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The New England Fold Belt in Queensland is a complex arrangement of terranes with boundaries dominated by structures that were active during the contractional Hunter–Bowen Orogeny (event). This event extended for around 35 million years from Late Permian (ca 265 Ma) to late Middle Triassic (ca 230 Ma) time. The present north-northwest-trending structural grain of the fold belt is largely due to this deformation, but most faults have been reactivated during post-Late Triassic faulting. The northern New England Fold Belt can be subdivided into:

(i) a northern region (Connors Arch and lateral structures) within which deformation is characterised by open folds and variable, but generally minor, thrusting; and (ii) a central region of thin-skinned, fold-thrust deformation with cross-oregon tear faults, and within which strain is strongly partitioned and there is variable cleavage development (Gogango Overfolded Zone and more eastern terranes); and (iii) a southern region of thick-skinned deformation within which basement appears to have been involved in deformation. Within the central region, the Marlborough Block is a composite out-of-sequence thrust nappe terrane of ophiolitic components, low- and high-grade metasedimentary rocks, and metagranitoid, juxtaposed, at deeper structural levels, by early thrusting and finally thrust at least 80 km west over the fold-thrust belt. Various elements of the fold belt, including the Yarrol/Calliope terrane and Gympie Block, may be allochthonous elements transported for distances of tens to hundreds of kilometres within the fold belt. Calc-alkaline magmatism in the northern New England Fold Belt during the Early and Middle Triassic may have been in response to the initiation, or onshore migration, of a magmatic arc, and its termination coincided with the last phase of contraction. The tectonic regime became extensional by the Late Triassic with widespread granite intrusion and development of silicic volcanic complexes and localised extensional sedimentary basins.

Pulses of contractional deformation in the fold belt are recorded by the distribution and nature of sediment in the foreland Bowen Basin to the west. Thrusting is indicated by the presence of coarse clastic wedges shed into the basin for greater distances at successively higher stratigraphic levels, reflecting the advancement of the thrust front. The final contractional event appears to have been re-initiated at the eastern margin of the fold belt, rather than stepped westward from the previous thrust front, and to have been more intense than previous pulses. Bowen Basin sedimentation closed at about 232 Ma following accumulation of the most voluminous of the clastic wedges. Fluid flow associated with shear and dilational structures during this final contractional event is thought to be responsible for gold mineralisation in the fold belt, and for widespread diagenetic mineralisation in sediments of the Bowen Basin.

Key words: crustal convergence, fold-thrust belt, New England Fold Belt, tectonics.

INTRODUCTION

The present geometry of folded terranes in the New England Fold Belt in coastal Queensland (Figure 1) is largely controlled by structures produced during the Permo-Triassic Hunter–Bowen event yet its nature and timing have been poorly defined. In a companion paper (Holcombe et al. 1997), we discussed the constraints on the transition from active accretion in mid-Carboniferous times to widespread extension through the Late Carboniferous and Early Permian. This transition is interpreted in terms of eastward retreat of the convergent slab, and migration of the volcanic arc offshore. This paper presents a synthesis of our current understanding of the Late Permian to Late Triassic tectonic evolution of this region (Holcombe et al. 1997)

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although the greatest intensity of deformation occurs within the Gogango Overfolded Zone (Figure 1) and in the old accretionary terranes east of the Yarrol Fault. Folds associated with thrusts in the Gogango Overfolded Zone are characterised by pervasive slaty cleavage in contrast to the much more localised cleavage development north and south of this area. It is in the Gogango Overfolded Zone that the magnitude and style of this contractional event can be most clearly characterised, but Late Permian thrusts have now been mapped in the North D’Aguilar Block in southern Queensland (Little 1992; Sliwa 1994; Donchak et al. 1995) although with eastward vergence.

The Late Permian to Late Triassic represents a major period of magmatism in the New England Fold Belt, although magmatic compositions appear to change through time and the igneous rocks of this interval can be separated into relatively discrete suites (Gust et al. 1993). Early Triassic volcanic and plutonic rocks with calc-alkaline geochemical characteristics occur within the broad contractional cycle, while Late Triassic silicic caldera-related volcanics and granite plutons overprint the fold-thrust belt structures.

The data presented here are derived from a number of research projects in southern and central coastal Queensland, as well as drawing on several Bowen Basin studies. In particular, the deformation history is based on ongoing study areas in the Fitzroy region around Rockhampton and Marlborough in coastal central Queensland (Figures 1, 2), and in southern Queensland (Figures 1, 3). Our understanding of the magmatic history is based on data gathered throughout the northern New England Fold Belt during our studies, and from the Connors Arch region (Dear 1989, 1994; Allen et al. 1994; C. M. Allen pers. comm. 1996).

FOLD-THRUST DEFORMATION

Marlborough–Fitzroy area

Two fault styles dominate the Fitzroy region: Late Permian–Triassic thrusts and associated tear faults; and Cretaceous–Tertiary normal faults (Figure 2). Significant post-Triassic strike-slip movement has also occurred on some of the faults in the region (e.g. Broad Sound Fault). Many of the Cretaceous–Tertiary normal faults exploit the pre-existing thrust-tear fault architecture of the region to such an extent that almost all faults, of any age, have a Cretaceous–Tertiary brittle overprint. Many of the thrusts in Figure 2 are continuous with a normal fault that forms the boundary to an adjacent Cretaceous or Tertiary basin. Although there are undoubtedly elements of crustal fracturing in the region that controlled basin development during Early Permian extension (Hammond 1987; Fielding et al. 1998), we have not positively identified any regional fault patterns within the northern New England Fold Belt that can be associated directly with this event.

Contractional structures developed during the Permo-Triassic thrust event (thrusts, folds, cleavage) are pervasively developed for a distance of at least 100 km inland from the coast and continue with varying intensity into the Bowen Basin. Regional deformation related to this event is strongly heterogeneous. The most deformed terranes in the eastern part of the belt include remnants of the Devonian–Carboniferous accretionary terranes in the Coastal Block and parts of the Calliope terrane (Mt Holly beds). Further west, the Gogango Overfolded Zone describes an arcuate shape in plan (Figure 2) that includes a ~20 km-wide, west-verging thrust-fold belt along the trend of the Connors–Auburn Arch (Figure 1). Much of the intervening Yarrol Basin units and Calliope terrane are significantly less deformed, at least at outcrop scale.

Several styles of contractional deformation are preserved across the region. In the Gogango Overfolded Zone, the most common style of deformation is multiple imbricate thrusts of small throw (few tens to few hundreds of metres) associated with well-developed mesoscopic folding and cleavage indicating a distributed ductile response. Broad areas of steep to
overturned dips suggest that thrust-propagation folds are common. Fergusson et al. (1990, 1993) described similar pervasive folding and cleavage in the accretionary rocks of the Coastal Block. The intervening terranes are characterised by fewer thrust faults that have larger throw, accompanied by fault bend folds but little cleavage.

The largest of these fault-bend folds is the Craigilee Anticline which appears to be a breached fault-propagation fold (Figure 4). The main floor thrust to this anticline (Rookwood Thrust, Figure 2) is a major shallow crustal discontinuity. Although time-equivalent Permian units are incorporated in both footwall and hangingwall, the thrust marks the eastern boundary of the well-cleaved rocks that define the Gogango Overfolded Zone. Rocks of the Yarrol and Calliope terranes (Figure 1) occur only within the hangingwall of the thrust, whereas rocks of the Permo-Carboniferous Connors–Auburn Arch occur only within the footwall. Early Permian marine units (e.g. Rookwood Volcanics, Berserker beds: Holcombe et al. 1998) apparently only occur to the east of the Rookwood Thrust.

The Marlborough Block is an enigmatic, thin (<2 km), composite terrane that was transported westward along a very low angle, out-of-sequence thrust (the Marlborough Thrust, Figure 2) over the earlier thrust packages (Figure 4). The basal thrust is a brittle structure with little ductile deformation, even within metres of the contact. In contrast, the Marlborough Block internally is an amalgam of numerous fault-bounded packages of greenschist to amphibolite facies rocks with kilometre-scale, ductile response in the rocks adjacent to most faults. Some of these faults and associated shear zones have clear thrust geometry and kinematics whereas others are more ambiguous in either dip or sense-of-shear. These latter structures tend to occur near foliated S-type granitoids, and may be either thrusts that were rotated during translation of the block, or remnants of extensional faults that developed during emplacement of the granitoids, as have been observed in the North D’Aguilar Block in southern Queensland (Holcombe et al. 1998). The internal thrusts of the Marlborough Block are interpreted to have developed during thrusting in a deeper part of the thrust belt and
Figure 3 Structural framework of the North D'Aguilar Block in southern Queensland showing units and features discussed in the text.

Figure 4 Cross-sections across the Gogango Overfolded Zone in the Fitzroy region. The Rookwood Thrust is a major thrust that carries Yarrol Block basement over Connors Arch basement in the footwall. Early Permian marine basins occur predominantly to the east (in the hangingwall) of this thrust. The Marlborough Thrust (section AB) is an out-of-sequence thin thrust nappe that overrides the earlier thrusts. The large antiformal structure in CD and EF is the Craigilee Anticline which is a breached propagation fold from a thrust that splays off the Rookwood Thrust. The steep faults are Cretaceous and Tertiary normal faults. The locations of section lines are shown on Figure 2. Both vertical and horizontal scale-bars are in 1 km increments.
the package translated to its present structurally high-level position along the younger Marlborough Thrust. In this model the Marlborough Thrust must represent an upper flat on a system that ramps down to the east. We interpret $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages of 248.8±0.5 Ma and 242.9±0.4 Ma on biotite from foliated granodiorite in the Marlborough Block (Holcombe et al. 1998) to reflect exhumation and cooling following the deeper level, more ductile, thrusting event.

Deformation is also strongly partitioned along the fold belt, with tear faults separating compartments with fold-thrust packages of differing geometry (e.g. in the area shown in Figure 2). The northern termination of the Gogango Overfolded Zone fold-thrust belt is a tear fault system (Holcombe et al. 1995) equivalent to the Stanage Fault Zone of Henderson et al. (1993). The system is a complex zone of linked faults that also separates the allochthonous and para-allochthonous fold-thrust belt and Marlborough Block to the south from a gently folded, autochthonous terrane to the north. Fault styles developed within the zone include pure thrusts, strike-slip and oblique-slip vertical faults, and oblique-slip thrusts. The Stanage Fault Zone thus appears to have been a major tear fault system to both the nappe emplacement of the Marlborough Block, and to the in-sequence thrust belt in the footwall.

The orientation of the overall thrust convergence vector appears to be southwest-directed, as indicated by the consistent orientation of tear faults. Strong strain partitioning in the fold-thrust belt makes both the construction of balanced cross-sections and precise estimation of the overall crustal shortening difficult. Fergusson (1991) estimated 60% shortening within the Gogango Overfolded Zone, an estimate consistent with the intensity of cleavage, and an overall upper crustal shortening of 50-90 km across the Gogango Overfolded Zone and Bowen Basin Folded Zone (Figure 2). By matching the eastmost exposures of rocks that we equate with Connors/Camboon Volcanics (Holcombe et al. 1998; Figure 1) north and south of the Stanage Fault Zone, we estimate thrust-tectonic contraction at about 296 Ma (Little et al. 1995), the structurally highest position along the younger Marlborough Thrust. The overall upright antiform is associated with late-stage, low-grade (anchizional) rocks within the older accretionary complex. The thrust can be traced for over 50 km to the south where it splits into a system of imbrications (Sliwa 1994) that are responsible for the >5 km thickness of the Jimna Phyllite (Figure 3). Other east-verging thrust imbrications have now been mapped on the eastern margin of the North D’Aguilar Block (Donchak et al. 1995).

The age of movement on the Claddagh Thrust and its imbricates is poorly constrained between Early Permian and Early Triassic. Both the ca 305 Ma Claddagh Granite (Little et al. 1995) and the Early Permian Marumba beds (Figure 3) are allochthonous within this thrust system. The upper limit for thrusting is the age of the Early and Middle Triassic Toogoolawah Group of the Esk Trough which unconformably overlies these early thrusts. Although poorly dated at this stage, a group of ca 241 Ma K/Ar whole rock and amphibole ages (240.9±11 Ma, hornblende; 241.9±8 Ma, 236±7, whole rock: Irwin 1973; Kerr 1974) from the Nara Volcanics is currently used to constrain the age of this group. The Monsildale Granodiorite is a multi-phased pluton that intrudes subvertical Marumba beds a few kilometres from where it is unconformably overlain by gently dipping Toogoolawah Group rocks (Bryden Formation). Although it is not known whether the pluton stitches the thrusts at depth, K/Ar hornblende ages of 247.5±3 Ma (Sliwa 1994) and 240.1±3 Ma (Kwiecien 1996) on the older phase of the granodiorite provide a minimum age on the thrusting and tilting, assuming that the granodiorite itself has not been involved in the tilting.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages on white mica from the Mt Mee area in the southern North D’Aguilar Block more tightly constrain the lower limit of thrust-related contraction in this area (Holcombe & Little 1994). Whereas the polymetamorphic rocks and syntectonic granitoids in the northern North D’Aguilar Block were exhumed through the blocking temperature for argon diffusion in these minerals (~350°C) during regional extension at about 296 Ma (Little et al. 1995), the structurally deeper epidote-blueschist rocks at Mt Mee remained below this blocking temperature until exhumed rapidly (~0.3 km/my) at ca 260 Ma (261±0.6 Ma to 257.9±0.8 Ma: Holcombe & Little 1994). At Mt Mee, a regional upright antiform is associated with third-generation axial plane fabrics which were initiated under greenschist facies conditions associated with the growth of coarse albite porphyroblasts. (Holcombe & Little 1994). These metamorphic fabrics, and associated mesoscopic folding, become very much more intense adjacent to the North Pine Fault which is the western boundary of this epidote–blueschist facies terrain. Although this fault is now defined by its post-Late Triassic movement, a precursor fault associated with contractual deformation clearly must have been active prior to the rocks passing through the ~350°C isotherm at ca 260 Ma. The rapid exhumation at ca 260 Ma is distinctly younger in age than the regional extension that initiated Bowen Basin sedimentation and is marginally younger than the initiation of thrust-loading sedimentation in the basin. Thus we would interpret the event creating the conditions for rapid exhumation at Mt Mee as being initiation of the regional thrust-fold contraction and the North Pine Fault as a likely early thrust.

**North D’Aguilar Block**

The effects of the Permo-Triassic contractional deformation are subdue in the southeast Queensland section of the New England Fold Belt, relative to the Fitzroy region. The earliest recognisable thrust structure is the west-dipping Claddagh Thrust (Little 1992) in the northern North D’Aguilar Block. The thrust juxtaposes amphibolite facies rocks over low-grade (anchizional) rocks within the older accretionary complex. The thrust can be traced for over 50 km to the south where it splits

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TRIASSIC marine sedimentary and volcanic sequences are preserved adjacent to the margins of the Esk Trough and ('boulder beds') characterise deposits within the axis of thick beds of coarse volcaniclastic conglomerate. Rocks are mainly volcanic-dominated, whereas North D’Aguilar Block. Thus, the present western least a depocentre, if not a fault-bounded basin, during the Neara Volcanics onlap the basement rocks of the margin appears to be broadly depositional and only margin reflects strong post-depositional fold and fault structures (east-verging thrust) but the current eastern Permian unit of unknown age. At the eastern margin of the belt steeply dipping, slightly metamorphosed, pillow basaltic subvertical Esk Formation units overlie a similarly clear defines an asymmetric structure with steeply faulted eastern margin but no basal structures suggestive of an extensional origin (Korsch et al., 1989). The predominant rock types within the Esk Trough are a terrestrial sequence of andesitic, mainly volcaniclastic, rocks (Narea Volcanics), a package of interbedded clastic sedimentary rocks (Bryden Formation) that at least locally underlie these volcanic rocks, and a sandstone-dominated alluvial and lacustrine sequence (Esk Formation) overlying the volcanic strata.

The present margins of the Esk Trough are sharply delineated faults that are characterised by Late Triassic or younger movement such that the original geometry of any trough is uncertain. In the central area of the Esk Trough we have observed local unconformable contacts with underlying sequences on both the eastern and western margin of the belt. At the western margin subvertical Esk Formation units overlie a similarly steeply dipping, slightly metamorphosed, pillow basaltic unit of unknown age. At the eastern margin of the belt in this area the shallowly dipping Bryden Formation is in strong angular unconformity with underlying ?Early Permian rocks, and further north gently tilted units of the Narea Volcanics onlap the basement rocks of the North D’Aguilar Block. Thus, the present western margin reflects strong post-depositional fold and fault structures (east-verging thrust) but the current eastern margin appears to be broadly depositional and only moderately modified by the late strike-slip faulting. Remnants of the Narea Volcanics that overlie the basement rocks are mainly volcanic-dominated, whereas thick beds of coarse volcaniclastic conglomerate ('boulder beds') characterise deposits within the axis of the belt. These data suggest that the Esk Trough was at least a depocentre, if not a fault-bounded basin, during the Early and Middle Triassic. Remnants of Permian marine sedimentary and volcanic sequences are preserved adjacent to the margins of the Esk Trough and may indicate an earlier history to trough development. Ongoing studies indicate that the dominant palaeoflow direction in the Esk Formation was southward and westward. There is, to date, no sedimentological evidence that the present fault margins confined either the coarse conglomeratic facies or the overlying Esk Formation.

Structures and stratigraphic relationships associated with the Esk Trough constrain elements of the Triassic part of the Hunter–Bowen event. The Narea Volcanics lie unconformably over east-verging thrusts along the western margin of the North D’Aguilar Block, providing a minimum age on the initiation of thrusting in this area. The sequences within the Esk Trough are also folded into >1 km-wavelength, strongly asymmetric, east-verging, low- to moderate-amplitude folds and are unconformably overlain by flat-lying 228.4±0.6 Ma volcanics of a later extensional magmatic phase (see below). This folding, constrained within the interval 241–228 Ma, appears to be the last Triassic contractional deformation in the area, and is interpreted as part of the final deformation associated with the Hunter–Bowen event. Fold axial traces generally lie parallel to the axis of the Esk Trough belt except near the fault margins where locally axial traces trend west to west-northwest in a sense that is consistent with a component of dextral wrenching parallel to the trough. West-trending axial traces also occur in fault slices of adjacent Late Permian fault blocks (Northbrook beds; Cressbrook Creek Group) that lie outside the belt. Deformation intensity in this folding event is low and the folds lack axial plane cleavage.

Unlike that in the Fitzroy region, Permian and Triassic thrusting in southern Queensland appears to be thick-skinned and involve basement rocks, rather than thin-skinned. Except for the metamorphic rocks of the Mt Mee area and within the Gympie Block, cleavage is rarely associated with folds related to the Permo-Triassic event in southern Queensland. Thrust vergence in southern Queensland is eastward, in contrast to the consistent westward vergence in central Queensland.

THRUST LOADING SIGNATURES IN BOWEN BASIN SEQUENCES

Development of the Bowen Basin began with extensional sub-basins in the Early Permian (Phase 1 of Fielding et al. 1995) that was followed by a period of thermal sag in the latest Early Permian to early Late Permian (Phase 2). A major change in the petrology and depositional environment of basinal sediments in the Late Permian (Baker et al. 1993) was manifested in the introduction of first-cycle, volcanic lithic detritus shed from the east. The basin developed a marked cross-sectional asymmetry typical of loaded foreland basins (Busby & Ingersoll 1995). Sediments shed westward across the Gogango Overfolded Zone joined major south-flowing, axial drainage systems (Fielding et al. 1995, 1998). Depositional environments were initially marine, but rapidly became coastal plain to alluvial plain systems as the basin was oversupplied with coarse sediment. This change is interpreted as a response to the
onset of thrust loading of the eastern Bowen Basin, and accompanied the resurgence of volcanism to the east (Phase 3, see below).

Carboniferous calc-alkaline volcanics in the Connors Arch (Figure 2) are widely interpreted as describing the position of a magmatic arc along the eastern margin of the Bowen Basin (Day et al. 1978). Fergusson (1991), in contrast, showed the Connors Arch as a structural high produced during Permo-Triassic thrusting. The Connors Arch west of Marlborough is an open, antiformal structure with shallow (<30°) limb dips, complicated locally (particularly on the eastern limb) by steep faults. A complete Permian succession is preserved on both limbs of the antiform and around the southern limit of the Arch (Malone et al. 1969). Continental and shallow-marine Permian sediments are transgressive across Connors Volcanics basement with only local angular discordance. West-directed palaeoflow directions occur in Phase 2 and Phase 3 sequences both east and west of the arch, and no basin-margin facies transitions are evident close to the arch. While Carboniferous volcanics along the arch may have been exposed during formation of the Early Permian extensional sub-basins, these had no topographic expression by the mid-Permian transgression. We suggest, on the basis of the characteristics of Triassic sediments within the Bowen Basin, that a topographic high did not form until the latest Middle Triassic as the thrust front migrated westward across the basin.

The sedimentological transition from thermal sag to thrust loading is exposed in the Moah Creek beds along the Fitzroy River, west of Rockhampton (Fielding et al. 1997b figure 4) where a monotonous sequence of thinly interbedded marine siltstone and fine sandstone passes abruptly upward into disorganised conglomerate and diamicite enclosed within thinly bedded strata similar to the thick interval exposed below. Slump folds encaised in a mud-brecia matrix are interpreted as the products of mainly debris and turbidity flow processes. The lower part of the exposed sequence is typical of the Phase 2 sag sequences and the first evidence of instability is a 5 m-thick, foundered horizon consisting of detached and transported masses of sandstone occurring within the siltstone package about 50 m below the main transition to conglomerate-rich units. The section is interpreted as having accumulated in an unstable submarine environment ahead of an approaching subsurface thrust front with the foundered horizon representing the earliest indication of the approaching front. Similar packages of coarse-grained mass-flow deposits have been recognised at this stratigraphic position over distances of at least 350 km along the eastern Bowen Basin margin (Fielding et al. 1997a).

Within the eastern Bowen Basin, a number of distinct wedges of coarse clastic sediments occur in the Late Permian to Early Triassic succession (Figure 5; Kassan 1994; Fielding et al. 1995). These wedges comprise conglomerates and breccias of metasedimentary, volcanic and intrusive, and intraformational lithologies. Clast composition and palaeocurrent data indicate derivation from a highland to the east, that was associated with active volcanism. Successive wedges appear to have penetrated further west into the basin (Figure 5). We interpret them as arising from pulses of thrusting in a rising hinterland to the east. In the case of the initial pulses recorded in the Late Permian sequences (such as the Moah Creek beds described above) this active volcanic hinterland was to the east of the current coastline. Elliott (1993) and Korsch and Totterdell (1995) have documented two discrete periods of thrust deformation within the Triassic Bowen Basin fill from seismic data. Each thrusting episode followed a period of westward propagation of a coarse clastic wedge, the later (late Middle Triassic) event terminating sediment accumulation across the entire basin.

**EARLY AND MIDDLE TRIASSIC CALC-ALKALINE SUITES**

About half of the exposed granitoid ages in the northern New England Fold Belt have K/Ar ages between 250–230 Ma (Gust et al. 1993), within the later part of the broad Hunter–Bowen thrust event. The granitoids are widely distributed throughout the fold belt south of Broad Sound and east of the Gogango Overfolded Zone and are predominantly intermediate in composition. The plutonic rocks are coeval with terrestrial volcanism that is overwhelmingly andesitic in composition.

![Figure 5 Time-stratigraphic distribution of coarse clastic sediment wedges shed into the Bowen Basin from the east, showing the extent and episodic nature of coarse siliciclastic sediment derived from the approaching thrust front to the east. Bar marked Au deposits indicates age range for K/Ar ages from structurally focused gold mineralisation in the northern New England Fold Belt. Small bars indicate specific K/Ar ages from ilite in the Bowen Basin (Faraj et al. 1996) interpreted as fluid-flux event(s). Three periods of thrust deformation are shown; the earliest is constrained mainly by 40Ar/39Ar dating in southeast Queensland, whereas the second and third are recognised from seismic records across the Bowen Basin (Korsch & Totterdell 1995).](image-url)
Volcanic rocks of this age are poorly represented north of the Stanage Fault Zone at Broad Sound, although Triassic radiometric ages are recorded from intrusives and minor volcanic rocks in the Whitsunday region (Ewart et al. 1992; Parianos 1993; Allen et al.; C. M. Allen pers. comm. 1996) and from mafic dykes and minor granitoid intrusions within the Urannah Complex (Allen et al. 1994; C. M. Allen pers. comm. 1996). Andesitic volcanic and volcanioclastic sequences south of Broad Sound unconformably overlie basement of Devonian–Carboniferous to Late Permian age.

**LATE TRIASSIC EXTENSIONAL BASINS AND MAGMATIC SUITES**

**High-level granites and volcanics**

In contrast to the intermediate-dominated composition of Early and Middle Triassic granitoids of southern Queensland, the Late Triassic (ca 230–220 Ma) is characterised by intrusions of predominantly silicic granite composition associated with the development of volcanic complexes of rhyolite and minor mafic lava and ignimbrite (Stephens et al. 1993). One large-scale caldera associated with ignimbrite development has been identified within these units (Stephens 1992) and the restricted distribution of many of these sequences suggests that other calderas may be present. Ignimbrites correlated with this event are unconformable on Early to Middle Triassic andesite in the northern Esk Trough.

In southern Queensland flat-lying andesite giving an $^{40}\text{Ar}/^{39}\text{Ar}$ cooling age of 228.4±0.6 Ma on amphibole unconformably overlies folded Early to Middle Triassic rocks (Little et al. 1993). Elsewhere, hornblende in the same sequence yielded a concordant $^{40}\text{Ar}/^{39}\text{Ar}$ total fusion age of 232±4 Ma (C. G. Murray pers. comm. 1992) and ca 225 Ma $K/\text{Ar}$ ages have been derived from similar andesitic and rhyolitic flows and dykes that overlie basement rocks in the North D'Aguilar Block (Holcombe et al. 1997 table 1; Roberts 1992; Sliwa 1994). The Station Creek Adamellite, which intrudes rocks of the North D'Aguilar Block, provides important constraints on the timing of events in the area as it also intrudes the thrust sheets within the North D'Aguilar Block and may be comagmatic with the overlying volcanics. We have recently obtained $^{40}\text{Ar}/^{39}\text{Ar}$ step heating plateau ages of ca 236 Ma and 232.8±0.4 Ma on biotite from this body, although the data have not yet been completely interpreted.

These Late Triassic volcanics and plutons are largely undeformed, although the Station Creek Adamellite on the northeastern flank of the North D'Aguilar Block is locally faulted and ductilely sheared (Edgar 1992; J. Tang pers. comm. 1996), and there is local brittle-ductile deformation in the North Arm Volcanics, to the east of the North D'Aguilar Block.

**Extensional basins**

The change in character of magmatism to silicic volcanioclastic structures was accompanied by development of small to moderate-sized north-northwest-longate basins with coarse-grained, grossly fining-upward, alluvial fills, thick localised coal bodies and evidence of synchronous bimodal volcanism. Basins of this nature include the Ipswich (Falkner 1986; Staines et al. 1995) and Tarong Basins (Pegrem 1995) and part of the Callide Coal Measures (Biggs et al. 1995). The Tarong Basin has a half-graben geometry (Williams 1993) as do a number of less well-described coeval basins in the subsurface (Wiltshire 1982). Although the cross-sectional geometry of the other major basins is not well constrained, our work (CRF unpubl. data) suggests that these basins are probably similar in geometry. Bimodal volcanism is most evident within the Ipswich Basin where basalt flows and a significant felsic pyroclastic unit (Brisbane/Hector Tuffs) lie at, or near, the base of the sequence. All three of the basins studied thus far contain abundant thin felsic tuffaceous horizons within coal-dominated sequences.

Models proposed for the origin of these basins are diverse (Murphy et al. 1976; Falkner 1986; Korsch et al. 1989; Pegrem 1995) but on the basis of the asymmetric cross-sectional basin geometry and regional association with extensive coeval bimodal volcanic sequences, we regard the basins as characteristic of an extensional tectonic environment.

**YOUNGER BASINS AND STRUCTURES**

The post-Triassic evolution of the region is marked by development of extensive, Jurassic–Cretaceous basins (e.g. Surat Basin, Clarence–Moreton Basin, Maryborough Basin) across the Late Triassic extensional basins. One of these basins that impacts on the interpretation of structures seen within the fold belt is the Maryborough Basin which, unlike others of its age, is gently to moderately folded. This deformation, which is constrained stratigraphically as mid-Cretaceous or younger, is the only recognised post-Triassic contractional episode in the region. It is most likely the event in which much of the late regional faulting within the northern New England Fold Belt formed. Effects of this deformation include small-displacement reverse faults that cut the Mesozoic basin rocks throughout southern Queensland, and presumed coeval faults of similar geometry and kinematics within the fold belt.

Major faults, commonly with ~10 km sinistral strike-slip, broadly define the structural grain of southern Queensland. Almost all of the older terranes are bounded by these younger faults which locally displace plutons of the ca 230–220 Ma magmatic suite. Examples of these faults exploiting the older fault architecture occur in the North D'Aguilar Block, where Early Permian synmetamorphic deformational structures intensify toward the North Pine Fault. This fault, however, appears to have sinistrally offset several Late Triassic plutons and a Late Triassic volcanic formation by ~8 km. The North Pine Fault is continuous with the composite Perry Lineament to the north, where a Late Triassic (ca 221 Ma) volcanic complex shows a sinistral
strike displacement of about 9 km (Stephens 1991).

Similar sinistral strike-slip faults occur in the central Queensland part of the northern New England Fold Belt [e.g. the Broad Sound Fault with ~20 km strike separation (Figure 2); offshore in the Whitsunday region (Ewart et al. 1992)] but fault patterns in the northern region are dominated by steep normal faults that bound the numerous Cretaceous and Tertiary Basins (e.g. the Cretaceous Styx Basin and the Tertiary Duaringa Basins).

**DISCUSSION**

The major contractual period defined here as the Hunter–Bowen event lasted for about 35 million years, from ca 265 to ca 230 Ma. Stratigraphic evidence from the foreland basin fill suggests that this event was strongly pulsed and that successive thrust pulses penetrated further into the basin. The final contractual event appears to have re-initiated at the eastern margin of the fold belt, rather than step westward from the previous thrust front, and to have been more intense than previous pulses. The presence of a broadly synchronous magmatic event within the northern New England Fold Belt suggests that arc magmatism was superimposed on the actively rising mountain belt.

In the Fitzroy region the commencement of thrust contraction is constrained as Late Permian (ca 265 Ma). The oldest sedimentary unit in this region that was derived from the approaching thrust front (and subsequently involved in the thrusting) lies within the Late Permian Moah Creek beds, Barfield Formation and the equivalent Boomer Formation. The maximum age on thrusting is thus constrained to Kazanian on biostratigraphic evidence (Fielding et al. 1997b). Episodic deformation in the Fitzroy area is indicated by the out-of-sequence thin-skinned emplacement of the Marlborough thrust nappe. This thrust overrides earlier thrusts that involve latest Permian rocks (Dinner Creek Conglomerate), and the only other constraint on the timing of this thrust are 248.8±0.9 Ma and 242.9±0.4 Ma 4°Ar/39Ar cooling ages on biotite in sheared and foliated meta-granites that we surmise were related to a deeper seated, earlier, thrust environment. The presence and magnitude of the nappe indicates a significant renewal of a contractual deformation from the east after this time.

The initiation of thrusting is less constrained in southern Queensland, but there is a clear indication of two phases of contractual deformation separated by an interval of calc-alkaline magmatism. On the western margin of the North D’Aguilar Block, thrusts that carry the Late Carboniferous Claddagh Granite and the ?Early Permian Marumba beds are unconformably overlain by the Early to Middle Triassic (ca 241 Ma) volcanic sequence of the Esk Trough. The youngest age for these thrusts is thus ca 241 Ma, but the oldest age is poorly constrained. Nonetheless, the white mica 4°Ar/39Ar ages from the Mt Mee area indicates rapid exhumation of the metamorphic basement rocks at ca 260 Ma, an event that may relate to the commencement of Hunter–Bowen contractual deformation in this area and an age that is consistent with initiation of this event elsewhere.

Termination of the thrust and folding events in southern Queensland is constrained to the interval 241–228 Ma. The folded Early and Middle Triassic volcanic succession within the Esk Trough is unconformably overlain by ca 228 Ma flat-lying intermediate volcanics but related rocks in the region have a range of K/Ar ages from ca 235 to 225 Ma. (Holcombe et al. 1997 table 1). The new ca 235 Ma 4°Ar/39Ar ages we have obtained on the Station Creek Adamellite (see above), might provide an even tighter constraint on the age of the terminal Hunter–Bowen folding in this area.

Analysis of radiometric dates (Gust et al. 1993) and local detailed mapping (Stephens 1992) clearly distinguishes the presence of Early and Late Triassic volcanic rocks of contrasting composition and style. All of these Triassic volcanics were grouped during the initial 1:250 000-scale mapping of the northern New England Fold Belt, and only recently has the presence of two compositionally distinct events been reflected in the stratigraphic nomenclature (Cranfield 1994).

Early and Middle Triassic magmatism has not been systematically studied at this time, but data on granitoids and volcanics (unpublished theses at University of Queensland and Queensland University of Technology) and limited isotopic data from volcanics in the Esk Trough (Ewart et al. 1992) show not only the calc-alkaline character of this event but the overwhelmingly intermediate composition of the rocks. These data are consistent with a period of continental margin arc-related magmatism during the Early and Middle Triassic. Such an interpretation is supported by the observation that the Late Permian–Early Triassic sediments derived from the approaching thrust front to the east contain first-cycle volcanic detritus. Holcombe et al. (1990) and Fielding et al. (1997) emphasise that there is no evidence in the Early to mid-Permian rocks of the northern New England Fold Belt for the presence of an arc-related volcanic terrane. In tectonic terms, the Permo-Triassic magmatism thus requires the initiation of subduction below the region, or the migration of the arc onshore from a position somewhere to the east, during the Hunter–Bowen contraction event.

Stephens (1992) and Stephens et al. (1993) interpreted Late Triassic silicic volcanism in terms of an extensional tectonic environment. Criteria cited included the discrete, caldera-forming nature of the volcanism, characteristic of continental extensional environments, the bimodal, silicic-dominated composition of the volcanics, and the regional silicic granite-dominated composition of coeval intrusives. These data suggest that the relatively rapid re-establishment of voluminous arc magmatism within the New England Fold Belt during the Permo-Triassic, clearly associated with a broader cycle of tectonic contraction, was replaced during the Late Triassic by an extensional environment and crustal melting of the recently arc-impregnated crust. The latest Triassic is further characterised by localised, discrete caldera development and emplacement of granite with mild A-type geochemical affinities (Stephens 1992; Gust et al. 1993), supporting the concept that the region underwent a transition from
convergence to extension that continued into the latest Triassic.

The position and nature of any arc that operated after the Middle Triassic, or of any Permo-Triassic subduction complex, is uncertain. However, a possible mechanism for the transition from presumed subduction to extension during this time may lie in one of our suggested interpretations of the Late Carboniferous–Early Permian evolution of the northern New England Fold Belt (Holcombe et al. 1997). We suggest one possible scenario is that the subducting slab again underwent roll-back during the late Middle Triassic driving extension and resulting in re-establishment of the volcanic arc some distance to the present east of the New England Fold Belt (and the present coastline). Voluminous first-cycle volcaniclastic debris and numerous tuffs within the Surat Basin (Exon 1976) suggest that volcanism sourced from an unidentified terrane continued through the Jurassic leading up to the major Early Cretaceous breakup-related magmatism (Ewart et al. 1992).

**Metallogenetic aspects**

Two major styles of mineralisation are associated with the broad Hunter–Bowen event in the northern New England Fold Belt. Porphyry-style mineralisation is commonly developed in association with the Permo-Triassic calc-alkaline intrusives of the fold belt (Horton 1978). Of somewhat more enigmatic origin is the occurrence of epithermal gold mineralisation, associated with quartz-rich alteration systems, and locally with carbonate veining, that consistently gives ca 245–235 Ma K/Ar alteration ages. Examples include the major deposits of Cracow and Gympie, plus the smaller deposits at Manumbar in the North D’Aguilar Block, Mt Mackenzie in the southern Connors Arch, and perhaps at Mt Wickham in the northern Connors Arch. We also include mineralisation at Rannes, in the Gogango Overfolded Zone, in this association on the basis of alteration style and structural association. In some instances, such as at Gympie and Rannes, mineralisation is within thrust-related sheared or cleaved rocks. In others, such as Cracow, Mt Mackenzie and Mt Wickham, mineralisation is more typical high level, mesothermal to epithermal in nature.

A line of significant gold deposits occurs along the eastern margin of the Bowen Basin, including Cracow, Rannes, Mt Mackenzie and Mt Wickham. Of these occurrences, only Rannes occurs within strongly thrust-deformed rocks. At Rannes, well-developed silicic alteration systems associated with gold and minor base-metal mineralisation occur in locally sheared Camboon Volcanics. Mineralisation appears to occur both on thrusts and in zones that cut across the thrust trend at a high angle. The other deposits comprise more classical alteration systems of similar high-T, low-P grade, but also overprint the Late Carboniferous–Early Permian volcanic succession.

Further east at Gympie, strain is strongly partitioned in the volcaniclastic sandstones of the Rammutt Formation. Where cleavage is developed, it is a strong pressure-solution fabric and is accompanied by a marked stretching lineation defined both by the shape of pressure-solved clasts and, more particularly, by mica beards and fringes developed on clasts. A characteristic feature of these rocks is the development of a network of fine extensional veins perpendicular to the stretching lineation, and infilled with fibrous quartz (and minor carbonate) that are parallel to this lineation. Similar veins sets occur perpendicular to the stretching lineation in the gold-bearing black slates and are known locally as the ‘Gympie vein set’. These veins (and the associated mineralisation) are thus syntectonic with the cleavage-forming deformation, and alteration associated with these veins has given a K/Ar age of ca 235 Ma (Cuneen 1994).

Gold mineralisation at Manumbar in the North D’Aguilar Block occurs in carbonate–quartz veins within rocks equated to the Early Triassic Neara Volcanics. Mining is currently occurring in a single, major vein, but numerous en echelon swarms of fibrous extensional veins occur in the field. There is no other obvious deformation apart from the brittle–ductile deformation associated with the vein swarm, and alteration associated with mineralisation has yielded a ca 235 Ma age (M. Garman pers. comm. 1995).

In all cases, the deposits are localised in volcanic or volcaniclastic rocks, and in areas that are characterised by late (i.e. post-Permian) Hunter–Bowen structures. The line of deposits along the eastern margin of the Bowen Basin occur along the western limb of the structural arch that defines the basin margin and which we regard as forming during the Middle Triassic. The timing of mineralisation clearly just precedes the late, major contractional pulse that closed the basin, and is broadly coeval with K/Ar ages on mineralogically pure cleat-filling illite in the Late Permian coal measures (Figure 5). We believe that this late pulse of the Hunter–Bowen event not only was responsible for the development of the structural Connors–Auburn Arch, but also promulgated a major fluid flux within structures deforming the northern New England Fold Belt and through sediments and structures within the eastern Bowen Basin (Faraj et al. 1996). The meteoric composition of the mineralising fluids at Cracow (Golding et al. 1987) is interpreted to reflect the nature of fluids generated during this event.

**Possible allochthony of the Yarrol/Calliope terranes**

The thrust geometries of the Gogango Overfolded Zone shown in the cross-sections of Figure 5 are regarded as a reasonable extrapolation of the available surface data. Strong strain partitioning and disruption by Cretaceous and Tertiary faults, however, makes confident interpretations of these sections to depth difficult. One source of variation in interpretation based on extrapolation of these sections, however, is that placed on the geometry of the Berserker Block. We have noted that basement to the footwall rocks of the Rookwood Thrust is
consistently Connors Volcanics or equivalents, whereas basement to the hangingwall rocks is consistently rocks of the Yarrol/Calliope terranes. If the Berserker Block is stratigraphically equivalent to the Connors Volcanics (*sensu lato*), as suggested by Holcombe et al. (1997), then the simplest geometry that satisfies this structural and stratigraphic interpretation is that the Berserker Block (Figure 2) is a window through the Rookwood Thrust system. The implication of this interpretation is that the hangingwall, with its Siluro-Devonian basement, is very thin skinned and must have a displacement of several tens of kilometres. The ramifications of such a model are that: (i) both the Calliope and Yarrol terranes may be very thin (<2 km); (ii) since both the hangingwall and footwall of the Rookwood Thrust contain Bowen Basin sequences, the thrust displacement of the allochthonous terranes would not be expected to greatly exceed a few tens of kilometres; and (iii) the Tungamull and Parkhurst Faults are part of a single imbricate thrust system (albeit reactivated during Cretaceous–Tertiary normal faulting) carrying allochthonous terranes that include both the accretionary rocks and elements of the Yarrol terrane.

While these interpretations are highly speculative, they do bear upon matters such as the position of the continental margin and accretionary complex during the Early Carboniferous and older convergent tectonic events.

**Gympie Block: how allochthonous is it?**

We see a paradox in the histories of different age packages of cleaved rocks of the North D'Aguilar Block. The cleaved Early Permian Cambroon beds on the eastern margin of the North D'Aguilar Block are in fault contact to the west with the ?Early Carboniferous Booloumba beds of the accretionary terrane (Figure 3) and structural relationships suggest considerable translation on this fault (tentatively correlated with an early phase of movement on the Bracalba Fault: Sliwa 1994). The folded chert–argillite sequences of the Booloumba beds contain a single upright cleavage characteristic of the anechzonal (upper plate) accretionary rocks that we interpret as being developed during the mid-Carboniferous accretion. There are, however, no overprinting cleavage fabrics in the older rocks that correspond to the cleavage present in the adjacent Early Permian rocks. That the cleavage-forming event in the Early Permian rocks was not sufficiently intense to be transmitted into the basement rocks is considered unlikely, given the polydeformational fabrics in the Permian rocks at some localities. More likely, the fault separating the two units has considerable displacement and was active after cleavage formation in the Early Permian rocks, but before the boundary was intruded by Late Triassic (*ca* 220 Ma) granite. The amount of any such displacement is unknown but must be sufficient to have juxtaposed rocks of entirely different deformational responses to the same event.

Terranes east of the Cambroon beds that may have been included in such a displacement include remnants of the accretionary rocks and the Early Permian–Early Triassic units of the Gympie Block. The concentration of post-Early Permian brittle and ductile deformation along the eastern margin of the North D'Aguilar Block, the probability of significant translation on the Bracalba (?) Fault, and the presence of Middle Triassic cleavage-forming deformation in the Gympie Block, suggests that the units of the Gympie Block also have been translated, to some degree, into its present location. Holcombe et al. (1997) noted the similarity of the Early Permian sediments and volcanics in the Gympie Block with other extensional marine basin sediments in the most eastern parts of the northern New England Fold Belt. In contrast with the much less cleaved rocks in the adjoining blocks in southern Queensland, the style of deformation in the Gympie Block with its widespread cleavage, and variable cleavage intensity and orientations typical of thrust terranes, is similar to that in the rocks of the fold-thrust belt that we have studied in the Fitzroy area to the north. We suggest that the Gympie Block may be an element of a more northerly terrane of the northern New England Fold Belt that has been displaced south by dextral strike-slip motion during the later part of the Hunter–Bowen event. We would speculate that it initiated as one of the suite of Early Permian marine extensional basins that formed within the old accretionary terranes along the New England Fold Belt, thus accounting for its present location to the east of the southern accretionary exposures.

The well-cleaved ?Early Triassic Kin Kin Phyllite is the youngest rock unit in the Gympie Block and thus any major strike-slip displacement must post-date that time and yet be completed by the end of Hunter–Bowen contraction at *ca* 230 Ma. Typical strike-slip fault displacement rates in California are within the range of 1–10 mm/y, increasing to 25–35 mm/y for the San Andreas plate margin system (Petersen & Wesnousky 1994). Hence a moderately fast movement rate of 10 mm/y would produce 100 km of displacement over 10 million years. We have noted that the ultimate Hunter–Bowen contractional event was more intense than previous pulses, and that it produced out-of-sequence thrust nappe structures at the eastern margin of the fold belt. It is this event that would be the most likely driving force for any displacement of the Gympie Block, although movement rates would have to be 10–20 mm/y.

**The New England Fold Belt 'double orocline' and dextral wrenching**

A major factor in the consideration of possible displaced terranes in the northern New England Fold Belt has been the problem of explaining the major double orocline flexure in northern New South Wales and southern Queensland. Murray et al. (1987) developed a model for the formation of the orocline flexure involving large scale dextral displacement of terranes in the eastern New England Fold Belt on a transform fault during the Late Carboniferous. This model, and
subsequent variations (Fergusson et al. 1993) postulate a large displacement (~500 km) dextral strike-slip fault in the northern New England Fold Belt that accommodates the oroclinal bending to the south. A major problem with this model has been the lack of documented dextral strike-slip structures of that age in the northern New England Fold Belt, although any such structure could well be masked by the later contractional deformation.

We would suggest that the most likely deformation event with the required geometry to produce the dextral oroclinal flexure would be during the Hunter–Bowen event. In the northern New England Fold Belt, the original meridional structural grain that was imparted by the Early Carboniferous accretionary events was overprinted by a north-northwest-trending grain transverse to west-southwest-verging thrusts during the Hunter–Bowen event. A west-southwest contractional vector would provide an ideal structural environment for dextral slip on the pre-existing structural grain.

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