beds (Bryan *et al.* 2001 pp. 309–310). Our reference to the Mt Morgan Trondhjemite suite being similar to other 'calc-alkaline' intrusives was in relation to commonly used trace-element discrimination diagrams (Bryan *et al.* 2001 figure 16). Many crust-derived granitoid suites plot in volcanic arc granitoid fields, the result of the nature of source materials rather than tectonic processes operating during magma emplacement (Arculus 1987; Roberts & Clemens 1993). Thus, such diagrams have little meaning and the interpretation of an arc setting for magmatism is ambiguous at best. An independent establishment of an arc setting is required, something Murray *et al.* have failed to do.

Murray *et al.* have clearly missed the point of both our paper and that of Roberts and Clemens (1993), with the latter directed specifically at the issues involved here: interpretation of calc-alkaline signatures (in low- to high-K igneous compositions, especially from ancient igneous sequences) without consideration of magma source materials will result in misleading tectonic interpretations. The work of Roberts and Clemens (1993 p. 828) was not exclusive to high-K igneous compositions and noted that partial melts of basaltic amphibolites are compositionally similar to trondhjemites and calc-alkaline dacites and rhyolites, an important point in the generation of lower-K, silicic, calc-alkaline rocks. Partial melting processes are considered a more efficient mechanism for tonalite–trondhjemite–dacite production, in which low-Al compositions represent low-pressure partial melts of a basaltic source (Drummond & Defant 1990; Drummond *et al.* 1996).

EVIDENCE FOR DOCKING AT THE END OF THE MIDDLE DEVONIAN

Evidence for a collisional event (docking of the 'exotic oceanic island arc' Calliope terrane) has hinged on intra-Devonian unconformities, with the latest Givetian unconformity occurring in the Mt Morgan area (Kirkegaard *et al.* 1970; Leitch *et al.* 1992; Hayward *et al.* 1998) the best recognised. The regional significance of a Middle–Late Devonian disconformity-producing event is also indicated by: (i) a Givetian hiatus occurring at the base of the Bundock Creek Group in the Broken River Province (Lang 1993; Withnall & Lang 1993), where it accompanies a major change from marine to terrestrial conditions; (ii) syntectonic granitoids indicating a Late Devonian event, probably starting in the Famennian in the Hodgkinson Province of north Queensland (Zucchetto *et al.* 1999); and (iii) a poorly constrained Late Devonian disconformity occurring in the Anakie area (Withnall *et al.* 1995).

Two questions are then relevant: (i) does the unconformity reflect crustal contraction rather than crustal extension; and (ii) if contractional, was west-verging deformation from the east or east-vergent deformation from more westerly sources the driving force for any crustal tilting?

Crustal contraction or extension as cause for unconformity

We strongly refute the proposition that disconformities/unconformities necessarily imply contraction. Middle to Late Devonian discordances, where observed or inferred by us, appear to be minor. Morand (1993b) also emphasised the subdued nature of the regional discordance across the widely cited unconformity in the Mt Morgan area, except in the vicinity of the Mt Morgan Tonalite in which discordances up to 50° occur. Simple tilt unconformities can arise from a number of tectonic processes, including simple basin-forming events. The 'cornerstone' model was erected at a time when the contractional 'orogenic' origin of simple tilt unconformities was unduly emphasised. At that time, very little was known about extensional tectonics, particularly the degree of discordance that can be produced by extensional structures. We now recognise much larger discordances related to extensional core complex geometry in southeastern Queensland (Little *et al.* 1993). For example, the map-scale unconformities that occur along much of the Upper Carboniferous – Lower Permian boundaries in the Yarrol terrane are considerably more obvious than those ascribed here to the Middle–Upper Devonian. These unconformities correspond to the early extensional regime of the Bowen Basin (Fielding *et al.* 1997, 2000) rather than to any contractional orogenic regime.

Murray *et al.* cite an observation of Middle Devonian cleaved rocks juxtaposed against Upper Devonian uncleaved, finer grained rocks, as further evidence not only of the unconformity, but of a cleavage-forming deformational event in the Middle to Late Devonian. The finding of an older cleavage revives one of the early lynchpins of the 'cornerstone' model, and specifically the one on which the original 'docking' of a Devonian Calliope terrane was based. That is, the occurrence of cleavage in the Calliope terrane rocks (Calliope beds, Mt Holly beds) and not in rocks of the overlying and adjacent Yarrol terrane, indicated a Devonian orogenic event (Kirkegaard *et al.* 1970). Not cited by Murray *et al.* was the thorough refutation of that lynchpin by Morand (1993b), who showed that variable cleavage occurrence was the result of strain partitioning during the Hunter–Bowen Orogeny and that there was no evidence of an earlier cleavage-forming event. Our own observations support Morand's regional conclusion. Thus, the cleavage observation by Murray *et al.* appears to be of only local significance. The lack of information on the geometry of the site precludes any interpretation of the nature of the boundary that 'juxtapose' the two rocks. We point out that there are examples elsewhere in the New England Fold Belt in which extensional faulting has juxtaposed rocks with a syn-extensional fabric against overlying younger rocks showing no such fabrics (Little *et al.* 1992, 1993). Another example is figure 8 of Morand (1993b), which illustrates a thrust fault boundary between older, cleaved and younger, uncleaved beds that was originally interpreted by Kirkegaard *et al.* (1970) as an unconformity. Until Murray *et al.* describe the precise boundary relationship, their observation is of little value to the current debate.

East- or west-vergent deformation

Even if crustal contraction can be shown, is it related to west-vergent convergence tectonics or to east-vergent, far-field responses to much stronger central Australian events? Deformational effects in the New England Fold Belt arising from this latter orogen have been largely ignored in the literature. Late Devonian – Carboniferous subduction-related, west-vergent contractional deformation is not under dispute for the accretionary complexes of the New England Fold Belt. However, seismic data and interpretation indicate that strongly east-vergent, major thrusts occur below the Early Permian unconformity in the Dennison Trough (Tuesley 2000). These structures may correlate with Early to mid-Carboniferous unconformities in the Drummond Basin, an interval that has no contractional signature in the Yarrol terrane. The vergence and the westerly increasing intensity suggests that central Australian events may be the driving forces for some of the structures in the Drummond Basin at least. Thus, we have at least two possible convergent scenarios for intra-Devonian unconformities, as well as extensional basin possibilities. Based on available data, neither we, nor Murray *et al.*, currently have sufficient evidence to separate these alternative scenarios.

Middle–Late Devonian mafic magmatism: the Monal volcanic facies association and base of the Bindawalla Stratigraphic Assemblage

We refute the arguments of Murray *et al.* that: (i) the Monal volcanic facies association must be Middle Devonian or older and related to the Capella Creek Group; and (ii) the Monal volcanic facies association geochemistry is most similar to island arc tholeiites, and not to backarc basin-forming volcanism as interpreted by Bryan *et al.* (2001).

RELATIONSHIP OF MONAL VOLCANIC FACIES ASSOCIATION TO THE BINDAWALLA STRATIGRAPHIC ASSEMBLAGE

We accept that the study of Bryan *et al.* (2001) is of a restricted area. However, the Cania–Monal area is one of only very few regional windows into the basal part of the Yarrol Basin in which stratigraphic relationships are relatively intact. We argue that stratigraphic contacts and lithological and petrological/geochemical similarities do support the Monal volcanic facies association occurring at the base of the Bindawalla Stratigraphic Assemblage.

Contacts between the Monal volcanic facies association and Lochenbar beds vary from being conformable to locally unconformable and faulted. Conformable contacts were described from Dooloo Creek (Bryan *et al.* 2001 pp. 299, 303; figure 4). Furthermore, there is no significant difference in bedding orientations between the Monal volcanic facies association (27° to 264°; GR 0294220 mE, 7308148 mN) and overlying sedimentary rocks (ranging from 26° to 230° to 37° to 260°) exposed in Callide Creek (Bryan *et al.* 2001 figure 5) to argue an unconformable relationship.

The lithological contrast between the Monal volcanic facies association and Capella Creek Group could not be more striking, providing no basis for a correlation. The Monal volcanic facies association consists entirely of a

>200 m-thick sequence of basaltic to basaltic andesite pillow lava, hyaloclastite and associated resedimented facies. In contrast, the Capella Creek Group and related Mt Morgan Stratigraphic Assemblage comprise rhyolite volcanic-derived, quartz–feldspathic sedimentary rocks (sandstone, siltstone, sedimentary breccia/conglomerate), dacitic to rhyolite pumice-bearing volcaniclastic mass-flow deposits (produced by voluminous, subaerial pyroclastic eruptions), rhyolite syn-sedimentary intrusives ± lavas, minor rhyolitic ignimbrite and limestone (Kirkegaard *et al.* 1970; Morand 1993a; Messenger 1996; Messenger *et al.* 1997; Yarrol Project Team 1997). Volcanic and volcanogenic compositions are silicic-dominated; mafic–intermediate compositions are volumetrically minor and restricted to cross-cutting dykes/intrusives (Figure 4a).

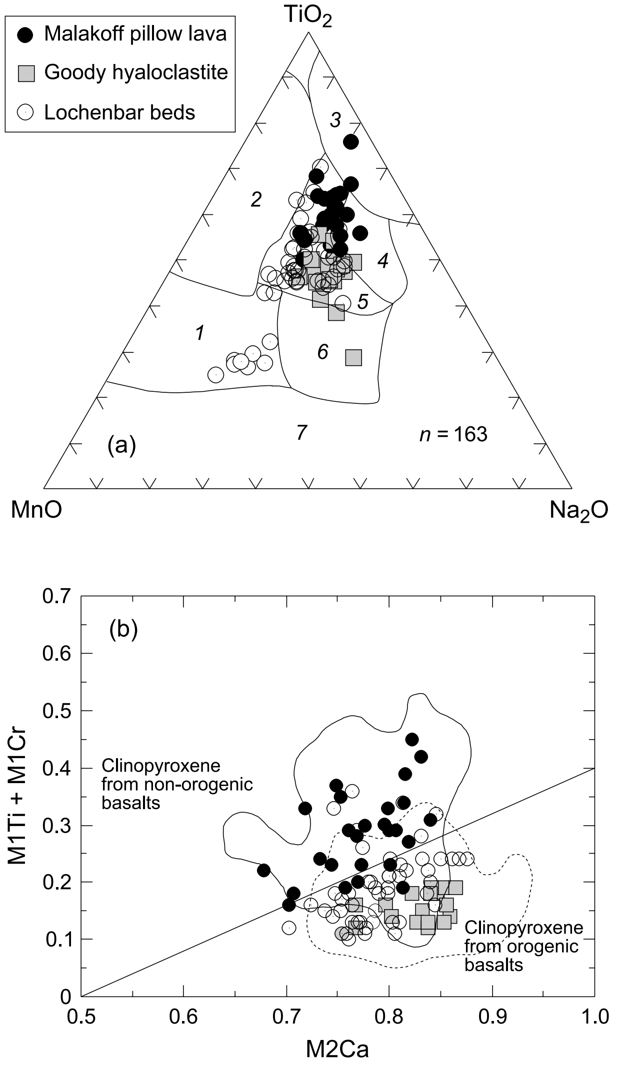

Figure 5 Clinopyroxene phenocryst compositions from volcanics of the Monal volcanic facies association compared with phenocryst compositions from lava clasts in sedimentary breccia units of the overlying Lochenbar beds. (a) TiO_2–MnO–Na_2O discrimination plot for mafic volcanics (Nisbet & Pearce 1977). Numbered fields are: 1, volcanic arc basalts; 2, ocean-floor basalts; 3, within-plate alkalic basalts; 4, volcanic arc, within-plate tholeiite and within-plate alkaline basalts; 5, all basalt types; 6, volcanic arc and within-plate alkali basalts; 7, within-plate alkali basalts. Clinopyroxene compositions range from within-plate to 'arc-like' fields. (b) Discrimination diagram of Leterrier *et al.* (1982) for non-alkali basalts (non-orogenic tholeiites/MORB and orogenic basalts), based on M1 site occupancy of Ti and Cr versus M2 site occupancy of Ca (based on 6 oxygens). Fields for clinopyroxene compositions from non-orogenic (—) and orogenic (– – –) basalts of Leterrier *et al.* (1982) are also shown. The non-orogenic/MORB-like clinopyroxene phenocryst compositions for the Malakoff pillow lava and the overlap in compositions between the Monal volcanic facies association and Lochenbar beds are emphasised. n, number of analyses. Samples: Malakoff pillow lava (SB234) and Goody hyaloclastite (RH1038) from Bryan *et al.* (2001); Lochenbar beds, SB163, GR 0277195 mE, 7292483 mN; SB253, GR 0299271 mE, 7782590 mN.

The Lochenbar beds represent a >1.5 km-thick sequence of mafic volcanic-derived sedimentary breccia/conglomerate (some beds are limestone clast-bearing), with minor sandstone and mafic to intermediate composition hyaloclastite (Yarrol Project Team 1997; Bryan *et al.* 2001). The Lochenbar beds unquestionably record the reworking and/or remobilisation of mafic volcanic-dominated lava sequences, such as the underlying Monal volcanic facies association. A close relationship between the Monal volcanic facies association and the Lochenbar beds is further evident in the overlap of clinopyroxene phenocryst compositions between volcanics from the Monal volcanic facies association and lava clasts in sedimentary breccias of the Lochenbar beds (Figure 5). The fact that a >1 km-thick sequence of mafic volcanic-derived sedimentary breccias has been emplaced extensively (>10 000 km^2) in the Yarrol Basin implies that mafic volcanic sources were also widespread. Although the primary volcanic record (Monal volcanic facies association) may not be widely preserved and exposed, the sedimentary response to mafic volcanism is extensive in the basin.

The geochemistry of the Monal volcanic facies association is different from volcanic rocks of the Mt Hoopbound Formation (base of the Bindawalla Stratigraphic Assemblage) because the latter are mostly andesites (55.7–63.45 wt% SiO_2; average is 58.9 wt% SiO_2 on an anhydrous basis), versus the more basaltic composition of the Monal volcanic facies association (51.7 wt% SiO_2 average on an anhydrous basis). The differences in Zr, Ti and Y contents to the Monal volcanic facies association as highlighted by Murray *et al.* are due to the more evolved nature of the andesites. However, the two basalt analyses (sample numbers RRRO47H, RRRO86B) reported by Randall (1996) overlap the Monal volcanic facies association with respect to Zr, Ti and Y contents and other element abundances. Differences in trace-element contents between andesites and basalts cannot be used to support the arguments of Murray *et al.*

MONAL VOLCANIC FACIES ASSOCIATION: INTRA-OCEANIC ISLAND ARC VERSUS CONTINENTAL BACKARC EXTENSION-RELATED VOLCANISM

Geochemical comparison of Monal volcanic facies association with other basalts

Selected data from the Monal volcanic facies association and the Izu–Bonin–Japan and Cascade arcs are compared by Murray *et al.* with the latter data used as definitive examples of supra-subduction zone, low-K tholeiite magmas (i.e. the generation of these magmas is directly linked to fluid-induced melting of the mantle wedge above a subducting oceanic plate). Murray *et al.* argue that the apparent geochemical similarity indicates that the Monal volcanic facies association is best interpreted as the products of intra-oceanic island-arc volcanism. However, none of the samples used by Murray *et al.* are true low-K island-arc tholeiites (two are backarc-basin basalts) and, consequently, their geochemical comparison is inappropriate.

For example, the low-K tholeiite from the Cascades (sample 81C621: Bacon *et al.* 1997) is a high-alumina olivine tholeiite (HAOT) that is part of a suite of rocks not restricted in occurrence to the Cascade arc itself. HAOT magmas have been erupted for the past 10 million years being associated with Basin and Range extension covering an area >22 000 km^2 in northwest USA (Hart *et al.* 1984), and occurring over a distance of >800 km from the present continental margin. Eruptions of HAOT in the Cascade area over the past 7 million years occur in a region where Basin and Range extension has impinged on the Cascade arc (Bacon *et al.* 1997; Conrey *et al.* 1997). Geochemical similarities between the HAOT lavas, MORB and backarc-basin basalts (BABB), coupled with the tectonic setting and age of the HAOT lavas, are consistent with the processes giving rise to extensional tectonism and HAOT magmatism being similar to those occurring in active backarc spreading regions (Hart *et al.* 1984; Bacon *et al.* 1997). All published work on the HAOT lavas interpret them to be derived from a MORB source-like mantle with the nearly anhydrous magmas generated by melting of dry mantle at relatively shallow depths (~35–70 km) and at very high temperatures (1300–1450°C: Bacon 1990; Bacon *et al.* 1997; Conrey *et al.* 1997; Elkins Tanton *et al.* 2001). The universal presence of minor LILE enrichment relative to MORB in the HAOT magmas is considered to be an old (pre-Cenozoic) subduction signature (C. R. Bacon pers. comm. 2002; Hart *et al.* 1984; Bacon 1990; Bacon *et al.* 1997). The associated, but geochemically distinct and unrelated, Cascade arc basalts represent higher degrees of partial melting of a depleted, relatively infertile source enriched in H_2O, LILE and LREE by a hydrous subduction component derived from the young Juan de Fuca Plate (Bacon *et al.* 1997 and references therein).

The low-K tholeiite from Izu–Bonin (Sample 788C-15H-3: Gill *et al.* 1992) is a BABB; it is not an island-arc tholeiite. The sample is a basaltic lithic clast from a debris-flow deposit that contains predominantly juvenile silicic pumice clasts. The pumice clasts are geochemically similar to rift-related rhyolites and distinct from those of the Quaternary arc (Gill *et al.* 1992). The basaltic scoria clast shows many geochemical and isotopic similarities to the Sumisu Rift sea-floor basalts, but is different from Quaternary basalts of the Izu arc (Gill *et al.* 1992 p. 387). The Sumisu Rift basalts are most similar to that of BABB found in other, more mature, backarc basins (Hochstaedter *et al.* 1990a, b; Taylor 1992).

The comparison of a fractionated andesite (58.5 wt% SiO_2 anhydrous) from Hakone Volcano (Fujimaki 1975) with basalts of the Monal volcanic facies association (average 51.7 wt% SiO_2 anhydrous) is erroneous. Murray *et al.* have compared fractionated andesite because only these more evolved arc magmas possess similar REE abundances and normalised patterns to the basaltic samples of the Monal volcanic facies association; the associated basaltic rocks from Hakone volcano show more strongly depleted REE abundances (4–6× chondrite), and are distinct from the Monal volcanic facies association.

The basalt from the Capella Creek Group is an altered basaltic dyke collected from drill core by Messenger (1996), and basaltic dykes are a minor rock type at Mt Morgan (Figure 4a). The dyke was intruded after lithification of the host sequences, based on sharp contacts and the absence of peperitic margins (which are observed for some quartz–feldspar porphyry intrusives: Messenger 1996; Messenger *et al.* 1997). Little age control exists for dykes in the Mt Morgan region and Triassic and Cretaceous intrusions also occur. If the dykes are broadly coeval, then cross-cutting relationships are consistent with our interpretation of magmatism changing from an early silicic to a later mafic volcanic phase, as outlined in the two-phase model of Fackler-Adams and Busby (1998). Any geochemical similarity between Middle–Late Devonian basaltic dykes at Mt Morgan and the Monal volcanic facies association is, therefore, not surprising.

In summary, none of the samples used by Murray *et al.* are true low-K island-arc tholeiites. On the contrary, their comparison shows the geochemistry of the Monal volcanic facies association is similar to: (i) basalts erupted at both continental margin to within-plate settings (i.e. HAOT) and backarc-basin settings in oceanic environments (e.g. Izu–Bonin example); and (ii) other magmas derived from MORB-like sources (e.g. similarity between HAOT and Monal volcanic facies association). Consequently, Murray *et al.* have no basis to interpret Devonian volcanism as occurring *only* within an oceanic environment. Their geochemical comparison reveals an underlying flawed premise: that volcanic rocks occurring at oceanic or continental convergent margins must be 'arc-related'. The Cascades region provides a useful example of the magmatic complexity that can occur at convergent margins, with flood basalt and hot-spot volcanism (Columbia River Flood Basalts and Snake River Plain – Yellowstone), Basin and Range extension-related bimodal volcanism and arc volcanism (Cascades) overlapping in space and time.

Other arguments for the Monal volcanic facies association representing island-arc tholeiite volcanism

LREE Depletion/Enrichment Murray *et al.* argue that the LREE depletion seen in the Monal volcanic facies association is also a characteristic of island-arc tholeiites (IAT). Chondrite-normalised REE patterns for the Monal volcanic facies association are LREE-depleted to slightly LREE-enriched ($La_N/Sm_N = 0.6–1.28$; average is 0.95) (Figure 6). Although there is some overlap, higher REE abundances distinguish the Monal volcanic facies association, BABB, and MORB from IAT (e.g. Tonga–Kermadec arc: Ewart *et al.* 1994; Smith *et al.* 1997). LREE depletion in IAT occurs at REE abundances <10× chondrite, whereas the Monal volcanic facies association have LREE abundances ≥10× chondrite (Figure 6a). The basaltic andesites and andesites of Gill (1981) referred to by Murray *et al.* similarly show LREE depletions occurring at significantly lower, overall REE abundances (4–6× chondrite for La); they are distinct from the Monal volcanic facies association. The Monal volcanic facies association (as do HAOT magmas) lacks the sigmoidal REE patterns of the Cascade arc basalts and basaltic andesites, which reflect modern subduction enrichment of the magma source (Bacon *et al.* 1997).

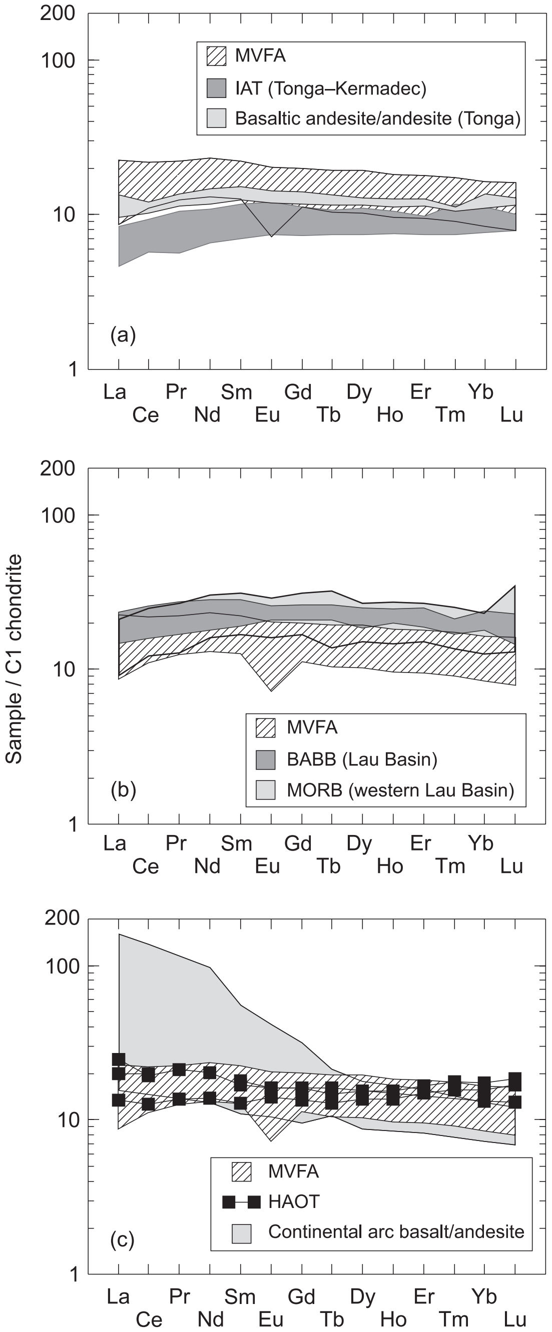

Figure 6 Chondrite-normalised (Sun & McDonough 1989) rare-earth element diagrams comparing the Monal volcanic facies association (MVFA) with other low-K basaltic and medium to high-K basaltic to andesitic rocks. Note: (i) the higher REE abundances for the Monal volcanic facies association compared with low-K island arc tholeiites; (ii) the transitional nature of the Monal volcanic facies association between island-arc tholeiites (IAT) and backarc-basin basalts (BABB) and overlap with MORB compositions; and (iii) the strong similarity between high-alumina olivine tholeiite (HAOT) and the Monal volcanic facies association. Fields for the various basalt types are based on samples listed in Table 1.

Th/Nb Ratios The similarity in Th/Nb ratios between the Monal volcanic facies association and frontal arc volcanoes of Izu–Bonin (Taylor & Nesbitt 1998) is an artefact of the element abundances. Th and Nb abundances for basaltic volcanics from the Izu–Bonin frontal arc are 0.037–0.397 ppm and 0.14–0.87 ppm, respectively (Taylor & Nesbitt 1998), and are distinctly less than the abundances of Th (0.48–0.92 ppm) and Nb (1.11–2 ppm) in the Monal volcanic facies association (Bryan *et al.* 2001 table 3). It is the backarc rift basaltic volcanics of the Izu–Bonin arc ('rear arc volcanoes' of Taylor & Nesbitt 1998) that have Th (0.494–1.188 ppm) and Nb (1.44–2.14 ppm) abundances similar to those of the Monal volcanic facies association (Taylor & Nesbitt 1998 table 2).

MORB-like abundances of high-field strength elements The statement that low-K arc suites show N-MORB-like abundances of high-field strength elements (HFSE) is false because the examples referred to in Ewart and Hawkesworth 1987) clearly have HFSE abundances *less than* MORB (Ewart & Hawkesworth 1987 figure 2; Ewart *et al.* 1994 figure 17). HFSE abundances for the Monal volcanic facies association, shown in Figure 7a, are clearly MORB-like in comparison. The Crater Lake HAOT sample is not a subduction-related, low-K tholeiite so the specific comparison in Figure 2b provides no justification for their arguments. With regard to Ti/Zr, V/Ti and Sc/Y ratios, although the element ratios may overlap, the Monal volcanic facies association is distinguished from IAT based on the *absolute abundances* of TiO_2, Zr and Y. This was the purpose of figure 17 in Bryan *et al.* (2001), which is essentially at issue here. Data for the Monal volcanic facies association is re-presented in Figure 8 and compared with other chemical groupings of mafic lavas. These figures are not particularly instructive and show considerable overlap of several igneous suites.

Arc-like signatures in the Monal volcanic facies association: source, fractional crystallisation or contamination effects?

Murray *et al.* assume that the 'arc-like' signatures of the Monal volcanic facies association can only be directly related to coeval subduction, and go to considerable length to show that fractional crystallisation cannot be the cause of internal geochemical variation in the Monal volcanic facies association. In their treatment of the geochemical data, Murray *et al.* focus on the more altered and/or more evolved samples (e.g. MA94); we placed more emphasis on the most primitive and least altered samples (e.g. SB234). The samples with which Murray *et al.* argue show the strongest 'arc' signatures in the Monal volcanic facies association, also show the strongest evidence from trace-element data for crustal contamination (e.g. anomalous Th contents). The Monal volcanic facies association show positive Cs, Rb, Th, Pb and U anomalies relative to N-MORB, although these are less pronounced for the MORB-like sample SB234 (Figure 7a). The anomalies occur at the same silica content as SB234 and there is no corresponding Ti, P or Sr depletions to suggest that fractional crystallisation caused these enrichments. High Cs, Rb, Pb and Th contents are characteristic of crustal material, and the selective enrichments of these elements in the Monal volcanic facies association suggest some crustal assimilation (Trumbull *et al.* 1999).

The role of crustal contamination is further explored in a Pb/Nd *vs* Nb/Th plot (Figure 9). Crustal rocks tend to have high contents of Pb and Th, but low Nb and Nd; mantle compositions are opposite, and characterised by low Pb/Nd and high Nb/Th ratios. The Monal volcanic facies association shows a spread of compositions with the MORB-like Malakoff pillow lava (SB234) as one end-member, whereas the remainder of samples show considerable variation in Pb/Nd ratios, and trend towards bulk continental and andesitic crust compositions (Figure 9). The 'arc-like' signature shown by some of the Monal volcanic facies association rocks cannot be interpreted as a primary source characteristic with any confidence.

Comparison with Tamworth Belt

Murray *et al.* argue that a transition from a northern zone (Yarrol Basin) undergoing backarc basin development to a southern zone (Tamworth Basin) occurring as a forearc basin is unlikely. Murray *et al.* have ignored recent literature on the Tamworth Belt that interpret arc rifting and emplacement of BABB in the Middle to Late Devonian and negate early held views of it being a forearc basin (Aitchison & Flood 1995; Offler & Gamble 2002). The modern Australian–Pacific plate margin illustrates that along-strike variations of backarc-basin development (Tonga–Kermadec arc and Lau Basin to Taupo Volcanic Zone) can exist at a convergent plate margin.

SUMMARY

Murray *et al.* through their geochemical comparison have reinforced our original interpretation that the Monal volcanic facies association shows greater geochemical affinity to MORB, BABB and basalts associated with intracontinental rifting (i.e. the HAOT lavas of western USA). They have not provided definitive examples of low-K tholeiites erupted at oceanic arcs with the same geochemical signatures as the Monal volcanic facies association. None of the geochemical data support the contention of an intra-oceanic setting for volcanism, nor does the submarine setting imply volcanism occurred at an oceanic island arc. Trace-element data suggest that crustal contamination produced the more 'arc-like' signatures of the basalts. We chose to compare our data with the Lower Permian Rookwood Volcanics because the available data also showed the similar spectrum of N-MORB to 'arc-like' geochemical signatures (Bryan *et al.* 2001 figures 12c, d, 15), a point overlooked by Murray *et al.* The volcanic and geo-

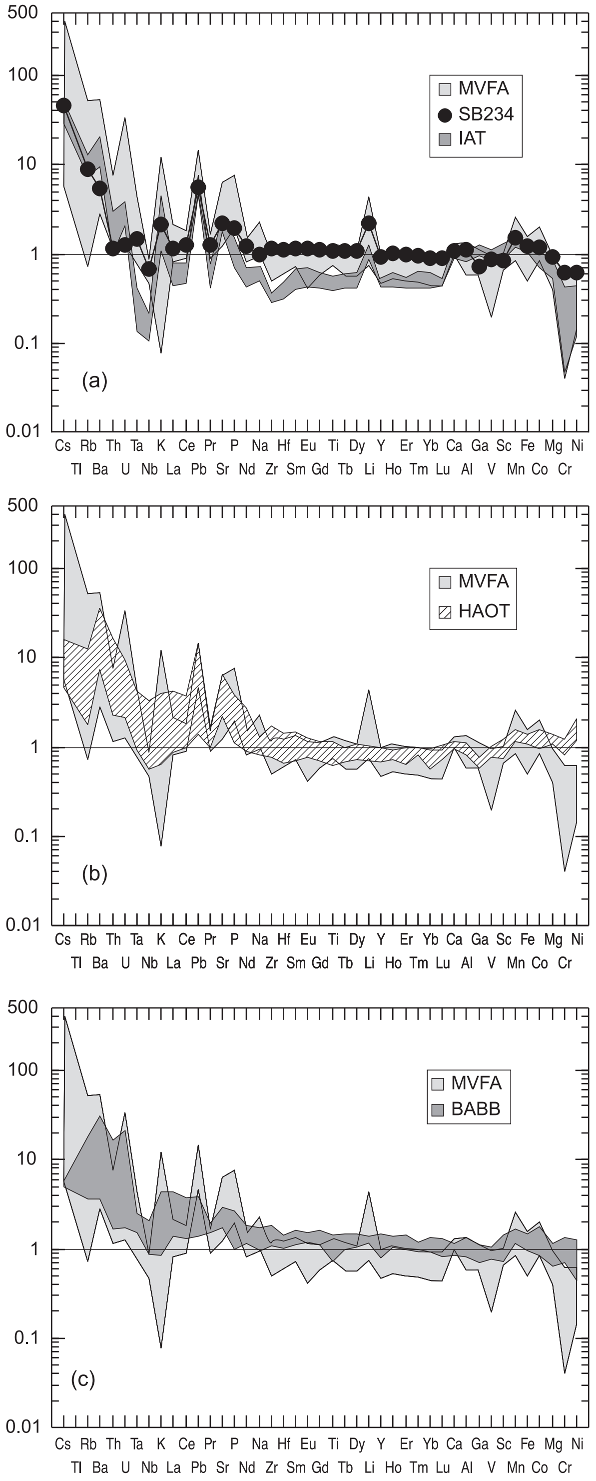

Figure 7 Monal volcanic facies association element abundances normalised to MORB values using the extended element set and order of Pearce and Parkinson (1993). (a) Monal volcanic facies association (MVFA) compared with representative island-arc tholeiites (IAT) from the Tonga–Kermadec arc. Note: (i) Nb, Ta depletions are more pronounced in the arc tholeiites; (ii) the MORB-like abundances of most incompatible elements in the Monal volcanic facies association, particularly for SB234, versus the more depleted character of the arc tholeiites; and (iii) the higher abundances of the large ion lithophile elements for the Monal volcanic facies association, although the increased scatter in some elements (e.g. K_2O) reflects alteration. (b) Monal volcanic facies association compared with high-alumina olivine tholeiite (HAOT) lavas from the Cascade region of northwest USA (Bacon *et al.* 1997; Conrey *et al.* 1997). Both show strong similarities in incompatible element abundances and enrichments in the large ion lithophile elements. (c) Monal volcanic facies association compared with backarc-basin basalts (BABB) from the Lau Basin (Ewart *et al.* 1998), with the latter showing incompatible element abundances slightly higher than MORB. Fields for the various basalt types are based on samples listed in Table 1.

chemical evolution from the Middle to Late Devonian is most consistent with extension producing an incipient backarc basin along the continental margin (e.g. two-phase evolutionary model of Fackler-Adams & Busby 1998). Although the western Pacific may be 'the most oceanic on Earth', the Lau–Tonga–Havre–Kermadec system represents the present configuration of the continuous migration of arc and backarc volcanism and tectonism eastwards during the past 100 million years leading to the fragmentation of eastern Australasia (Yan & Kroenke 1993; Ewart *et al.* 1998). Therefore, we consider this to be an appropriate modern analogue to the development of the New England Fold Belt during the Palaeozoic, which was marked by repeated, extension-related magmatic and basin-forming events (e.g. Yarrol Basin, Drummond Basin, Bowen–Sydney Basins).

Late Devonian – Early Carboniferous silicic explosive volcanism

Implicit in the discussion by Murray *et al.* is that volcanism was sourced from a supra-subduction zone continental volcanic arc along the Connors–Auburn Arches during this period. All volcanic products observed by us in the Three Moon Conglomerate and Rockhampton Group and in the correlative parts of the Campwyn Volcanics are subaerially emplaced welded rhyolitic ignimbrites, or syn- to post-eruptive, subaqueously emplaced, rhyolitic pyroclastic breccias (Bryan *et al.* 2001, in press). Lower Carboniferous lithologies from the Connors Arch are also rhyolite ignimbrite or granite (Hutton *et al.* 1999). The ignimbrites are mostly low- to high-silica rhyolites; mafic compositions are absent (Figure 4c). High-silica rhyolites (≥75 wt% SiO_2), 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), and these compositions tend to be volumetrically minor. The presence of ignimbrites in the western part of the Yarrol Basin cannot necessarily be used to prove the existence of vent(s) and proximity to a volcanic arc along the Connors–Auburn Arch. The ignimbrites are typical outflow facies (metres to a few tens of metres thick) and lack features/structures indicating proximity to vent (e.g. coarse lithic breccias and significant deposit thickness). Pyroclastic density currents emplacing ignimbrite can travel ≥100 km from source, and no eruptive sources (i.e. calderas) for Early Carboniferous ignimbrites have yet been identified along the Connors–Auburn Arch.

The Late Devonian to Early Carboniferous (*ca* 360–340 Ma) represents another, less well-recognised period in which silicic magmatism was voluminous and widespread in the northern New England Fold Belt. This coeval silicic volcanism collectively defines an area $>2 \times 10^5$ km^2, and was emplaced across terranes variably interpreted as backarc (Drummond Basin), foreland to intracratonic (Broken

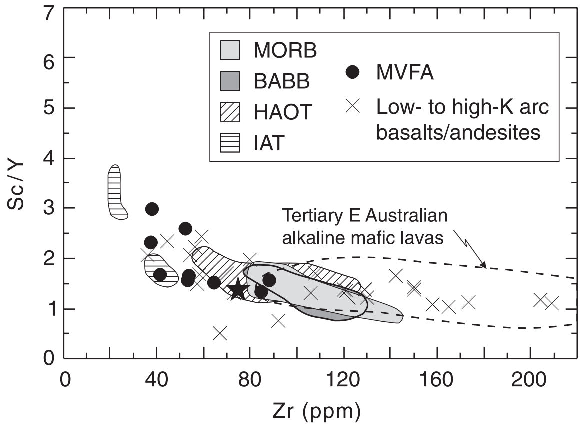

Figure 8 Sc/Y *vs* Zr plot as used by Murray *et al.* Note: (i) the transitional character of the Monal volcanic facies association (MVFA) between island-arc tholeiites (IAT) and MORB/backarc-basin basalts (BABB)/high-alumina olivine tholeiite (HAOT) compositions; (ii) the higher Zr abundances of the Monal volcanic facies association compared with modern lavas from the Kermadec arc; (iii) that BABB do not extend to high Zr abundances (>140 ppm) at low Sc/Y ratios; and (iv) that the very high Zr contents of basaltic lavas from the Rookwood Volcanics (see Figure 3a) show more affinity with within-plate basaltic compositions as represented by Tertiary mafic volcanics from Eastern Australia. The star represents MORB composition of Sun and McDonough (1989). Field for Tertiary eastern Australian alkaline mafic lavas is based on Ewart *et al.* (1988) and references therein; fields for MORB, BABB, HAOT and IAT based on samples listed in Table 1.

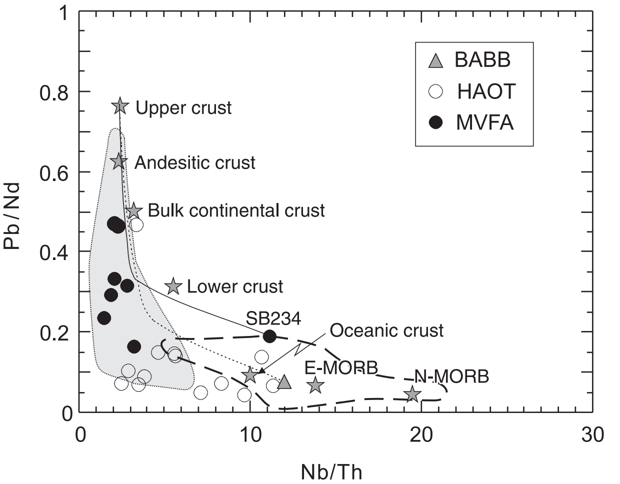

Figure 9 Pb/Nd *vs* Nb/Th plot to illustrate potential effects of crustal contamination. Element ratios for the Monal volcanic facies association (MVFA) and high-alumina olivine tholeiite (HAOT) lavas overlap, and Nb/Th ratios of an averaged backarc-basin basalt (BABB) composition (based on samples in Table 1), oceanic crust and sample SB234 (Monal volcanic facies association) are similar. These latter compositions also overlap the field for Tertiary within-plate mafic lavas of eastern Australia (– – –, data source as in Figure 8). Shaded field is the Mt Morgan Trondhjemite suite (Messenger 1996), with the range of Pb/Nd values independent of SiO_2 and Zr contents (i.e. indexes of fractionation). Simple mixing curves are also shown between an upper crustal end-member and mafic end-members of SB234, Monal volcanic facies association (——), and the averaged BABB composition (· · ·). Samples lie closest to a mixing curve using a mafic end-member with the lowest Pb/Nd ratio (e.g. similar to some of the HAOT lavas). Compositions for N-MORB and E-MORB are from Sun and McDonough (1989) and the different crustal compositions are from Taylor and McLennan (1985).

River Province,), arc (Connors Arch) and forearc (Campwyn/Yarrol). We see no evidence for an intervening belt of high-standing, basaltic to andesitic stratovolcanoes to separate these depositional elements.

Palaeogeography and provenance of the Bindawalla Stratigraphic Assemblage

The crux of Murray *et al.*'s argument with respect to palaeogeographical reconstruction is 'the evidence shows that at all times . . . the depositional basin deepened eastward'. The evidence they cite, however, is once again selective, in large part unpublished, and gathered by disparate groups and individuals over a long period of time. The data and observations on which their argument are based were gathered mostly prior to the advent of modern techniques and concepts in sedimentology and basin analysis. The statements made by Murray *et al.* reflect outmoded misconceptions on the relationships between facies and depositional environments. Testing our ideas against previous interpretations has been hindered by the way in which they have been presented in mapping reports (Dear 1968; Kirkegaard *et al.* 1970; Dear *et al.* 1971).

There are several problems with the assertion of Murray *et al.* that 'mapping of this assemblage clearly demonstrates progressively deeper water facies from west to east'. First, the degree and quality of exposure and the moderately complex structure in the Yarrol terrane do not facilitate assessment of directional trends related to basin development nor the establishment of stratigraphic equivalence. It is, therefore, possible only to correlate strata at the assemblage level (hundreds of metres of section). At this level, it is unwise to make sweeping generalisations concerning facies trends. Second, their assertion is based largely on the premise that coarse-grained facies reflect shallow-water environments, finer-grained facies reflect deep water and rhythmically interbedded sandstone–mudrock intervals reflect deep-water turbidites. Such misconceptions are endemic to all of the map commentaries relevant here and cited by Murray *et al.* Sedimentological literature over the past 30 years demonstrates that these are oversimplifications. For example, rhythmically interbedded sandstone–mudrock intervals with partial or even complete 'Bouma sequences' are now known from all water depths and are not uniquely associated with turbidity current processes (Nelson 1982; Aigner & Reineck 1982). Turbidites can form in any water depth and on flat surfaces (Leeder 1999). A characteristic of the Yarrol Basin sedimentary rocks is an apparent scarcity of primary physical sedimentary structure, making the diagnosis of depositional process and, hence, environment difficult. However, this does not argue for any particular interpretation as to water depth and may simply be a reflection of the grainsize distribution and diagenetic history of the rocks. Throughout the history of research on the Yarrol terrane, no one has yet been able to fully document the lithofacies assemblage and stratigraphic relationships of the Bindawalla Assemblage.

Two specific examples illustrate the unreliability of the sweeping generalisations made by Murray *et al.* First, exposures of the Crana beds section in Dan Dan Creek west of Bororen (now Mt Alma Formation of Yarrol Project Team 1997) are part of the 'distal, deep-water' assemblage of Murray *et al.*, but contain ≤10 m-thick, primary welded ignimbrite deposits, which by definition must be emplaced in a hot state, and most commonly on exposed ground. Associated thin-bedded sandstone–mudrock facies contain small-scale wave-influenced ripple structures that indicate shallow-water environments. One bedding plane exposure in particular, at GR 56J 0297549 mE 7314965 mN, shows symmetrical miniripples that could only have formed in very shallow water (Allen 1982). Second, oolitic limestones of the Rockhampton Group, which preserve bipolar ('herringbone') cross-bedding indicative of deposition under shallow tidal currents, are found from the far west of the region (e.g. Cania) to the far east near Rockhampton and Mt Larcom. Webb (1998) described a series of small reefal structures from exposures near Rockhampton in the far east of the terrane, despite Murray *et al.* stating that such shallow-water features are absent from the east. These reefs are laterally equivalent to cross-bedded oolite units displaying bipolar palaeocurrent directions. We reiterate our original interpretation that the palaeogeography of the region during Late Devonian and Early Carboniferous times cannot have been a simple eastward-deepening gradient.

Interpretations of deepening are, in part, based on an overall fining-upward trend for the Late Devonian to Early Carboniferous volcanosedimentary sequences. Concomitant with the change from mafic to silicic volcanism occurring near the Devonian–Carboniferous boundary are changes in the primary fragmentation and eruptive style that have imparted a strong control on sediment grainsize. Primary fragmentation of the mafic lavas was dominated by quench and autobrecciation processes that produced volcanic material mainly in the pebble to boulder size range: hence, the dominance of sedimentary breccia and conglomerate facies for the Lochenbar beds. In contrast, the explosive eruptive style (i.e. pyroclastic fragmentation) of silicic magmas produced large volumes of sand-grade volcaniclastic material: hence, the sand-prone character of the Three Moon Conglomerate and Rockhampton Group volcaniclastic sedimentary units. The finer grainsize of these and correlative formations (e.g. Mt Alma Formation, Crana beds) cannot, therefore, be used to simply record basin-deepening trends. Such strong controls on sediment grainsize by volcanic fragmentation processes are well expressed in the contiguous Late Devonian to Early Carboniferous Campwyn Volcanics to the north (Bryan *et al.* in press).

The palaeogeographical interpretation of Murray *et al.* requires: (i) a western volcanic 'arc' producing large volumes of dacitic to high-silica rhyolite pyroclastic material; (ii) a central zone characterised by extensive oolitic limestone development, which by definition must be largely devoid of siliciclastic input; and (iii) an eastern, deep-water zone receiving a continual supply of volcanogenic sediment. Murray *et al.* provide no explanation as to why or how volcanogenic sediment largely bypasses ooid shoals in the western part of the Yarrol Basin (which should be more proximal to the volcanic sources) to be mostly deposited in eastern parts of the basin. Our alternative explanation is more consistent with the observed lateral facies changes (e.g. limestones containing higher proportions of volcaniclastic material eastwards) and palaeocurrent data, with the mainly ooid and limestone-forming areas on the western side of the Yarrol Basin being more remote from volcanogenic sediment supplied mainly from the east.

Generalisations as to fossil distribution cited by Murray *et al.* are also misleading. The lack of a shallow-water macrofossil assemblage cannot be used to invoke deep-water environments because there are many other reasons why calcareous macrofossils might not be preserved in sedimentary successions. Conodonts are not widely accepted as water depth indicators because they reflect pelagic organisms that are not environmentally specific and, likewise, radiolarians do not in themselves indicate water depth.

Palaeocurrent data give an additional source of insight into the problems discussed here. Palaeocurrent data in isolation can be misleading, and for a regional investigation, data should be collected from as many locations and facies as possible. Murray *et al.* clearly have not put any significant value on palaeocurrent data as their previous investigations (Yarrol Project Team 1997) did not provide such data. They are, therefore, unable *prima facie* to dispute our data, which are gathered from a variety of sites and facies across the study area. We took care to separate data from facies affected by tidal currents (e.g. in the Rockhampton Group), but the overall trends of those data are consistent with azimuths from underlying formations. Although the dataset in Bryan *et al.* (2001) is limited in number, it nonetheless shows regional consistency. A substantially larger dataset collected by us from the stratigraphically equivalent Campwyn Volcanics in the Mackay–Proserpine region (Bryan *et al.* in press) shows exactly the same trends. These data, in combination, present a persuasive case for volcanogenic sediment derivation from the east. We emphasise that we gathered our own data in a consistent manner, whereas Murray *et al.* have merely searched old Honours theses for pre-existing data over which there is no quality control.

Permo-Carboniferous magmatism

Although not pertinent to the paper under discussion, the selective and misleading references to Permo-Carboniferous magmatism reveal Murray *et al.* do not recognise the magnitude, regional extent and character of this magmatic event. Without presentation of data, the statement of 'uniform, very strong subduction-related geochemical signatures in mafic volcanics' represents another false premise of the dogma that where rocks are found with calc-alkaline geochemical signatures, they must represent an island or continental arc generated at a subduction zone. We would argue most categorically that the interpretation of a continental arc for Permo-Carboniferous magmatism in the New England Fold Belt is invalid.

Permo-Carboniferous magmatism preceded the opening of the Bowen–Sydney Basin system. The scale (>2000 km long and ≥300 km wide), extrusive volume (≥500 000 km^3), age range (*ca* 320–280 Ma) and silicic-dominated nature of igneous compositions (Figure 4d) are similar to other well-known extension-related, silicic large igneous provinces, such as Sierra Madre Occidental, Mexico (Swanson & McDowell 1984; Ward 1995), the Chon Aike Province of South America and Antarctica (Pankhurst *et al.* 1998; Riley & Leat 1999; Riley *et al.* 2001) and the Whitsunday Volcanic Province of eastern Queensland (Ewart *et al.* 1992; Bryan *et al.* 1997, 2000, 2002). Lithologically, it is dominated by rhyolite ignimbrite (Oversby *et al.* 1994; McPhie 1988; Jones 2002) and an extensive granitic batholithic system is preserved in central and northern Queensland (Allen *et al.* 1998). Igneous compositions become weakly bimodal up-sequence with more mafic volcanic compositions in the Early Permian (Fielding *et al.* 1997; Allen 2000; Jones 2002). Extensive dyke swarms are characteristic, developed over a distance of ≥1000 km from Rockhampton to Cooktown (Stephenson 1990; Allen 2000), with the same silicic to mafic transition observed in the dyke intrusive history (Allen 2000). Eruptive sources for the silicic ignimbrites were multiple caldera vents, several of which are well documented [Featherbed caldera (Mackenzie 1989); Bulgonunna Volcanics (Oversby *et al.* 1994)].

Trace-element and radiogenic-isotope geochemistry reflect the overwhelming influence of crustal melting in the generation of the 'calc-alkaline' silicic magmas, with crustal source ages ranging mostly from 800 to 1100 Ma (Allen *et al.* 1998; Allen 2000). Associated, but volumetrically minor, basaltic andesites and andesites are crustally contaminated (Jones 2002), and their geochemistry cannot be used to interpret the tectonic setting of magmatism. The most primitive basaltic rocks show N-MORB (Rookwood Volcanics: O'Connell 1995; Stephens *et al.* 1996) to within-plate or E-MORB compositions (Allen 2000; Bruce *et al.* 2000; Landenberger & Collins 2000). Note that basalts from the Rookwood Volcanics with high Zr contents (>140 ppm; Figure 3) overlap Tertiary intraplate lavas from eastern Australia (Figure 8), whereas BABB (e.g. from the Lau Basin) show more restricted Zr contents. Therefore, there may be nothing 'typical' about the Early Permian mafic volcanics being backarc basin lavas.

COMPARISON OF PERMO-CARBONIFEROUS MAGMATISM WITH SUPRA-SUBDUCTION ZONE 'ANDESITIC' MAGMATISM

In general, supra-subduction zone magmatism has the following characteristics: (i) erupted products are predominantly basaltic andesite to andesite in composition (Ewart & Hawkesworth 1987; Graham & Hackett 1987); (ii) frequent eruptions of magma batches that are typically small in volume, but with a short lifespan, from impersistent, small magma chambers (Hobden *et al.* 1999); (iii) eruptions construct typically high-standing shield and stratovolcanoes because of frequent, relatively small volume eruptions (Cas & Wright 1987); (iv) volcanic sequences are mafic–intermediate lava-dominated (Hackett & Houghton 1989; Hildreth & Fierstein 2000); and (v) the volcanic arc is typically narrow (tens of kilometres wide) at a given time (Cas & Wright 1987).

All aspects of the Permo-Carboniferous igneous rocks of the New England Fold Belt (including the Connors–Auburn Arch) are inconsistent with them representing supra-subduction zone magmatism: (i) igneous compositions are predominantly rhyolitic; (ii) ignimbrite is volumetrically dominant; (iii) multiple calderas represent the main eruptive sources forming a major continental caldera system; (iv) the silicic volcanics are chemically and temporally related to, and underlain by, large silicic plutons and batholiths; (v) magmatism was widespread (>300 km), orthogonal to the inferred margin; and (vi) magmatism overlapped extension and basin development, with significant extension locally producing core complexes and syntectonic magmatism, occurring at least as far back as *ca* 305 Ma (Little *et al.* 1992, 1993, 1995; see Holcombe *et al.* 1997 for summary).

Murray *et al.* ignore stratigraphic and sedimentological data for the Early Permian successions of the northern New England Fold Belt that do not support the existence of an active continental volcanic arc sited along the Connors–Auburn Arch during accumulation of the Bowen Basin succession (Fielding *et al.* 1997). One of the fundamental misconceptions of Murray *et al.* and earlier papers interpreting the Connors–Auburn Arch as a supra-subduction zone magmatic arc, is that major batholiths are the roots of subduction-related volcanic arcs. From better studied examples of silicic batholiths, it is clear that major silicic batholiths and continental caldera systems form at distinctly different times from 'andesitic' arc volcanic rocks: the batholiths form during trench-normal extension, whereas andesitic volcanoes form in a regime of trench-normal contraction (Ward 1995).

Conclusions

The discussion by Murray *et al.* reveals five underlying assumptions that have driven the interpretation of igneous and sedimentary geology and tectonics of Queensland over the past 30–40 years: (i) a field-based assumption that feldspar porphyritic volcanic rocks are andesitic in composition and the associated igneous suite is, therefore, calc-alkaline; (ii) that calc-alkaline geochemical signatures (regardless of whole-rock composition) indicate that magmas were generated in a supra-subduction zone setting (i.e. continental-margin or oceanic-island arc); (iii) that major linear batholiths are the roots of subduction-related volcanic arcs; (iv) that turbidites and rhythmically bedded, fine-grained sedimentary sequences indicate only deep-water to abyssal settings; and (v) that unconformities only represent contractional events.

As shown, both by us for the New England Fold Belt and other workers in these fields, such assumptions are not valid. Bryan *et al.* (2001) referred to the lack of evidence for Late Devonian (to Permian) supra-subduction zone volcanism along the site of the Connors–Auburn Arch, a conclusion that has been increasingly drawn by other workers over the past 10 years (Stephens *et al.* 1996; Fielding *et al.* 1997; Holcombe *et al.* 1997; Allen *et al.* 1998; Jones 2002). It is implicit from the discussion by Murray *et al.* that they reject this body of work. However, their discussion has, in fact, reinforced our interpretations.

The purpose of the paper of Bryan *et al.* (2001) was to draw attention to significant inconsistencies in the existing model and to provide an alternative. We presented an integrated dataset comprising stratigraphic sections, geological maps, detailed lithological descriptions constraining interpretations on depositional processes and facies analysis, whole-rock geochemical data, sandstone petrology, palaeocurrent data and structural information. Data of this sort has been lacking for the Late Devonian to Early Carboniferous sequences of the Yarrol Basin. Murray *et al.* admit that the arc–forearc – accretionary wedge model is indeed simplistic: a model that is underpinned by an outdated data source, and which draws on overly simplistic premises about continental margin magmatism, tectonics and (volcanogenic) sedimentation.

Appendix 1

List of samples and data sources used for the geochemical plots.

Reference	Sample nos
Monal volcanic facies association	
Bryan *et al.* (2001)	MA94, RH1038A, RH1038B, SB247C, AC150, RH1151, SB234, SB247M.
High-alumina olivine tholeiite	
Conrey *et al.* (1997)	RCBD-21, RCBD-41, RCGR-236, RMC92-8, TED-733
Bacon *et al.* (1997)	MA-767, MA-696, MA-120, 81C621, 82C894, 84C1143, 88C1540, 881530, LC86-1046, LC82-970, LC88-1311
MORB	
Ewart *et al.* (1994)	834B 8R-2, 834B 11R-3, 834B 13R-1, 834B 13R-3, 834B 33R-2, 834B 35R-1, 834B 37R-1, 834B 40R-1, 834B, 55R-1, 834B 57R-1
Hergt and Farley (1994)	834B 31R-2, 834B 33R-1, 834B 34R-2, 834B 35R-2, 834B 36R-1, 834B 39R-1, 834B 40R-1, 834B 46R-1, 834B, 59R-2, 834B 14R-1, 834B 15R-2, 834B 18R-1, 834B 26R-1, 834B 31R-1
Island-arc tholeiite and basaltic andesite	
Ewart *et al.* (1973, 1998)	HHBF, HHUF, 38984, 38983, 64T4C, 64T6, T103c, T101p, T102, Late20, Late21, Late3, Late13, Late7
Smith *et al.* (1997)	A46316, A7114, A7125
Backarc basin basalt	
Ewart *et al.* (1977, 1998)	N_107, N_108, N_110, N_111, N_131
Arc basalt to high-K calc-alkali basalt	
Smith *et al.* (1997)	E-90/4A, E89-77, V14765, V14854, V16721
Bacon *et al.* (1997)	SH75-268, SH75-317, SV75-3, CL80C354, CL88C1521, CL88C1523, CL88C1557, LC82-905, LC85-671, LC86-1005, LC86-855, LC88-1312, LM87-1384, MA-322, MA-953
Conrey *et al.* (1997)	RCDS-197, RCW-85, TB92-16

Their discussion reveals a conceptual lock that has hindered understanding of the geology and tectonic evolution of the New England Fold Belt for the past 25 years.

Acknowledgements

Valuable discussions with Tony Ewart, Cathy Busby, John Jell, Paul Messenger, Chris Stephens, Charlie Bacon, Balz Kamber, Thomas Ulrich and Amanda Jones on aspects of this reply are greatly appreciated. S. E. Bryan also wishes to recognise the research efforts and ideas of Chris Stephens over the past 10 years that have been instrumental in advancing our understanding of New England Fold Belt geology. Charlotte Allen is thanked for providing geochemical data for the Urannah Batholith. Financial support has been provided by ARC Large Grant A10027005 to R. J. Holcombe and C. R. Fielding.

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