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Structural history of the Greenvale Province, north Queensland: Early Palaeozoic extension and convergence on the Pacific margin of Gondwana

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Abstract

The southeastern Georgetown Inlier (Greenvale Province) consists of Early Palaeozoic metamorphic rocks in fault contact along the Lynd Mylonite Zone with the Palaeoproterozoic to Mesoproterozoic craton of northeastern Australia. It has a central assemblage of metamorphosed silicic volcanic and sedimentary rocks considered equivalent to the Late Cambrian to Early Ordovician Seventy Mile Range Group that developed in an extensional backarc in the Charters Towers Province to the southeast. In the western part of the Greenvale Province the Oasis Metamorphics has a U-Pb zircon SHRIMP metamorphic age of 476 ± 5 Ma and is intruded by the granodioritic Lynwater Complex with U-Pb zircon ages of 486 ± 5 Ma and 477 ± 6 Ma. These ages are consistent with these rocks forming basement and intrusive equivalents to the extensional volcanic basin. Existing geochronological constraints on the Halls Reward domain, located at the eastern margin of the province, are consistent with it being basement to the extensional basin. Several domains are recognised in the Greenvale Province with either dominantly steep or low to moderate dips of the main foliation and each experienced multiple deformation with locally up to four overprinting structural phases. Steepening of foliation in several of the domains is attributed to contractional deformation in the Early Silurian that is inferred to have overprinted low-angle foliation developed during extensional tectonics in the backarc setting. Contractional deformation related to the Early Silurian Benambran Orogeny is considered responsible for multiple deformation in the Greenvale Province and reactivation of domain-bounding faults.

Keywords

Structural, history, Greenvale, Province, north, Queensland, Early, Palaeozoic, extension, convergence, Pacific, margin, Gondwana, GeoQUEST

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Structural history of the Greenvale Province, north Queensland: Early Palaeozoic extension and convergence on the Pacific margin of Gondwana

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Running Title: Structural history of the Greenvale Province

The southeastern Georgetown Inlier (Greenvale Province) consists of Early Palaeozoic metamorphic rocks in fault contact along the Lynd Mylonite Zone with the Palaeoproterozoic to Mesoproterozoic craton of northeastern Australia. It has a central assemblage of metamorphosed silicic volcanic and sedimentary rocks considered equivalent to the Late Cambrian to Early Ordovician Seventy Mile Range Group that developed in an extensional backarc in the Charters Towers Province to the southeast. In the western part of the Greenvale Province the Oasis Metamorphics has a U-Pb zircon SHRIMP metamorphic age of 476 ± 5 Ma and is intruded by the granodioritic Lynwater Complex with U-Pb zircon ages of 486 ± 5 Ma and 477 ± 6 Ma. These ages are consistent with these rocks forming basement and intrusive equivalents to the extensional volcanic basin. Existing geochronological constraints on the Halls Reward domain, located at the eastern margin of the province, are consistent with it being basement to the extensional basin. Several domains are recognised in the Greenvale Province with either dominantly steep or low to moderate dips of the main foliation and each experienced multiple deformation with locally up to four overprinting structural phases. Steepening of foliation in several of the domains is attributed to contractional deformation in the Early Silurian that is inferred to have overprinted low-angle foliation developed during extensional tectonics in the backarc setting. Contractional deformation related to the Early Silurian Benambran Orogeny is considered responsible for multiple deformation in the Greenvale Province and reactivation of domain-bounding faults.

KEY WORDS: Contractional deformation, extensional tectonics, metamorphic rocks, north Queensland, Palaeozoic, U–Pb zircon ages, Tasman Line.

INTRODUCTION

The Tasman Orogenic Zone is considered an accretionary orogen formed by dominantly convergent margin related processes involving extensional and contractional orogenesis, widespread magmatic activity and sedimentary basin evolution (Coney *et al.* 1990; Collins

2002; Gray *et al.* 2003; Glen 2005). In northeastern Australia, the Tasman Orogenic Zone is divided into several units including the Thomson Fold Belt, and the Broken River and Hodgkinson Provinces (Figure 1). The exposed part of the Thomson Fold Belt includes the Anakie Inlier, Charters Towers Province, and the southeastern part of the Georgetown Inlier herein termed the Greenvale Province. On the basis of reconnaissance K-Ar, Rb-Sr and chemical dating of zircon and monazite it has been inferred that the Delamerian Orogeny at 510–500 Ma was the major metamorphic and deformational event in the Halls Reward Metamorphics in the eastern Greenvale Province (Nishiya *et al.* 2003). This is consistent with K-Ar ages of 500 Ma for metamorphic cooling from the Anakie Metamorphic Group in the Anakie Inlier (Withnall *et al.* 1996).

We have conducted a structural transect across the structural grain of the Greenvale Province with the aim of resolving the nature of the Early Palaeozoic deformation history and tectonic setting of the Early Palaeozoic margin. Several domains are recognised each with distinctive structural histories and having either dominant steeply dipping or low-angle orientation of the main foliation. In the western part of the Greenvale Province three new SHRIMP U-Pb zircon ages provide constraints on the depositional, plutonic and deformational history. These new data indicate significant Early Ordovician foliation development in the western Greenvale Province and require reassessment of the significance of the Delamerian Orogeny in northeastern Australia. We present a new interpretation of the Early Palaeozoic tectonic history of the Tasman Orogenic Zone in northeastern Australia and also reassess the significance of the Tasman Line, the contact between the Tasman Orogenic Zone and the Palaeoproterozoic to Mesoproterozoic craton (Direen & Crawford 2003).

REGIONAL SETTING AND LITHOSTRATIGRAPHY

Three main assemblages of Palaeozoic and older age rocks occur in the Georgetown Inlier and adjacent Broken River Province near Greenvale, north Queensland: (1) Palaeoproterozoic to Early Mesoproterozoic Einasleigh Metamorphics of the Georgetown Inlier, (2) Early Palaeozoic metamorphic units and intrusions of the southeast Georgetown Inlier, herein referred to as the Greenvale Province, and (3) slightly metamorphosed to unmetamorphosed sedimentary and volcanic units of the Broken River Province (Withnall *et al.* 1997). The Einasleigh Metamorphics are a unit dominated by biotite gneiss and calc-silicate gneiss; minor leucocratic gneiss have ages of 1700–1550 Ma in the area immediately west of the Lynd Mylonite Zone (Black *et al.* 2005; Figure 1).

In the Greenvale Province, Early Palaeozoic metamorphic rocks have been divided into a number of rock units whose lithostratigraphy, metamorphism and structure has been described by Withnall (1989), Withnall *et al.* (1997, 2002) and outlined in Table 1. Several domains are recognised from west to east across the northerly to northeasterly trending structural grain away from the Palaeoproterozoic to Early Mesoproterozoic craton (Figure 2).

The Lynd domain lies between the Lynd Mylonite Zone and the Balcooma Mylonite Zone and consists of a metamorphic unit (Oasis Metamorphics) and deformed plutonic rocks (Lynwater Complex). These units were recognised by Withnall *et al.* (2002) who suggested that they were likely to be either Neoproterozoic or Early Palaeozoic rather than part of the Palaeoproterozoic–Mesoproterozoic Einasleigh Metamorphics (Withnall 1989; Withnall *et al.* 1997). Confirmation of this younger age is provided by new U–Pb zircon ages reported herein that indicate the Oasis Metamorphics were both metamorphosed and intruded by the Lynwater Complex in the Early Ordovician.

The Balcooma domain is located between the Balcooma Mylonite Zone in the west and the northeast-trending Early Silurian Dido Tonalite in the east. It is dominated by the Early

Palaeozoic metavolcanic and metasedimentary succession of the Balcooma Metavolcanic Group, considered an equivalent of the Upper Cambrian to Lower Ordovician Seventy Mile Range Group in the Charters Towers Province (Huston 1990; Withnall *et al.* 1991, 1997). A metavolcanic assemblage, the Lucky Creek Metamorphic Group, consists of mafic to silicic volcanic and volcanoclastic rocks and dominates the Lucky Creek domain east of the Dido Tonalite (Withnall 1989, 2004). The eastern part of the Lucky Creek Metamorphic Group consists mainly of the Paddys Creek Phyllite that has a more complex structural history than other units assigned to the group and is separated as the Paddys Creek domain (Tables 1, 2). The Halls Reward domain consists of the Halls Reward Metamorphics and the Boiler Gully Complex and lies between the Nickel Mine and Halls Reward Faults (Figure 2).

East and southeast of the Georgetown Inlier is the Broken River Province with two main subprovinces (Arnold & Henderson 1976). The western Graveyard Creek Subprovince has a thick Early Ordovician to Carboniferous sedimentary assemblage overlying Early Palaeozoic mafic and silicic volcanics (Donaldsons Well Volcanics), related tonalite (e.g. Saddington Tonalite) and mafic/ultramafic basement (Gray Creek Complex; Withnall & Lang 1993). These rocks developed in a continental margin setting with the Silurian to Devonian units interpreted as part of a forearc basin (Henderson 1987). The eastern Camel Creek Subprovince is dominated by highly deformed Ordovician to Devonian turbidite successions with lesser chert and mafic volcanics that have been interpreted as part of an east-facing subduction complex (Henderson 1987). A magmatic arc associated with both these features may be represented by Palaeozoic intrusive complexes to the west in Palaeozoic and Precambrian metamorphics (Henderson 1980).

STRUCTURAL TRANSECT

We describe the main structural features along a west to east transect across the Greenvale Province (Figures 2, 3); the structural succession is summarised in Table 2, although it is important to note that deformations are specific to individual domains and are not necessarily matched across the whole transect. The Lynd Mylonite Zone, marking the western extent of Palaeozoic metamorphics (Figure 2), is represented by intensely foliated granitic gneiss with steeply dipping to vertical foliation that strikes north-northeast (mean of 80°/308° from four measurements). Exposure is limited in the transect area and no detailed information on shear sense is available, but 10 km along the mylonite zone to the south-southwest, just beyond the map area in Figure 2, Withnall (1989, p. 89) noted an east-over-west shear sense based on sigmoidal asymmetry in feldspar porphyroclasts with a steeply pitching lineation in the foliation. To the west, in the Einasleigh Metamorphics, foliation is much weaker and trends easterly at a high angle to the mylonite zone. East of the Lynd Mylonite Zone, the Oasis Metamorphics contain two foliations (Table 2) with the earlier layering/foliation defining the most obvious structure and defined by aligned diopside and hornblende in calc-silicate gneiss, biotite, quartz and feldspar in pegmatite, biotite and quartz in schist and gneiss, and amphibole in amphibolite. The main foliation (S_g) along with lithostratigraphic units is tightly folded by plunging F_2 that overall verge west on the eastern limb of a largescale antiform (Figures 3, 4a-d). Amphibolite metamorphism accompanied the D_1 deformation in the Oasis Metamorphics with granitic veins and segregations formed subparallel to S_g and also along the axial planes of rare mesoscopic F_2 folds. Larger lenticular granitic masses are present throughout the metamorphics and contain weak to locally strong foliation (labelled S_f , Figure 4c). No pervasive fabric development accompanied D_2 indicating that it was not accompanied by an appreciable metamorphic overprint of pre-existing mineralogies. The meta-igneous

Lynwater Complex contains a steeply dipping, northerly striking foliation defined by aligned quartz, feldspar and biotite in addition to amphibolite enclaves.

The Balcooma Mylonite Zone consists of mylonitised rocks of the Oasis Metamorphics and metarhyolite of the Balcooma Metavolcanic Group (Figures 4e, 5, 6a). It is at least 1 km in width and in the area of Figure 5 has been offset by several easterly trending faults with apparent dextral strike-slip displacements of up to 2 km (Withnall 2004). Rocks in the mylonite zone contain a ubiquitous, intense foliation (S-plane) overprinted locally by an obliquely orientated, widely spaced foliation (C-plane) indicative of sinistral shear (Figures 5, 6a).

Structure of the Balcooma Metavolcanic Group has been studied in detail around the Balcooma massive sulphide deposit some 20 km northeast of the area shown in Figure 5 by Huston (1990) and Withnall *et al.* (1991) with more regional work undertaken by Withnall (1989). Huston (1990) recognised four deformations with the main deformation (D₂) responsible for the prominent foliation evident in the assemblage and near isoclinal folding (Withnall *et al.* 1991; Table 2). We have mapped dominant S₂ in the Balcooma Metavolcanic Group (Figure 4f-h) that grades into the intense mylonitic foliation of the Balcooma Mylonite Zone implying that the D₂ deformation and sinistral movement along the boundary fault were at least partly overlapping. Note that the northeasterly trend of the Balcooma Metavolcanic Group represented in Figure 5 is a local feature; regionally the unit trends north-northeasterly (Withnall 1989). Amphibolite facies metamorphism is indicated by widespread staurolite and andalusite in pelitic schist aligned along the main S₂ foliation and associated with the D₂ deformation north of the transect area (Withnall 1989).

The Dido Tonalite of Early Silurian age (Bain *et al.* 1997) has a weak to locally strong foliation trending subparallel to the northeast trend of the elongate pluton and typically steeply dipping that was considered synchronous with intrusion (Withnall 1989). The steep orientation of the foliation is consistent with contractional deformation.

Metavolcanic and metavolcaniclastic units of the Eland Metavolcanics in the Lucky Creek domain (Figure 7) have an intense foliation, S₂, defined by chlorite, muscovite and actinolite with hornblende at higher metamorphic grades in addition to flattened and stretched fragments in metasandstone and metaconglomeratic units (Figure 6b, c). S₁ is rarely preserved (Table 2). The S₂ foliation dips mainly steeply to the northwest but is folded about F₃ which plunge moderately to the southwest (Figures 7, 8a). A strong lineation is formed from intersection of early layering with the main foliation and also from stretching of lithic fragments and mineral elongation consistent with high strain (Withnall 1989). Lineation is moderately to steeply plunging to the southwest (Figure 8b). Locally in the Eland Metavolcanics shear bands are developed at *ca* 20° oblique to S₂ (Figures 6d, 8c) and have mainly a dextral shear sense. When unfolded to the west the dextral shear bands imply west-over-east transport consistent with higher metamorphic grade to the west. In the eastern part of the domain upright F₃ folds plunge at 40° or less (Table 2, Figure 8d) and indicate that S₂ initially formed at a moderate to low inclination. Overall the Paddys Creek Phyllite has a lower metamorphic grade than the Lucky Creek domain but exhibits a more complicated structural history with four main deformations (Table 2, Figures 8e-h, 9, 10a, b). The low dip of S₂ in this domain and the metapelitic lithology has resulted in abundant mesoscopic F₃ folds.

In the Halls Reward domain, mafic to ultramafic rocks and the Halls Reward Metamorphics both have one main foliation (S₂, Table 2, Figure 11, Arnold & Rubenach 1976). S₂ is mainly east-west striking and steeply dipping to the north with moderate north plunging L₂ lineations (Figures 11, 12a, b). It is folded about northerly trending late folds (Figure 12a, c) although further southeast S₂ is north-northeast trending and steeply dipping (Figure 12d). Amphibolite facies metamorphism was synchronous with the major deformation

(Withnall 1989). The Nickel Mine Fault is expressed as a mylonite zone between the Halls Reward Metamorphics and the Paddys Creek Phyllite with foliation dipping steeply to the west and S and C planes indicating west-over-east shearing (Figure 10c). The Halls Reward Fault is steeply dipping with a strongly deformed mylonite zone up to 200 m wide (Withnall 1989). Several mylonite zones also occur west of the Halls Reward Fault and have a foliation that overprints S_2 and dips gently to the west (Figure 12e) with S-C planes and shear bands indicating southwest transport (Figure 10d).

GEOCHRONOLOGY

We selected one sample from the Oasis Metamorphics and two samples from the Lynwater Complex to obtain ages on the metamorphic and igneous history. A further sample from the Lucky Creek Metamorphic Group contained no zircons. Zircons were separated using standard techniques (crushing and desliming, magnetic separation, heavy liquids and hand picking). Cathodoluminescence images (CL) taken prior to analysis were used to target specific areas within the sectioned zircon grains. Analysis was undertaken on the sensitive high-resolution ion microprobe (SHRIMP) at the Research School of Earth Sciences, The Australian National University following techniques given by Williams (1998 and references therein). Analyses consist of six scans through the mass range with a spot size of *ca* 20 μm . U/Pb ratios are determined by reference to 1099 Ma Duluth Gabbro zircon grains (sample FC1, Paces & Miller 1993). Data are reduced using the SQUID Excel Macro of Ludwig (2000), uncertainties are given at the one sigma level with weighted average age uncertainties at the 95% confidence level; plots and calculations using ISOPLOT/EX (Ludwig 1999). Ages greater than around 800 Ma have common Pb correction based on the measured $^{204}\text{Pb}/^{206}\text{Pb}$ ratios, whereas for ages less than around 800 Ma common Pb is corrected using measured $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{238}\text{U}/^{206}\text{Pb}$ ratios (Tera & Wasserburg 1972; Williams 1998).

Results

Sample IWGT016 is calc-silicate-bearing gneiss from the Oasis Metamorphics. The sample was taken from an isolated outcrop, but elsewhere along the creek in which it occurs, similar rocks form 'beds' about 10–30 cm thick, interlayered with fine-grained, diffusely laminated, hornblende-biotite to biotite schist and locally thin marble beds. In the field, these rocks were interpreted to have originally been slightly calcareous or dolomitic, feldspathic sandstone beds within a sedimentary sequence represented by the biotite schist and marble. Amphibolite layers, commonly thin and laminated, are also common. The sample is diffusely laminated and consists of 40–50% quartz, 30–40% plagioclase, subsidiary (about 10% each) diopside and hornblende and 1–2% titanite. Plagioclase occurs as discrete subequant grains up to 1 mm across, but the quartz forms granular mosaics with individual subgrains about 0.25 mm across or less. No textures that could be ascribed to either a sedimentary or igneous origin are preserved because of the degree of metamorphism and deformation. The diffuse layering is tectonic in origin.

Zircons from this sample are subhedral with complex internal structure reflecting a multiphase history. Many have zoned interiors interpreted to reflect a magmatic precursor that gives rise to the subhedral elongate shape, with thin (bright CL) metamorphic overgrowths forming subround terminations (Figure 13a, b). Analyses of the central areas to grains include minor clusters at 1300–1250 Ma, 1200–1150 Ma and 540–520 Ma (Table 3) indicating a detrital signature. Most importantly 14 rim analyses give a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of

476 ± 5 Ma (MSWD = 0.59) for the final growth phase (Figures 13a, b, 14a), which is interpreted as the timing of D₁ metamorphism. Due to the complex nature of the grains a number of analyses overlap two different zircon growth periods. Analyses 6.1, 8.1 and 9.1 are poorly sited and these have been excluded from any of the plots or calculations and are shown in italics in the tabulation of data. This study concentrated on resolving the age of the metamorphic rims and further work would be needed to provide a full provenance spectrum.

Samples IWGT207 and IWGT238 are both from the Lynwater Complex. Sample IWGT238 is a well-foliated hornblende-biotite tonalite with subhedral grains of oscillatory zoned magmatic zircon (Figure 13c). Some inherited zoned igneous cores range to ~2480 Ma, with most indicating Mesoproterozoic ages (Figure 13c), but a dominant group of analyses form a peak at 485 Ma (Table 3). A weighted mean ²⁰⁶Pb/²³⁸U age for 13 analyses gives 486 ± 5 Ma (MSWD = 0.76, Figure 14b). Sample IWGT207 is a muscovite-biotite orthogneiss with in general a simple population of zoned igneous zircon. In CL detail, there appears to be a range of magmatic internal structures with zoned zircon overgrowths formed on existing zoned igneous zircon (Figure 13d). The data correspondingly shows significant dispersion on the Tera Wasserburg plot (Figure 14c) and is interpreted to result from combination of slightly older magmatic zircon (*ca* 500–490 Ma) mixed with the dominant zoned magmatic population. A weighted mean of 16 analyses that form the dominant peak yield a ²⁰⁶Pb/²³⁸U age of 477 ± 6 Ma (MSWD = 1.7) and is considered the intrusive age of this tonalite body.

The Oasis Metamorphics and the Lynwater Complex are clearly not part of the Palaeoproterozoic – Early Mesoproterozoic Einasleigh Metamorphics as previously thought (Withnall 1989; Withnall *et al.* 1997). Two of the samples have an inherited component of Late Mesoproterozoic age as found in other metasedimentary successions in the region including the Halls Reward Metamorphics, Anakie Metamorphic Group, Cape River and Argentine Metamorphics (Fergusson *et al.* 2001, unpub. data; Nishiya *et al.* 2003). However the age of D₁ metamorphism in the Oasis Metamorphics and associated syntectonic granitoid intrusions, represented mainly by the Lynwater Complex, is in the range 485–475 Ma (Early Ordovician).

DISCUSSION

Location of the Tasman Line

SHRIMP U–Pb zircon ages of 1700–1550 Ma demonstrate that the Einasleigh Metamorphics west of the Lynd Mylonite Zone are part of the Palaeoproterozoic to Early Mesoproterozoic craton (Black *et al.* 2005). U–Pb zircon ages reported herein in addition to those of Withnall *et al.* (1991) for the Balcooma Metavolcanic Group and ages by various techniques reported by Nishiya *et al.* (2003) for the Halls Reward Metamorphics show that the Greenvale Province is part of an Early Palaeozoic orogenic belt and that the Palaeoproterozoic to Early Mesoproterozoic craton lies west of the Lynd Mylonite Zone. Unlike the Palmerville Fault further north (Shaw *et al.* 1987), which has the Precambrian craton thrust eastwards over Lower Palaeozoic low-grade sedimentary and volcanic rocks, the Tasman Line in the southeastern Georgetown Inlier is marked by a steeply dipping mylonite zone which according to Withnall (1989) has an east-over-west sense of shear. In contrast to central Queensland and southeastern Australia where the location and significance of the Tasman Line is unresolved (Direen & Crawford 2003), in north Queensland it is clearly defined as the western contact of the Tasman Orogenic Zone along the Lynd Mylonite Zone in the southeast Georgetown Inlier and the Palmerville Fault at the western margin of the Hodgkinson

Province. We concur with Direen and Crawford (2003) that the Tasman Line has no significance in terms of rifting of a Proterozoic supercontinent.

Depositional development and setting

A latest Cambrian to Early Ordovician age is inferred for the primary volcanic and associated sedimentary succession of the Balcooma Metavolcanic and Lucky Creek Metamorphic Groups. This is supported by U–Pb zircon ages (Withnall *et al.* 1991) and their lithological similarity with the uppermost Cambrian to Lower Ordovician Seventy Mile Range Group of the Charters Towers Province (Henderson 1986; Withnall *et al.* 1997). Igneous rocks in the Seventy Mile Range Group have a lower part containing mafic dykes, sills and volcanic rocks with an intraplate/rift geochemical signature overlain by voluminous volcanic units with a subduction-related signature that formed in an extensional backarc setting (Henderson 1986; Stolz 1995). Geochemistry of volcanic rocks in the Balcooma Metavolcanics is limited and scattered in tectonic affinities but published analyses, as well as more recently obtained unpublished data by the Geological Survey of Queensland, are consistent with a calc-alkaline signature for the Eland Metavolcanics, whereas the Lugano Metamorphics contain tholeiitic metabasalts (Withnall 1989). An overall extensional backarc setting is favoured for the formation of these rocks to the west of a subduction-related arc similar to the setting inferred for the Seventy Mile Range Group.

The Oasis Metamorphics contain metasedimentary and meta-igneous rocks derived from dolomitic carbonates and impure carbonate of probable shallow marine setting, shale and quartzo-feldspathic sandstone and mafic volcanic and/or intrusive rocks of tholeiitic affinities (unpublished data, Geological Survey of Queensland). They have a late Neoproterozoic to Early Palaeozoic depositional age constrained by ages of detrital zircons and the 476 ± 5 Ma age for metamorphic rims on zircons indicating timing of amphibolite facies metamorphism and providing an upper age limit. The primary rocks of the Oasis Metamorphics are likely to have formed along the Gondwanan margin during this interval, predating the backarc basin infill associated with the Seventy Mile Range Group and equivalents. Intrusive ages of the strongly deformed Lynwater Complex at 486 ± 5 Ma and 477 ± 6 Ma are consistent with D₁ metamorphism in the adjoining Oasis Metamorphics. The Lynwater Complex is equivalent in age to the older part of the Lolworth Batholith (Hutton *et al.* 1997) and is overlapped in age by the subjacent Seventy Mile Range Group (Henderson 1984).

The Halls Reward Metamorphics have been considered a Proterozoic element of the southeast Georgetown Inlier (Withnall 1989) although the isotopic ages of Nishiya *et al.* (2003) indicate that they are much younger than previously supposed. Ages of detrital zircons, determined by a chemical U–Th–total Pb isochron method (CHIME), are as young as 600 Ma with metamorphism and deformation determined from the same method on monazite along with K–Ar mineral and Rb/Sr whole rock and mineral ages at 510–500 Ma suggesting a late Neoproterozoic to Middle Cambrian depositional age (Nishiya *et al.* 2003). Primary relationships between metasedimentary rocks of the Halls Reward Metamorphics and the meta-igneous rocks of the Boiler Gully Complex are severely overprinted by intense D₂ deformation (Arnold & Rubenach 1976) and the age of the latter is no better constrained than Late Neoproterozoic to Middle Cambrian. Strongly deformed ultramafic and mafic rocks also occur in the Gray Creek Complex at the base of the Graveyard Creek Subprovince (Henderson 1987) no more than 5 km distant from the Halls Reward domain. The Gray Creek Complex also has experienced amphibolite facies metamorphism and is overlain by the Early Ordovician Judea Formation, which has a low-grade metamorphic history (Arnold & Henderson 1976; Withnall & Lang 1993).

Deformation history of the Greenvale Province

The characteristic structural feature of much of the Greenvale Province is the development of intense syn-metamorphic foliation. West of the Dido Tonalite much of this foliation is steeply dipping although it is clear from the Oasis Metamorphics that the present steep dip is a result of tight folding in a younger contractional deformation. The U-Pb ages indicate that D_1 amphibolite metamorphism in the Oasis Metamorphics is of Early Ordovician age and accompanied intrusion of the Lynwater Complex which contains intense foliation that we consider also developed at this time.

Steeply dipping intense foliation (S_2) affects the Balcooma Metavolcanic Group but the nature of an earlier deformation is difficult to resolve. In the Lucky Creek and Paddys Creek domains, folds that affected the S_2 foliation have a low to moderate plunge and indicate that S_2 must have had an initial low to sub-horizontal dip. Subparallel intersection and stretching lineations, which are particularly well developed in the Eland Metavolcanics, consistent with high strain associated with the D_2 deformation.

The intense foliation (S_2) in the Lucky Creek domain overall dips westwards and is associated with increasing metamorphic grade towards the Cockie Spring Tonalite and the Dido Tonalite (greenschist facies in the Paddys Creek Phyllite through to amphibolite facies in the western part of the Lugano Metamorphics). Late shear bands developed along this foliation after unfolding indicate west-over-east transport consistent with the metamorphic pattern. Reactivation of the S_2 foliation in a contractional setting must have followed its formation and accompanied contractional deformation (D_3) in the Lucky Creek and Paddys Creek domains. The increasing metamorphic grade is at least partly attributed to the Cockie Spring Tonalite which is intensely foliated and similar to the Lynwater Complex. We consider that steepening of the S_2 foliation in the Lucky Creek domain reflects reactivation prior to and during intrusion of the Dido Tonalite in an Early Silurian contractional regime recognised in the Greenvale Province and adjacent Broken River Province by Henderson (1987). This contractional deformation also accounts for all post- D_2 deformation in the Lucky Creek and Paddys Creek domains (Table 2).

Fault zones separating domains, and at the boundaries of the Greenvale Province, show diverse movement history. They are defined mainly by steeply dipping intense foliation apart from low-angle mylonite zones in the eastern part of the Halls Reward domain. The steep dip of most fault zones is inconsistent with contractional orogenesis unless they formed either earlier as strike-slip and/or normal faults or they have been rotated to a steep dip during contractional deformation. These alternatives are difficult to evaluate given the overprinting associated with late deformation along these zones and the limited geochronology available. The last main deformation along the Lynd, Balcooma and Nickel Mine Faults are considered to represent reactivation during high-angle reverse slip and probably developed in the Early Silurian event. Sinistral strike-slip motion along the Balcooma Mylonite Zone is consistent with regional northwest-orientated contraction during the Silurian. The Balcooma Mylonite Zone is truncated by the Dido Tonalite so that movement along it predated 431 Ma (Bain *et al.* 1997).

Rb/Sr ages of whole rocks and muscovites, K/Ar ages of muscovites, and CHIME ages on monazite (Nishiya *et al.* 2003), have been forwarded as evidence that the Halls Reward Metamorphics and associated meta-igneous units were deformed and metamorphosed at 510–500 Ma during the Delamerian Orogeny. These rocks have an inferred age and detrital zircon age signature similar to other units in Queensland such as the Anakie Metamorphic Group (Fergusson *et al.* 2001). Such data are consistent with this domain representing Early

Palaeozoic metamorphic basement that predated initiation of the backarc basin volcanic and sedimentary succession represented by the Balcooma, Lucky Creek and Paddys Creek domains in the Late Cambrian to Early Ordovician (500–470 Ma).

Early Silurian contractional deformation affected the Early Silurian Dido Tonalite (Withnall 1989) and induced uplift that generated the thick, northwest-derived Lower Silurian Graveyard Creek Conglomerate which is at the base of the thick Silurian-Devonian succession of the Graveyard Creek Subprovince (Arnold & Henderson 1976; Henderson 1987; Withnall & Lang 1993). This formation contains abundant metamorphic, mafic and ultramafic clasts and demonstrates that the Greenvale Province was being actively uplifted and eroded at this time. We also attribute overprinting deformation that rotated foliation to steep dips in the western part of the Greenvale Province, multiple deformation east of the Dido Tonalite and reactivation of fault zones to this contractional deformation. These features indicate Early Silurian tectonism in northeastern Australia, referred to here as the Benambran Orogeny, and correlative with contractional tectonism in southeastern Australia on which this term is based.

Low-angle foliation – evaluation of its significance

The separation of contractional from extensional processes involved in the development of low-angle foliations in metamorphic rocks is a widely recognised problem (Harris *et al.* 2002). Low-angle foliation and associated recumbent folds have been documented in metamorphic rocks associated with shortening in continental collision zones such as the European Alps (Ramsay *et al.* 1981). In contrast, extensional processes are involved in the exhumation of rocks affected by high-pressure and/or ultra-high pressure metamorphism as found in Norway (Andersen 1998). Extensional processes are also illustrated by the development of low-angle foliation, usually with intense shearing, low-pressure metamorphism and plutonic activity, in metamorphic core complexes formed during Early Tertiary extension in the Basin and Range Province of the southwestern USA (Malavieille 1993).

The development of low-angle foliation in middle to lower upper crust rocks with accompanying amphibolite to greenschist facies metamorphism is especially problematic where evidence for either earlier high-pressure metamorphism or distinctive features associated with metamorphic core complexes are lacking. Fergusson *et al.* (2005) argued that the low-angle, intense foliation (S_2) and recumbent folds of the Early Palaeozoic Cape River Metamorphics, located 100 km south of the Greenvale Province in the Charters Towers Province, formed in an extensional tectonic setting. They also reinterpreted low-angle foliation and associated large-scale recumbent folds in the Anakie Inlier (Withnall *et al.* 1995; Green *et al.* 1998) as a result of ductile thinning involving a substantially pure shear mode of deformation in an extensional regime. No detachment faults have been identified in these examples and simple shearing type deformation is subsidiary to pure shear with pervasive ductile thinning of the middle to lower upper crust. Similar extensional metamorphic rock assemblages that lack many of the distinctive characteristics of metamorphic core complexes have been described from the Hercynian belt of Europe (Cagnard *et al.* 2004), the Pyrenees (Gibson 1991) and the Yukon-Tanana terrane in Alaska (Pavlis & Sisson 1993).

In the Greenvale Province, low-angle foliation developed during D_2 in the Lucky Creek and Paddys Creek domains and probably also as D_1 in the Lynd domain. We favour development of the low-angle foliation by dominantly pure shearing (i.e. ductile flattening) in an extensional crustal environment consistent with the regional backarc setting as argued for the Cape River Metamorphics (Fergusson *et al.* 2005). Subsequent contractional deformation

has resulted in rotation of the low-angle foliation to steep dips as illustrated by the structure of the Lynd, Lucky Creek and Paddys Creek domains.

Regional significance

Based on this study, we can better place the development of the Greenvale Province in the regional Early Palaeozoic tectonic history of the northern Tasman Orogenic Zone. Rifting occurred along the Australian part of East Gondwana in the Late Neoproterozoic around 600 Ma (Direen & Crawford 2003). It is not known if the rifted fragment was a continent such as Laurentia or a ribbon continental fragment such as the Lord Howe Rise. In northeastern Australia, sedimentation on this rifted margin is represented by the older protolith of metasedimentary rocks comprising the Anakie Metamorphic Group and accompanying interlayered mafic igneous units (Withnall *et al.* 1995; Fergusson *et al.* 2001). Equivalents of these rocks occur in the Charters Towers Province in the Cape River and Argentine Metamorphics (Fergusson *et al.* 2005 and unpublished data) and are identified here as the protolith of the Oasis Metamorphics.

It has been considered that northeastern Australia was affected by the Delamerian Orogeny on the basis of K-Ar mineral, Rb-Sr mineral and whole-rock and CHIME monazite ages (Withnall *et al.* 1996; Nishiya *et al.* 2003). These reconnaissance studies need to be followed up by more systematic research including *in situ* dating of monazite, U-Pb dating of zircon, monazite and titanite and $\text{Ar}^{39}/\text{Ar}^{40}$ dating of amphibole and micas. These mid Cambrian ages, if vindicated, indicate that the Halls Reward Metamorphics represent a basement block that was upstanding as a horst during the Early Ordovician extensional episode (Figure 15a) and was not influenced by ductile deformation that affected deeper crustal levels of the adjacent backarc basin. The Halls Reward domain includes the Boiler Gully mafic-ultramafic assemblage, the Sandalwood Serpentine and the Stenhouse Amphibolite which may represent oceanic crust (Withnall 1989). The Oasis Metamorphics most probably represent a Neoproterozoic continental margin sedimentary package which lay beneath the extensional basin system and experienced extensional deformation (Figure 15a).

The application of extensional tectonics in north Queensland is demonstrated by the backarc basinal setting of the Late Cambrian and earliest Ordovician succession comprising the Seventy Mile Group which contains thick volcanic intervals. Metamorphic rocks of the Greenvale Province contain a record of similar type (Figure 15a). Employing the timescale of Gradstein and Hogg (2004) our new U-Pb zircon ages of 485–475 Ma provide evidence of amphibolite metamorphism and accompanying silicic intrusions in the Greenvale Province correlative with the Lancefieldian-Chewtonian graptolite ages for extensional volcanism and associated sedimentation in the Seventy Mile Range Group. For the Greenvale Province, high heat-flow and magmatism was coincident with the deep levels of a backarc rift within a regime of ductile deformation accompanied by the development of low-angle foliation. The extensional regime may reflect roll back in plate engagement and general extension of an active margin sector as described by Hamilton (1995).

This crustal tract represented by the Greenvale Province, with widespread extensional fabric development, was subsequently overprinted by Early Silurian (Benambran) contractional deformation. As suggested by Thompson *et al.* (2003) sectors of crust thinned by extension and weakened by long-lived thermal softening are especially prone to shortening strain generated by enhanced plate coupling during convergence. A subduction-related, Late Ordovician island arc is represented by a narrow belt of calc-alkaline volcanic rocks and volcanoclastic strata represented by the Everetts Creek Volcanics and Carriers Well Formation at the western margin of the Camel Creek Subprovince (Withnall & Lang 1993). These rocks

were accreted in Early Silurian contractional deformation with subsequent large-scale growth of an accretionary subduction complex in the Silurian to Devonian Camel Creek Subprovince and Hodgkinson Province (Henderson 1987).

Although there are major differences in the extent and nature of domains and rock units in the Greenvale Province, this tectonic evolution has some resemblance to that recognised in the Adelaide and Lachlan Fold Belts of southeastern Australia. Early to Middle Cambrian extensional tectonics (520–510 Ma) produced the vast marginal sea represented by oceanic and infant island arc basement of the Lachlan Fold Belt (Crawford *et al.* 2003a). Development of the Adelaide Fold Belt occurred in the Delamerian Orogeny arising from a relatively short-lived collision of the rifted margin with an outboard island arc terrane (Crawford *et al.* 2003b). An extensional tectonic regime characterised the Lachlan Fold Belt throughout the Ordovician accompanied by development of the Macquarie Arc in its northeastern part (Powell 1984; Glen *et al.* 1998; Squire & Miller 2003). Blueschist metamorphism in the adjoining New England Fold Belt (Fukui *et al.* 1995) marks the development of an outboard subduction complex at this time.

Protolith of the Halls Reward domain could represent Early to Middle Cambrian extended crust with oceanic elements overprinted by Delamerian orogenesis. A long lived Ordovician extensional regime followed, represented by the remaining domains of the Greenvale Province and a Late Ordovician magmatic arc is also in evidence in the adjoining Broken River Province. In north Queensland, Early Silurian Benambran orogenesis terminated the proceeding extensional regime and was a relatively short-lived episode of contractional deformation as is also characteristic of the Lachlan Fold Belt.

CONCLUSIONS

A structural transect across the southeast Georgetown Inlier in conjunction with new U–Pb zircon ages from the western part of the traverse has significant implications for the regional geology of the northern Tasman Orogenic Zone. The Tasman Line is shown to occur along the Lynd Mylonite Zone 60 km west of its previously defined position on the Burdekin River Fault. In north Queensland, the Tasman Line does not represent the position of breakup of the Rodinian continent but instead is the western contact of the Tasman Orogenic Zone with the Palaeoproterozoic to Early Mesoproterozoic craton. Plutonism and amphibolite metamorphism in the Early Ordovician at *ca* 480–475 Ma are interpreted as part of an extensional crustal continuum represented by various rock assemblages of the region with ductilely deformed deeper levels of a backarc extensional rift setting in the Greenvale Province equivalent to the upper crustal basin fill represented by Seventy Mile Range Group of the Charters Towers Province. Ductile extensional deformation generated low-angle foliation in basement to the rift and also in the deeper parts of rift-fill volcanic and sedimentary successions. These foliations were subsequently reactivated and rotated to steeper orientations during mainly Early Silurian contractional deformation of the Benambran Orogeny.

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FIGURES

Figure 1 (a) Major elements of the Tasman Orogenic Zone in eastern Australia. Tasman Line is as shown by Scheibner and Veevers (2000) and has been questioned by Direen and Crawford (2003). Abbreviations: BHB = Broken Hill Block, CTP = Charters Towers Province, GZ = Glenelg Zone, GP = Greenvale Province (southeast Georgetown Inlier), WB = Wonominta Block. (b) Palaeozoic and older elements of the Townsville region. Abbreviations: BMZ = Balcooma Mylonite Zone, CCS = Camel Creek Subprovince, GCS = Graveyard Creek Subprovince, LMZ = Lynd Mylonite Zone.

Figure 2 Regional geology of the southern Greenvale Province modified from Withnall (2004) with locations of detailed figures. Abbreviations: BMZ = Balcooma Mylonite Zone, BRF = Burdekin River Fault, LMZ = Lynd Mylonite Zone, NMF = Nickel Mine Fault.

Figure 3 Map and cross section CD of 'The Lynd' area. Lw = Lynwater Complex (on cross section).

Figure 4 Lower hemisphere equal area stereographic projections of structural data from the ‘The Lynd’ and the southern part of the Balcooma Mylonite Zone. Number of measurements shown at lower left of each stereonet. (a) Poles to gneissic layering (S_g) in the Oasis Metamorphics – β axis $49^\circ/059^\circ$. (b) L_m (mineral lineation). (c) Poles to foliation (S_f) in granitic segregations and axial planes to folds in gneissic layering of the Oasis Metamorphics – mean $61^\circ/091^\circ$. (d) Lineation (L) in granitic segregations and folds (F) in S_g in the Oasis Metamorphics. (e) Poles to mylonitic layering (S_m) in Balcooma Mylonite Zone – mean $89^\circ/112^\circ$. (f)–(h) Structural data from east of Balcooma Mylonite Zone. (f) Poles to S_2 foliation – mean $83^\circ/138^\circ$. (g) Poles to bedding (S_0) – mean $82^\circ/152^\circ$. (h) F_2 fold axes and L_2 intersection lineations – mean $85^\circ/131^\circ$.

Figure 5 Detailed map and cross section EF for the southern part of the Balcooma Mylonite zone.

Figure 6 Photographs of structures from the Balcooma and Lucky Creek domains [grid references are to Conjuboy (7860) 1:100 000 sheet]. (a) S-C planes in mylonitised rhyolitic volcanic rocks in the Balcooma Mylonite Zone (247966 7906311). (b) Flattened fragments within the S_2 foliation in Eland Metavolcanics (266451 7899920). (c) Photomicrograph of amphibolite from the Lugano Metamorphics with foliated hornblende, plagioclase and magnetite (sample LG27, 264263 7898724). Cross-polarised light. (d) Dextral shear bands (S_b) in the Eland Metavolcanics (same location as (b)).

Figure 7 Detailed map of the Lucky Creek area with cross sections GH and IJ.

Figure 8 Lower hemisphere equal area stereographic projections of structural data from the Lugano Metamorphics and Eland Metavolcanics (a)–(d). Number of measurements shown at lower left of each stereonet. (a) Poles to S_2 foliation in the Lugano Metamorphics and Eland Metavolcanics – mean $73^\circ/310^\circ$, β -axis $55^\circ/245^\circ$, contours at 1, 2, 4, 8 and 16% per 1% area. (b) L_2 (intersection lineation, fold axes, mineral lineation) – mean $61^\circ/242^\circ$, contours at 1, 2, 4, 8 and 16% per 1% area. (c) Shear bands (dextral) – mean $71^\circ/335^\circ$. (d) Poles to AP3 (AP = axial plane, dots – axial planes), mean = $86^\circ/295^\circ$. F_3 fold axes (crosses). Both 5 measurements each. (e)–(h) Structural data from the Paddy Creek Phyllite (e) Poles to S_2 in the Paddys Creek Phyllite, β -axis $17^\circ/043^\circ$. (f) Poles to S_3 – mean $76^\circ/132^\circ$. (g) F_3 – mean $23^\circ/044^\circ$. (h) Poles to S_4 – mean $29^\circ/054^\circ$.

Figure 9 Detailed map of the Paddys Creek area and cross section KL.

Figure 10 Photographs of structures from the Paddys Creek and Halls Reward domains [grid references are to Conjuboy (7860) 1:100 000 sheet]. (a) S_2 foliation folded by F_3 folds with axial planar crenulation cleavage (scale – 15 cm rule, Moore Creek, 283300 7909645). (b) Boudinaged layering in S_2 foliation, Paddys Creek Phyllite (same location as (b)). (c) S and C

Figure 12 Lower hemisphere equal area stereographic projections of structural data from the Stenhouse Creek area and mylonite zones in the region. Number of measurements shown at lower left of each stereonet. (a) Poles to S_2 – β -axis $71^\circ/016^\circ$, contours at 1, 2, 4 and 8% per 1% area. (b) L_2 – mean $45^\circ/005^\circ$. (c) Poles to S_3 – mean $90^\circ/298^\circ$. (d) Greenvale railway – poles to S_2 – mean $86^\circ/286^\circ$. (e) Greenvale pipeline track – poles to S_m (dots) – mean $21^\circ/280^\circ$. L_m (crosses).

Figure 13 Representative CL images of the zircon grains analysed by SHRIMP: (a, b) paragneiss sample IWGT016 – images highlight the bright luminescent metamorphic rims

developed on the zoned igneous, inherited older cores; (c) orthogneiss sample IWGT238 – image shows dominantly oscillatory zoned igneous zircon, with in some grains inherited zoned igneous cores; and (d) orthogneiss sample IWGT207 – image highlights the oscillatory zoned igneous nature of the zircon.

Figure 14 Tera and Wasserburg Concordia plots and histogram of U–Pb ages with superimposed probability distribution for samples (a) IWGT016 (paragneiss) from the Oasis Metamorphics (241380 7913120 Conjuboy (7860) 1:100 000 sheet), (b) IWGT238 (orthogneiss) from the Lynwater Complex (245100 7912730) Conjuboy (7860) 1:100 000 sheet) and (c) IWGT207 (orthogneiss) from the Lynwater Complex (247175 7912000 Conjuboy (7860) 1:100 000 sheet).

(a) Latest Cambrian to Early Ordovician

Figure 15 Schematic cross sections displaying the development of the Greenvale Province. (a) Latest Cambrian to Earliest Ordovician phase of backarc igneous activity and

sedimentation in an extending backarc basin (490–470 Ma). (b) Present-day cross section showing upright folding in foliation and reactivation of early faults during the Early Silurian contractional event.

TABLES

Table 1 Rock units in domains along the transect across the Greenvale Province (Withnall 1989, 2004; Withnall *et al.* 1991, 1997, 2002).

Table 1 Rock units in domains along the transect across the Greenvale Province (Withnall 1989, 2004; Withnall <i>et al.</i> 1991, 1997, 2002).					
Domain	Lynd	Balcooma	Lucky Creek	Paddys Creek	Halls Reward
Units and Rock Types	Oasis Metamorphics - 3 subunits (from base up) (1) O1 - calc-silicate gneiss, (2) O2 - amphibolite with lesser biotite schist, (3) O3 - biotite gneiss with less common amphibolite, calc-silicate gneiss, and lenses of dolomitic marble. Lynwater Complex - hornblende-bearing and two-mica granitoids grading into orthogneiss. Less strongly foliated Silurian McKinnons Creek Granite.	Balcooma Metavolcanic Group - lower Clayhole Schist with massive pelite and quartzose metasandstone, overlain by massive metarhyolitic volcaniclastics with prominent metarhyolite in west, some metadolerite and meta-andesite. Dido Tonalite - biotite and biotite-hornblende bearing tonalite pluton.	Lucky Creek Metamorphic Group - divided into Lugano Metamorphics with amphibolite unit in west (with relict pillow lavas, hyaloclastites and amygdales), a mixed unit of amphibolite, metarhyolite and metasedimentary rocks of the Lugano Metamorphics in the centre, and mafic to silicic metavolcanics and metavolcaniclastics of the Eland Metavolcanics in the east. Metamorphosed clastic rocks (derived from feldspathic sandstone, breccia, conglomerate, chert and limestone) occur in Lugano Metamorphics and Eland Metavolcanics. Cockie Spring Tonalite - hornblende and biotite bearing tonalite with minor amphibolite.	Paddys Creek Phyllite - pelite, lesser quartzite	Halls Reward Metamorphics - coarse-grained muscovite-quartz schist with biotite, sillimanite and garnet. Bioler Gully Complex - Sandalwood Serpentine and Stenhouse Creek Amphibolite - layered amphibolite and metagabbro. Units are intermixed at outcrop to map-scales.
Metamorphism	Upper amphibolite facies shown by co-existing hornblende and diopside in calc-silicate gneiss, and widespread granitoid and pegmatite segregations	Amphibolite facies in Balcooma Metavolcanic Group - andalusite, staurolite and garnet in addition to widespread biotite	Amphibolite to greenschist facies - hornblende in amphibolite, chlorite, actinolite and muscovite in greenschist Eland Metavolcanics. Metamorphic grade decreases eastwards.	Greenschist facies - muscovite, quartz and lesser chlorite	Halls Reward Metamorphics - amphibolite facies - biotite, garnet, sillimanite, abundant leucogranite and pegmatite. Stenhouse Creek Amphibolite - hornblende.
Age constraints	Oasis Metamorphics - detrital zircons (U-Pb ages) of 540-520 Ma, metamorphic rims 476 ± 5 Ma (Early Ordovician). Lynwater Complex - U-Pb zircon ages of 486 ± 5 Ma and 477 ± 6 Ma (Early Ordovician). Depositional age of Cambrian to Early Ordovician for the Oasis Metamorphics.	Balcooma Metavolcanic Group - U-Pb zircon age 471 ± 4 Ma - Ordovician age (Withnall <i>et al.</i> 1991). Dido Tonalite - U-Pb zircon age of 431 ± 7 Ma - Early Silurian (Bain <i>et al.</i> 1997).	Considered Early Palaeozoic - no zircon ages have so far been obtained	Considered Early Palaeozoic - no zircon ages have so far been obtained	U-Th-Pb chemical dating of zircon and monazite, Rb/Sr ages of schist and K/Ar dating of muscovite indicate ages of ca 500-510 Ma (Nishiya <i>et al.</i> 2003) - Middle Cambrian, considered a metamorphic age
Interpretation	Shallow marine clastic succession with mafic volcanics and/or intrusions. Lynwater Complex - intrusions of tonalite, granodiorite and granite.	Dominant silicic volcanism and fine-grained sedimentation	Silicic to mafic volcanism (bimodal) with associated sedimentation	Fine-grained sedimentation	Fine-grained sedimentation and mafic to ultramafic intrusive activity

Table 2 Deformations in domains along the transect across the Greenvale Province (including data from Withnall 1989).

Table 2 Deformations in domains along the transect across the Greenvale Province (including data from Withnall 1989).

Domain	Lynd	Balcooma	Lucky Creek	Paddys Creek	Halls Reward
Deformation	D ₁	D ₁	D ₁	D ₁	D ₁
Structural elements	S _g , L _m	S ₁	S ₁	S ₁ , F ₁	S ₁
Description	Main compositional layering, foliation and rare mineral lineation (amphibole, biotite), boudinaged amphibolite and pegmatite layers	Early foliation and compositional layering subparallel to bedding and largely obliterated by S ₂	Rarely preserved S ₁ foliation, differentiated layering is locally developed	S ₁ is a rarely preserved continuous cleavage within S ₂ microlithons	Relict crenulations of S ₁ preserved in some siliceous rocks
Orientation	Mainly steeply dipping to east, lineation plunges moderately northeast	Subparallel to bedding	Tightly folded and transposed mainly subparallel to S ₂	Transposed parallel to S ₂	Largely transposed parallel to S ₂
Deformation	D ₂	D ₂	D ₂	D ₂	D ₂
Structural elements	S ₁ , AP ₂ , F ₂ , L ₂ , (note AP = axial plane)	S ₂ , F ₂ , L ₂	S ₂ , F ₂ , L ₂ , L _s	S ₂ , F ₂	S ₂ , F ₂
Description	Sinusoidal to box-shaped, open to near isoclinal folds with steeply inclined axial planes, granitic veins locally developed along axial planes, weak foliation in granitic veins and along axial planes	Crenulation cleavage varying to a continuous foliation defined by aligned muscovite and biotite with elongate porphyroblasts of andalusite(?), steeply plunging tight to near isoclinal folds	S ₂ is a well developed foliation defined by aligned chlorite, muscovite, quartz and amphibole in metavolcanic units. F ₂ folds are tight to isoclinal in earlier compositional layering. Pressure fringes, mineral elongation (hornblende) and elongate fragments indicate L ₂ intersection lineation is also a stretching lineation. Boudinaged veins of quartz occur in the foliation.	S ₂ is a well developed, laminar crenulation cleavage with aligned muscovite and quartz in cleavage domains, microlithons up to 1-2 cm in width, rare S ₁ -S ₂ intersection lineation is found on S ₂ surfaces. Boudinaged veins of quartz occur in the foliation.	S ₂ is a strong foliation in amphibolite defined by hornblende, and a differentiated crenulation cleavage in schist with aligned muscovite and biotite, intrafolial isoclinal folds abound in places. Exposed contacts between main rock units are at oblique to high angles to the main foliation.
Orientation	S ₁ is steeply dipping to east with rare F ₂ folds plunging moderately to northeast	S ₂ is steeply dipping to the northwest with a northeast strike, F ₂ folds are steeply plunging	S ₂ is folded around open to broad map-scale folds, pre-D ₃ S ₂ was gently dipping to northwest	S ₂ is folded around abundant F ₃ and F ₄ , prior to D ₃ S ₂ was gently dipping to the northeast	S ₂ is steeply dipping to north and northwest with common variations in strike due to later refolding and development of intrafolial folds in S ₂ during D ₂ , S ₂ dips steeply to west in Greenvale railway cuttings, F ₂ are variably plunging to north
Deformation		D ₃	D ₃	D ₃ and D ₄	D ₃
Structural elements		S ₃ and F ₃	AP ₃ and F ₃	S ₃ and F ₃ , S ₄ and F ₄	AP ₃
Description		S ₃ is a weak crenulation cleavage with no associated metamorphic mineral growth	Open to close, upright folds that verge to east-southeast. No axial planar structure is present.	F ₃ are open to close, upright folds with S ₃ axial planar crenulation cleavage defined by dissolution along limbs of microlithons. F ₄ are broad to open folds with weak S ₄ axial planar crenulation cleavage.	Broad to open kink bands
Orientation		S ₃ strikes easterly and is steeply dipping	AP ₃ strike north-northeast and dip steeply, F ₃ have subhorizontal to gentle plunges	F ₃ are upright folds gently plunging to northeast. S ₃ is dipping steeply to southeast. F ₄ plunge gently to northwest. S ₄ dips gently to moderately to northeast.	AP ₃ are steeply dipping and northerly striking

SUPPLEMENTARY TABLE

Table 3 Summary of SHRIMP U–Pb zircon results.

Table 3 Summary of SHRIMP U-Pb zircon results.

Sample MGTG106 (paragneiss - Oasis Metamorphics)																						
Grain spot (ppm)	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁶ Pb/ ²³⁸ U	f ₅₀₈ %	Total Ratios				Radiogenic Ratios				Age (Ma)		% Disc					
							²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	ρ	²⁰⁶ Pb/ ²³⁸ U		±				
1.1	526	144	0.27	35.1	0.000207	0.14	12.664	0.157	0.0579	0.0007	0.0776	0.0010			481.9	5.8						
2.1	507	87	0.17	37.4	-	<0.01	11.653	0.145	0.0568	0.0008	0.0859	0.0011			531.5	6.5						
2.2	217	166	0.76	40.5	0.000105	0.17	4.608	0.063	0.0799	0.0009	0.2168	0.0030	2.372	0.043	0.0793	0.0009	0.763	1265	18	1180	23	-7
3.1	112	72	0.64	20.5	0.000259	0.43	4.703	0.095	0.0643	0.0011	0.2123	0.0043	2.428	0.060	0.0830	0.0012	0.822	1241	25	1268	27	2
3.2	182	43	0.24	13.4	-	0.11	11.665	0.183	0.0589	0.0014	0.0856	0.0014			529.7	8.2						
3.3	160	32	0.20	10.4	0.000235	0.27	13.187	0.184	0.0586	0.0012	0.0756	0.0011			470.0	6.4						
4.1	172	46	0.27	10.5	0.000237	0.15	14.004	0.228	0.0570	0.0015	0.0713	0.0012			444.0	7.1						
5.1	248	68	0.27	17.1	0.000059	0.20	12.409	0.165	0.0588	0.0010	0.0804	0.0011			498.7	6.5						
6.1	173	56	0.33	12.6	0.000796	<0.01	11.729	0.175	0.0549	0.0012	0.0856	0.0013			529.4	7.7						
6.2	205	69	0.34	13.3	0.000095	0.20	13.224	0.164	0.0581	0.0009	0.0755	0.0010			469.0	5.7						
7.1	210	56	0.27	14.5	0.000007	0.03	12.460	0.170	0.0574	0.0017	0.0802	0.0011			497.5	6.7						
8.1	98	2	0.02	5.4	0.002043	1.63	15.813	0.354	0.0676	0.0027	0.0622	0.0014			389.1	8.7						
8.2	1313	129	0.10	84.4	0.000438	0.80	13.363	0.141	0.0627	0.0008	0.0742	0.0008			461.6	4.8						
9.1	122	12	0.10	7.7	0.000520	0.13	13.679	0.224	0.0571	0.0016	0.0730	0.0012			454.3	7.3						
10	470	163	0.35	43.0	0.000417	1.08	9.388	0.190	0.0700	0.0007	0.1054	0.0022			645.8	12.8						
10	506	130	0.26	48.4	0.000246	1.17	8.984	0.102	0.0716	0.0006	0.1100	0.0013			672.8	7.5						
11	231	75	0.32	15.6	0.000008	0.09	12.715	0.165	0.0576	0.0009	0.0786	0.0010			487.6	6.2						
12	303	65	0.21	20.0	-	<0.01	12.995	0.164	0.0562	0.0014	0.0770	0.0010			478.2	5.9						
12	323	201	0.62	52.3	-	<0.01	5.302	0.101	0.0830	0.0007	0.1886	0.0036	2.161	0.045	0.0831	0.0007	0.921	1114	20	1271	16	12
12	252	51	0.20	16.5	0.000325	0.38	13.096	0.163	0.0596	0.0009	0.0761	0.0010			472.6	5.8						
14	624	161	0.26	41.2	0.000115	<0.01	13.011	0.146	0.0567	0.0006	0.0769	0.0009			477.3	5.2						
14	191	107	0.56	31.6	0.000029	0.05	5.200	0.078	0.0712	0.0009	0.1926	0.0029	2.090	0.040	0.0787	0.0009	0.786	1136	17	1164	23	2
14	199	31	0.15	13.3	0.000326	0.13	12.881	0.174	0.0578	0.0010	0.0775	0.0011			481.4	6.4						
16	111	47	0.43	13.8	0.000206	0.36	6.944	0.332	0.0870	0.0021	0.1435	0.0069	1.664	0.098	0.0841	0.0029	0.811	864	39	1295	67	33
17	152	30	0.20	10.2	0.000229	0.37	12.817	0.183	0.0598	0.0012	0.0777	0.0011			482.6	6.8						
17	258	59	0.23	18.5	0.000078	0.25	11.967	0.159	0.0596	0.0010	0.0834	0.0011			516.1	6.7						
17	190	45	0.24	12.6	0.000089	0.18	13.024	0.227	0.0581	0.0010	0.0766	0.0014			476.0	8.1						
18	331	79	0.24	25.3	0.000152	0.24	11.266	0.144	0.0604	0.0009	0.0886	0.0012			547.0	6.9						
18	207	101	0.49	34.5	0.000414	0.70	5.152	0.161	0.0778	0.0023	0.1944	0.0061	2.116	0.090	0.0790	0.0023	0.737	1145	35	1171	57	2
19	374	57	0.15	25.6	-	<0.01	12.526	0.147	0.0563	0.0007	0.0799	0.0010			495.6	5.7						
20	405	68	0.17	26.7	0.000342	0.44	13.047	0.158	0.0601	0.0007	0.0763	0.0009			474.0	5.6						
21	159	46	0.29	10.6	0.000264	0.21	12.934	0.178	0.0584	0.0011	0.0772	0.0011			479.1	6.5						
22	549	65	0.12	36.1	0.000122	0.06	13.067	0.147	0.0570	0.0006	0.0765	0.0009			475.1	5.2						
23	311	105	0.34	20.6	0.000057	0.31	12.959	0.156	0.0592	0.0009	0.0769	0.0009			477.7	5.6						
24	174	21	0.12	11.3	0.000031	0.18	13.250	0.178	0.0579	0.0011	0.0753	0.0010			468.2	6.2						
25	186	64	0.34	25.0	0.000072	0.72	6.416	0.097	0.0759	0.0011	0.1557	0.0024	1.608	0.035	0.0749	0.0012	0.701	933	13	1066	31	13
Notes :																						
1. Uncertainties given at the one σ level.																						
2. Error in FC1 Reference zircon calibration was 0.71% & 0.38% for the analytical sessions.																						
(not included in above errors but required when comparing ²⁰⁶ Pb/ ²³⁸ U data from different mounts).																						
3. f ₅₀₈ % denotes the percentage of ²⁰⁶ Pb that is common Pb.																						
4. For areas older than ~800 Ma correction for common Pb made using the measured ²⁰⁶ Pb/ ²³⁸ U ratio.																						
5. For areas younger than ~800 Ma correction for common Pb made using the measured ²⁰⁶ Pb/ ²³⁸ U and ²⁰⁷ Pb/ ²³⁵ U ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).																						
6. For % Disc, 0% denotes a concordant analysis.																						
Sample MGTG238 (orthogneiss - Lynwater Complex)																						
Grain spot (ppm)	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁶ Pb/ ²³⁸ U	f ₅₀₈ %	Total Ratios				Radiogenic Ratios				Age (Ma)		% Disc					
							²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	ρ	²⁰⁶ Pb/ ²³⁸ U		±				
1.1	113	77	0.68	7.2	-	0.36	13.365	0.208	0.0592	0.0013	0.0746	0.0012			463.5	7.1						
1.2	398	235	0.59	26.9	0.000121	0.05	12.699	0.163	0.0573	0.0009	0.0787	0.0010			488.4	6.1						
1.3	167	108	0.65	11.0	0.000000	0.08	13.045	0.224	0.0572	0.0010	0.0766	0.0013			475.8	8.0						
2.1	149	105	0.71	9.4	0.000386	0.31	13.671	0.224	0.0586	0.0018	0.0729	0.0012			453.7	7.3						
2.2	70	43	0.61	12.3	0.000450	0.76	4.873	0.091	0.0830	0.0016	0.2046	0.0038	2.267	0.062	0.0804	0.0016	0.678	1200	23	1206	40	1
3.1	362	196	0.54	24.8	0.000305	0.05	12.524	0.159	0.0575	0.0009	0.0798	0.0010			494.9	6.2						
4.2	144	97	0.67	9.6	0.000528	0.45	12.849	0.173	0.0604	0.0011	0.0775	0.0011			481.0	6.4						
6.1	438	128	0.29	68.4	0.000339	0.07	5.495	0.065	0.0862	0.0007	0.1819	0.0022	2.148	0.031	0.0856	0.0007	0.811	1077	12	1330	17	19
6.2	102	35	0.35	17.3	0.000369	0.61	4.909	0.107	0.0757	0.0009	0.1201	0.0015	2.214	0.064	0.0821	0.0019	0.579	1165	19	1272	44	7
7.1	163	82	0.50	50.3	-	<0.01	2.777	0.045	0.1614	0.0018	0.3601	0.0058	8.014	0.156	0.1614	0.0018	0.822	1963	27	2470	19	20
8.1	239	132	0.55	27.8	-	<0.01	7.370	0.099	0.0717	0.0008	0.1357	0.0018	1.342	0.025	0.0717	0.0009	0.727	820	10	978	26	16
8.2	436	273	0.63	29.6	0.000144	0.13	12.668	0.162	0.0580	0.0009	0.0788	0.0010			489.2	6.1						
9.1	167	167	0.89	36.5	0.000054	0.09	4.369	0.061	0.0884	0.0009	0.2276	0.0032	2.752	0.059	0.0877	0.0014	0.648	1322	17	1375	32	4
9.3	353	154	0.43	23.4	0.000044	0.17	12.955	0.158	0.0580	0.0007	0.0771	0.0010			475.5	7.7						
10	236	153	0.65	16.6	0.000396	0.56	12.199	0.175	0.0619	0.0012	0.0815	0.0012			505.2	7.1						
10	198	115	0.58	13.3	0.000051	0.01	12.771	0.162	0.0569	0.0009	0.0783	0.0010			486.0	6.1						
11	490	59	0.12	56.1	0.000058	0.10	7.504	0.089	0.0692	0.0007	0.1331	0.0016	1.255	0.021	0.0684	0.0008	0.704	806	9	881	25	34
12	318	139	0.44	32.9	-	<0.01	8.307	0.107	0.0577	0.0009	0.1205	0.0015	1.268	0.023	0.0764	0.0009	0.722	733	11	905	25	34
13	212	134	0.63	14.7	-	0.21	12.418	0.177	0.0589	0.0012	0.0804	0.0012			493.3	7.0						
14	177	120	0.68	11.9	0.000075	0.20	12.846	0.172	0.0584	0.0010	0.0777	0.0011			482.3	6.3						
16	236	237	0.65	24.1	0.000019	0.07	12.898	0.148	0.0573	0.0007	0.0755	0.0009			481.0	5.4						
16	134	90	0.67	9.4	-	0.14	12.292	0.200	0.0585	0.0014	0.0812	0.0013			503.5	8.0						
17	273	174	0.64	18.5	-	0.07	12.709	0.172	0.0575	0.0010	0.0786	0.0011			488.0	6.5						
18	207	96	0.27	43.0	0.000455	0.75	4.127	0.096	0.1185	0.0011	0.2454	0.0023	3.458	0.091	0.1043	0.0023	0.527	1389	17	1702	41	18
20	101	57	0.17	7.1	0.000000	0.46	12.255	0.208	0.0611	0.0019	0.0812	0.0014			503.4	8.4						
20	783	19	0.02	50.4	0.000000	<0.01	13.346	0.143	0.0560	0.0005	0.0750	0.0008			466.0	4.9						
21	243	391	1.61	0.06	-	<0.01	5.133	0.069	0.0785	0.0011	0.1950	0.0026	2.130	0.042	0.0792	0.0012	0.681	1148	14	1178	29	2
21	339	167	0.49	23.2	0.000265	0.11	12.545	0.136	0.0580	0.0011	0.0796	0.0011			493.9	6.5						
22	126	79	0.45	8.5	0.000159	<0.01	12.736	0.172	0.0584	0.0008	0.0785	0.0009			487.4	6.2						
23	128	87	0.68	8.6	0.000035	0.40	12.779	0.174	0.0572	0.0011												