From intrabasinal volcanism to far-field tectonics: causes of abrupt shifts in sediment provenance in the Devonian–Carboniferous Drummond Basin, Queensland

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\textbf{ABSTRACT}

The Drummond Basin of central Queensland preserves a large-volume succession of little studied, predominantly fluviatile, coarse-grained sedimentary rocks of mid-Mississippian age. The stratigraphy of the basin has been subdivided into three sedimentary cycles. The Cycle 1/Cycle 2 boundary records a distinct, but poorly understood change in provenance from a volcanic-dominated succession related to initial basin rifting (Cycle 1) to a quartz-rich, craton-derived succession (Cycle 2). Cycle 3 has been thought to mark a resumption of intrabasinal volcanism and related sedimentation. The purpose of this study was to enhance the understanding of the basin-wide siliciclastic sedimentation of Cycles 2 and 3, and causes for the changes in sediment provenance. This objective was achieved by constraining large-scale spatial and temporal depositional trends and investigating sediment transport pathways into and through the basin. Petrographic, QFL, paleocurrent and conglomerate clast analyses were undertaken. The observations presented here have several implications relevant to understanding the stratigraphy of the Drummond Basin and regional tectonic events at this time. Cycle 3 is revised here primarily to be a continuation of Cycle 2-style basement-derived sedimentation, rather than recording a resumption of volcanism in the area, as per prevailing models. Quartz-rich sedimentation in the Drummond Basin was, therefore, more long-lived than previously envisaged, and once established, was not significantly disrupted by volcanism. Cycle 2 formation thicknesses appear highly variable across the basin. This is unlikely to be a result of pre-existing rift-related topography as suggested in previous models. The thickness variations are more likely related to sediment bypassing and post-depositional deformation in the area. The distinctive coarse-grained, relatively quartz-rich sedimentation of Cycles 2 and 3 is unusual in its volume and extent. The sediment was transported into the basin from its southern/southwestern margin, implying long-distance transport and extrabasinal sediment supply. While the specific source terrain(s) remain unknown, one plausible tectonic driver was far-field influence of the intraplate Alice Springs Orogeny.

\textbf{INTRODUCTION}

The Drummond Basin of central Queensland (Figure 1) is distinctive for preserving an extensive, thick (7600 m) and large-volume (up to \(\sim 282,000 \text{ km}^3\)) succession of predominantly fluviatile, coarse-grained, basement-derived sedimentary rocks of mid-Mississippian age (Fenton & Jackson, 1989; Henderson & Blake, 2013; Johnson & Henderson, 1991; Olgers, 1972). The large area covered by these coarse deposits is unusual, and very few studies to date have documented such coarse-grained sediment dispersal at a similar scale (see Ryder & Schölten, 1973; Janecke, VanDenburg, Blankenau, & M’gonigle, 2000). Typically, conglomeratic units in continental sedimentary basins are more restricted in extent and volume, primarily reflecting proximity to their sources (e.g. DeCelles, 1988; Dickinson, 2008; Ferguson, Hoey, Wathen, & Werritty, 1996; Leier, McQuarrie, Horton, & Gehrels, 2010; Miall, 1977, 1992; Nilsen, 1969; Wandres et al., 2004). Furthermore, the basement-derived quartz-rich conglomeratic succession buried a relatively thick (\(\sim 2000\)–\(3000 \text{ m}\)) Upper Devonian–lower Mississippian volcanic-dominated succession related to initial basin rifting (Davis & Henderson, 1996; Fenton & Jackson, 1989; Henderson & Blake, 2013; Henderson, Davis, & Fanning, 1998; Johnson & Henderson, 1991; Olgers, 1970, 1972).

In this study, we explore the sedimentological characteristics of the Cycles 2 and 3 (division by Olgers, 1972)
Figure 1. Location of the Drummond Basin with the distribution of sedimentary Cycles 1, 2 and 3, and outcrop areas of the Mt Hall Formation. Modified after Henderson & Blake (2013), Henderson et al. (1998), and Olgers (1972). Subsurface extents of the Drummond Basin after Nicoll et al. (2015). Dashed line shows the boundary between northern and southern parts of the basin, as referred to in this study. Key field locations described in this study are numbered in red: 1. Reklaw Park (S23°22'99.8", E147°24'22.6"), 2. Withersfield (S23°27'09.3", E147°26'53.8"), 3. Pebbley Creek tributary (S23°27'76.2", E147°11'75.0"), 4. Snake Range East Pit (S24°00'51.6", E147°37'00.1"), 5. Snake Range National Park (S24°07'95.1", E147°34'82.2"), 7. Telemore Road (S24°11'11.2", E147°44'00.0"), 8. Omega (S23°55'13.6", E146°58'35.9"), 9. Old Banchory (S23°00'18.9", E147°13'26.5"), 10. Springvale (S22°44'57.4", E146°57'49.9"), 11. Star of Hope (S22°42'45.3", E146°55'29.5"), 12. Namin NP (S22°30'59.7", E146°58'03.5"), 13. Laglan (S22°30'27.1", E146°44'21.0"), 14. Llanarth (S21°15'45.5", E146°48'46.1"), 15. St Ann's (S21°15'46.2", E146°53'48.8"), 16. Hanging Rock (S21°10'46.6", E146°38'27.8"), 17. Scartwater (S21°04'28.8", E146°49'12.5"), 18. Dawsonvale (S21°25'45.3", E146°28'40.2"), 19. Dandenong (S20°55'03.8", E146°43'07.5"), Local thicknesses of Mt Hall Formation observed in this study are shown in black italics text.
formations of the Drummond Basin. Given their quartz-rich composition, the formations are relatively resistant to weathering and produce small hills scattered across the basin, and where post-depositional tilting and folding provide cross-sectional exposures of the formations. The primary purpose of this study was focusing on the sediment characteristics to clarify compositional and textural changes, these being proxies for provenance shifts that reflect evolving tectonic controls on the basin. Specific objectives were: (1) to constrain large-scale depositional trends over the ~470 x 100 km wide basin tract; (2) to explore the spatial and temporal transition from intrabasinal rift-related volcanism and associated volcaniclastic sedimentation (Cycle 1) to coarse-grained, craton-derived and likely extrabasinal fluvial sedimentation (Cycle 2); and (3) to understand sediment transport pathways into and through the Drummond Basin.

**Geological setting**

**Overview**

The Drummond Basin is exposed in a N–S-oriented belt and straddles the boundary between the early Paleozoic Thomson Orogen and the mid–late Paleozoic New England Orogen of the Northern Tasmanides (e.g. de Caritat & Braun, 1992; Henderson & Blake, 2013; Murray, 1994; Murray & Kirkegaard, 1978; Rosenbaum, 2018). An uplifted basement block of the Thomson Orogen known as the Anakie Inlier now divides the basin in two (Olgers, 1972; Figure 1). The basin developed in the Famennian as an extensional structure in a back-arc geographic setting relative to an active convergent margin well to the east (e.g. Davis & Henderson, 1996; de Caritat & Braun, 1991, 1992; Olgers, 1972). Earliest deposition was recorded in the northern part of the basin, while subsidence in the south may not have initiated until the Tournaisian (Henderson & Blake, 2013; Henderson et al., 1998). The Drummond succession was deposited predominantly in non-marine fluvial, and to a lesser extent, lacustrine environments (e.g. Henderson & Blake, 2013; Johnson & Henderson, 1991; Olgers, 1972). Sedimentation across the basin was terminated by the end of the Visean (de Caritat & Braun, 1992; Henderson et al., 1998; Johnson & Henderson, 1991; Olgers, 1972) after reaching a total thickness of 7600 m (as revised by Henderson & Blake, 2013). Except for mild folding and associated faulting of the Drummond sequence during the Kanimblan Orogeny in the mid-Carboniferous, and reactivation of existing faults during the Permo-Triassic Hunter–Bowen Orogeny (de Caritat & Braun, 1992; Douth & Nicholas, 1978; Olgers, 1972; van Heeswijck, 2006; Veveys, Jones, & Powell, 1982), the basin remains relatively undeformed (for general geometry of the basin, see Fenton & Jackson, 1989, figures 7 and 10; Henderson & Blake, 2013, figure 3.108). Most deformation is concentrated around the margins of the Anakie Inlier (de Caritat & Braun, 1992; Fenton & Jackson, 1989; van Heeswijck, 2006). The subsurface extents of the basin are buried by the younger Permian–Triassic Bowen Basin in the east, the Permian–Triassic Galilee Basin in the west and the Mesozoic Great Australian Basin system to the west and south (Figure 1).

**Drummond Basin stratigraphy**

The Drummond Basin stratigraphy was subdivided by Olgers (1972) into three distinct sedimentary cycles. Cycle 1 comprises the Mt Wyatt Formation, Silver Hills Volcanics and St Ann’s Formation, Cycle 2—the Telemon, Scartwater, Mt Hall and Raymond formations, and Cycle 3—the Star o Hope, Ducabrook, Bulliwallah and Natal formations (Figure 2). Scattered exposures of rocks from all three cycles are present west of the Anakie Inlier across the length of the basin.

**Cycle 1**

All Cycle 1 formations record basin-wide contemporaneous volcanism. The volcanic units are interpreted to be mostly derived from vents within the basin itself, and potentially from volcanically active areas to the east (Bryan, Holcombe, & Fielding, 2001; Bryan, Fielding, Holcombe, Cook, & Moffitt, 2003; Bryan et al., 2004; Davis & Henderson, 1996; Henderson et al., 1998; Johnson & Henderson, 1991). Although highly variable in thickness, the volcanic strata extend across the entire basin.

Volcanic and volcaniclastic rocks of the top of Cycle 1 are overlain by thick successions of compositionally distinct sandstone, pebbly sandstone and conglomerate with increased quartz content and bereft of volcanic rocks. The boundary between Cycle 1 and the siliciclastic part of the Drummond succession is critical to understanding the basin depositional history. However, determining whether the transition was abrupt or gradual is hindered by the absence of field exposure of contacts. Regardless, the transition is marked by pronounced lithological changes indicative of profound changes in sedimentological regimes.

**Cycle 2**

In contrast to Cycle 1, Cycle 2 is characterised by more quartzose and mature sedimentary rocks and an absence of volcanic rocks (Henderson & Blake, 2013; Johnson & Henderson, 1991; Olgers, 1972). This implies cessation of extension-related volcanism (Henderson & Blake, 2013; Olgers, 1972).

Regional mapping indicates that Cycle 2 disconformably overlies Cycle 1 in the southern part of the basin (Hill, 1957; Olgers, 1972). Here, the basal Telemon Formation has an estimated thickness of 2100 m (Olgers, 1972) and is dominated by locally variable sandstone, mudstone and conglomerate. Primary volcanic rocks are thought to be absent.

The Scartwater Formation in the north consists of similar rock types, except for fewer conglomerates and the presence of microbial limestone, as well as sparse tuff (de
Cycles 1, 2 and 3. Olgers (1972) and van Heeswijck (2006) for the Scartwater, Mt Hall, Raymond, (1996) and Henderson and Blake (2013) for the Silver Hills Volcanics; and on Star of Hope, Bulliwallah and Natal formations; on Davis and Henderson et al. Henderson Formation thicknesses are based on Olgers (1970, 1972) for the Mt Wyatt, St Ann the Mt Hall Formation is additionally constrained based on (U,Th)/He zircon geochronology (ca 330 Ma, Kerrison, 2013; ca 340 Ma, Zhang, 2014). Formation thicknesses are based on Olgers (1970, 1972) for the Mt Wyatt, St Ann’s, Telemom and Ducabrook formations; on Henderson & Blake (2013), Olgers (1972) and van Heeswijck (2006) for the Scartwater, Mt Hall, Raymond, Star of Hope, Bulliwallah and Natal formations; on Davis and Henderson (1996) and Henderson and Blake (2013) for the Silver Hills Volcanics; and on Henderson et al. (1998) and Johnson and Henderson (1991) for cumulative Cycles 1, 2 and 3.

The first formation believed to record the lithological reversal to more volcanogenic sedimentation is the Star of Hope Formation (de Bretizel, 1966; Johnson & Henderson, 1991; Olgers, 1970, 1972). The Star of Hope Formation is conformably overlain by the Ducabrook Formation in the north (Figure 2). The Ducabrook Formation consists of different varieties of biostratigraphy (Henderson & Blake, 2013; Henderson et al., 1998).

The thickness of the Mt Hall Formation varies but is estimated up to 3 km in the north, thinning rapidly towards the basin margins (Olgers, 1972). The variability is attributed to compartmentalisation of the basin into depocentres, owing to transfer faulting associated with rifting (Davis & Henderson, 1996; Henderson et al., 1998; Johnson & Henderson, 1991; van Heeswijck, 2006). Van Heeswijck (2006) recognised some depocentres in the northernmost part of the basin from seismic imaging. Available seismic data clearly show, however, that the faulting was associated exclusively with the rifting phase of the basin development (Cycle 1) and did not project up into Cycle 2 (Davis & Henderson, 1996; Fenton & Jackson, 1989; Johnson & Henderson, 1991).

The Mt Hall Formation is conformably overlain by the finer-grained Raymond Formation that is reported to reach a similar thickness (Henderson & Blake, 2013; Olgers, 1972). The formation is dominated by flaggy to cross-bedded, texturally and compositionally mature sandstone and mudstone (Hill, 1957; Veevers et al., 1964), with rare calcareous concretions and lenses of limestone (Olgers, 1972).

**Cycle 3**

The top formations of the Drummond succession were grouped into Cycle 3, as recording an abrupt resumption of volcanism in the basin (Henderson & Blake, 2013; Johnson & Henderson, 1991; Olgers, 1972). Tuffs and red volcanolithic sedimentary rocks are thought to be common across the basin, particularly in the north. The duration of Cycle 3 is poorly constrained but based on stratigraphic relationships it is believed to have terminated by the end of the Visean with the onset of the Kanimblan Orogeny (Henderson & Blake, 2013; Olgers, 1972).

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sandstone (quartz, lithic and feldspathic) and mudstone, commonly interbedded with tuffs and volcanolithic sedimentary rocks (de Bretizel, 1966; Olgers, 1972; van Heeswijck, 2006). The Natal Formation rests conformably on the Bulliwallah Formation in the north of the basin and is distinguished from the underlying units by finer grainsize (fine-grained sandstone, siltstone and mudstone), better sorting and uniform thin bedding. The sandstones are quartz to feldspathic in composition (Olgers, 1972).

Methods
Exposures of volcanic and sedimentary rocks from the uppermost parts of Cycle 1 and from the entire stratigraphic span of Cycles 2 and 3 were examined. The study focusses on the Mt Hall, Raymond and Star of Hope formations to assess their lithological variability and the distribution of conglomeratic sedimentary rock across the basin. Outcrops, although relatively sparse, were available at multiple locations across the basin, typically within a number of anticlines and synclines roughly oriented along the N–S axis of the basin, on average dipping at ~27° (Figure 1). Nineteen locations were targeted to provide sufficient spatial and vertical coverage of the basin stratigraphy. Each location contains several specific study sites where detailed sedimentological sections were logged. Surface exposure studies have been complemented by examination of a series of drill cores from the northwestern corner of the basin (Campaspe DDH 1–4 drill holes; Fenton & Jackson, 1989; Figure 1; Supplementary papers, Appendix 1), which provide valuable insight into the transition from Cycles 2 to 3. Drill core provided valuable information on vertical grading patterns not apparent in field exposures.

Sixty-two samples were thin-sectioned for petrographic examination and modal abundance estimates of detrital grains, including QFL classification of sandstone samples (Dickinson & Suczek, 1979; Dickinson et al., 1983; Supplementary papers, Appendix 2). Limitations of this method, including overlap in sandstone composition from different tectonic settings, have been increasingly recognised in many studies (e.g. Bryan et al., 1997, 2004, Garzanti, 2016; von Eynatten, Barceló-Vidal, & Pawlowsky-Glahn, 2003; Weltje, 2006). Therefore, in this paper, the QFL diagrams are used to illustrate the nature and magnitude of provenance changes across the Cycle 1/Cycle 2 and Cycle 2/Cycle 3 transitions, and to characterise sediment composition, with less emphasis on tectonic provenance interpretation. Further sedimentological data were obtained from the field through paleocurrent analysis and conglomerate clast analysis (Supplementary papers, Appendix 3).

Results
Basin stratigraphy
This section details new observations arising from field studies and focuses on three main aspects of the basin stratigraphy: (1) the Cycle 1/Cycle 2 transition from exclusively volcanioclastic to cratonic quartz-dominated sedimentation; (2) the Mt Hall and Raymond formations—the dominant formations of Cycle 2; and (3) the Cycle 2/Cycle 3 transition and Cycle 3 strata. Lithostratigraphic logs from both field outcrops and drill cores are used and presented in full in Appendix 1.

Cycle 1/Cycle 2 transition
Although previously mapped as conformable (Olgers, 1972), the contact between Cycles 1 and 2 formations is
obscured by zones of no outcrop for >700 m of stratigraphic thickness. Regardless, strata on either side of the contact show a pronounced lithological contrast. The uppermost Silver Hills Volcanics (Figures 3a and 4) and the Llanarth Volcanic Member of the St Ann’s Formation are characterised by thick-bedded to massive dacitic and rhyolitic ignimbrites, with minor dacitic and rhyolitic lavas, and volcanolithic conglomerates, sandstones and siltstones showing poor sorting and rounding. The ignimbrites typically contain plagioclase and, less frequently, K-feldspar (commonly sanidine) and quartz phenocrysts, with rare hornblende and biotite. No muscovite was observed.

The lowermost exposures of the overlying Cycle 2 typically comprise cross-bedded and sometimes ripple cross-laminated or horizontally bedded sandstones, siltstones and minor conglomerates of the correlative Telemon and Scartwater formations (Figure 5). The Telemon Formation is distinctly enriched in quartz and detrital muscovite in contrast to the underlying strata, marking a distinct change from Cycle 1. The formation is dominated by cross-bedded sandstones, with only occasional thin horizons of volcanioclastic rocks (Figure 3). The Scartwater Formation, while also dominated by siliciclastic sedimentary rocks, is more
lithic-rich than its southern stratigraphic equivalent and contains more tuff and ignimbrite horizons, especially at Scartwater and St Ann’s stations (e.g. Figure 4). This inter-fingering of primary volcanic units with relatively quartzose sedimentary rocks can be observed over ~1000 m of stratigraphic thickness.

Mt Hall and Raymond Formations

The overlying Mt Hall Formation is the most distinctive and quartz-rich formation in the basin succession (Figure 6). The formation varies significantly in thickness (Figure 1): at the thickest measured section in the central basin, it is >1082 m (Springvale), but at some locations in the southernmost part of the basin, it can be thinner than 100 m (81 m at Foyle Park; 21 m at Snake Range East Pit; Figure 7). In the north, the formation is relatively thick, notably at Hanging Rock where a minimum thickness of 785 m was recorded (Appendix 1), although in none of the locations studied does it approach the 3 km reported by Olgers (1972).

The transition from Telemon and Scartwater formations to the Mt Hall Formation records an abrupt increase in grainsize, as seen at Dandenong, Foyle Park (Figure 7) or Reklaw Park (Appendix 1). Persistence of thick beds of coarse-grained (medium sand to pebble-grade) sedimentary rocks defines the formation. Individual conglomeratic beds are typically 1.5–2 m thick, but many are 3–4 m thick. The conglomerates are typically pebble-grade, composed of well-rounded milky quartz pebbles (Figure 6b), with minor sandstone, siltstone, ignimbrite and rhyolite clasts, in poorly rounded, quartz-dominated sandy matrix, commonly pale red. Both matrix- and clast-supported varieties are present, showing medium to poor sorting. Sandstones are distinctively quartzose and rich in muscovite. Siltstones are rare and form only thin intervals.

The sandstones and conglomerates are commonly tabular and trough cross-bedded on a large scale (Figure 6a), or internally massive. Bed bases commonly erosionally downcut into underlying finer-grained units (e.g. at Foyle Park, Snake Range East Pit; Figure 7, Appendix 1; at Campaspe DDH-1; Figure 8) and contain rare Lepidodendron and cor-daitalean fossils. The exact amount of downcutting is difficult to assess, since few of the basal contacts were fully exposed, but erosional relief of up to decimetre-scale was observed. Evidence of vegetation destruction is present, such as fossilised wood and plant debris found in the Mt Hall Formation (as well as the Raymond Formation) conglomerate and sandstone beds.

The top of the Mt Hall Formation records an abrupt grainsize change (e.g. Pebble Creek tributary, Figure 7; Campaspe DDH-1, Figure 8), and the formation is overlain again by finer-grained sedimentary rocks of the Raymond Formation (Figures 7, 8 and 9). The base of the Raymond Formation is defined by the appearance of mudstones, siltstones and fine-grained sandstones, and disappearance of thick conglomerate packages. Single beds of quartz conglomerate resembling the Mt Hall conglomerate are only locally present, and typically thin (e.g. Campaspe DDH-1) with the exception of Omega where they form a thicker interval (Figure 4). The Raymond Formation is typically quartz-lithic in composition, and commonly ripple cross-laminated (Figure 9a) or horizontally laminated. Plant, indeterminate shell debris and trace fossils are locally present (e.g. Pebble Creek tributary and Campaspe DDH-1, 126–132 m depth). The thickness of the Raymond Formation reaches >1210 m (Old Banchory 1; Appendix 1) but is significantly thinner at some locations, e.g. Foyle Park (<108 m) or Campaspe DDH-1 borehole (263 m). Volcanic influence, overall rare within Cycle 2, is relatively
common in the basal part of the Raymond Formation, especially in the north. The volcaniclastic rocks typically form thin (~1–2 cm to 50 cm) beds.

Cycle 2/Cycle 3 transition and Star of Hope Formation
The Cycle 2/Cycle 3 contact was observed at two locations in the southern basin (Old Banchory and Omega; Figure 4), as well as in the Campaspe DDH-2 drill core (Appendix 1). The transition is gradational and no evidence of a major unconformity was observed, other than one of many erosional contacts related to grainsize change in the Campaspe DDH-2 drill. A coarsening-upward trend to coarse sandstone and conglomerate interbeds is apparent within the topmost section of the Raymond Formation. Thick intervals of fine-grained sedimentary rocks are gradually replaced by mostly coarse-grained sandstones, commonly interbedded with conglomerates. The transition is also marked by a gradual decrease in the number and thickness of volcaniclastic beds, leading to their virtual disappearance towards the top of the Raymond Formation and in the Star of Hope Formation.

The Star of Hope Formation is intersected by the Campaspe DDH-2 and 3 drill holes. The maximum thickness of the formation observed in this study is 378 m in the Campaspe DDH-2 drill core; however, the entire stratigraphic thickness was not observed in field exposures. The formation is almost exclusively siliciclastic and dominated by coarse-grained quartz sandstones and pebble conglomerates (Figures 4, 10 and 11), commonly large-scale trough- and planar cross-bedded (up to 3 m cross-bed sets). The conglomerates in the southern basin are more quartzose with moderately to well-rounded milky quartz pebbles in a light-grey to red sandy matrix (Figure 11a). In the north, the conglomerate clast composition tends to be more varied, as shown in Figure 11b. The coarse-grained rocks of the Star of Hope Formation are indistinguishable from the Mt Hall Formation and are only discerned by their stratigraphic position. Petrographically, the Star of Hope sandstones are slightly less quartzose compared with the Mt Hall Formation (see below), and interbeds of siltstone and fine-grained sandstone are more common. Finer-grained rocks were mostly observed in the Campaspe DDH-2 drill core and are very rare in the field exposures in the southern part of the basin, which may reflect either a lateral fining trend from the south to the north, or the finer units are poorly exposed and preferentially do not crop out. Evidence of volcanic influence in the formation is sparse in the northern part of the basin and virtually absent in the south, a notable exception being an occurrence
of a crystal-rich ignimbrite at Withersfield (S23°29′49.1″, E147°27′29.0″).

**Bulliwallah, Natal and Ducabrook formations (Cycle 3)**

Both the Bulliwallah and Natal formations were only examined in the Campaspe drill cores. The top ~50 m of the Star of Hope Formation intersected by the Campaspe DDH-2 core shows a fining-upward trend (Appendix 1) and is erosionally cut by the overlying sandstones of the Bulliwallah Formation. No major change in dip angle or other indicators for an unconformable contact between the two formations are evident. The Bulliwallah Formation has a minimum thickness of 400 m and is dominated by sand-grade sedimentary rocks. This formation is the most lithologically diverse unit in the Drummond Basin succession, varying from siltstone, through sandstone to sedimentary breccia and conglomerate (Figures 12 and 13). The conglomerates and breccias are typically rich in lithic intra- and extraformational clasts, especially siltstone rip-up clasts at bed bases, although they still contain large amounts of quartz. The sandstones are notably more feldspathic than the underlying units (see below). Fine plant debris, rootlet structures and bioturbation are locally present in the fine-grained rocks, while rare shell fragments show poor preservation, hindering species identification. Interbedded primary volcaniclastic beds of silicic tuffs and ignimbrites of various thicknesses (~2 cm up to 11 m; Appendix 1) are common. They are typically non-welded and both crystal- and ash-rich. Quartz and plagioclase are the dominant phenocryst phases, and vitric textures are rarely preserved. Above a distinct gravel-sized interval in the middle of the sequence (Campaspe DDH-3, 206 to 92 m depth, Campaspe DDH-4, 500 to 455 m depth; Figure 12; Appendix 1), the Bulliwallah Formation shows a fining-upward trend and terminates with a siltstone interval (Figure 12).
The Natal Formation erosionally cuts into the Bulliwallah Formation and marks a pronounced and abrupt change to persistent coarse-grained, erosionally based facies, with few siltstones and no volcanic or volcaniclastic beds (Figure 12). The minimum thickness of the formation is 202 m as recorded in the Campaspe DDH-4 drill core. The Natal Formation conglomerates contain a variety of clast types including quartz, ignimbrite, rhyolite and siltstone, much like the Bulliwallah Formation, but are overall much more quartzose. The sandstones are almost exclusively coarse-grained, typically contain >80 vol% quartz, and show good sorting and rounding. A gradual fining-upward trend is apparent throughout the Natal succession. The Ducabrook Formation of the southern part of the Drummond Basin was only examined in one location (Foyle Park; Figure 7), where it was composed of horizontally and cross-bedded sandstones and siltstones with near 100 vol% quartz content.

**Sandstone compositions**

QFL analysis of sandstone samples throughout the basin stratigraphy reveals temporal changes in sediment grain composition through the three sedimentary cycles. Results for each formation are shown in Figures 14 and 15, and the methodology used is detailed in Appendix 2.

Cycle 1 formations are dominated by lithic fragments and plagioclase, with less abundant quartz and minor K-feldspar (Figure 16c, d), with all but three samples...
Cycle 2 sandstones have crystal faces (Figure 16d). Lithic clasts show various degrees of rounding, as can be seen in Figure 16c. A major change in sandstone composition is observed for Cycle 2 formations (Figures 14–16). All analysed Cycle 2 sandstones have >60 vol% quartz, and most of the Telemon and Mt Hall formations contain >80 vol% quartz (Figure 15), with few lithic grains and even less detrital feldspar. Most samples plot within the recycled orogen field. Quartz occurs as both monocrystalline and polycrystalline varieties (including chert). The majority of the quartz grains (in some samples—all grains) show weakly undulose extinction and contain fluid inclusion trails (Figure 16b), contrasting with Cycle 1 sandstones. Mineral inclusions such as apatite, are present inside some large quartz grains. There is also a small number of inclusion-free quartz grains with straight extinction. Feldspar, where present, is dominated by plagioclase and usually sericitised to various extents. Mica grains are commonly present, with muscovite more abundant than biotite; zircon and apatite are common detrital heavy minerals. The grain composition is consistently quartz-rich in the south and most of the northern parts of the basin, although samples collected from the northernmost locations (Dandenong and Campaspe DDH-1) show a slight increase in the percentage of feldspar and lithic grains, and consequently less quartz (Appendix 2). Unlike Cycle 1, Cycle 2 quartz grains are consistently well rounded across most of the basin. The grains become more angular in the Campaspe DDH-1 drill core, as noticeable for all clast types in both Mt Hall and Raymond formations intersected in the core.

The compositional change between Cycle 1 and 2 is most evident when juxtaposing sandstones from the top of Cycle 1 with the base of Cycle 2. The contrast is more pronounced for the southern formations (Silver Hills Volcanics and Telemon Formation): for example, when comparing sample S45 (Silver Hills Volcanics, Figure 16c, d) with sample S1/16 (Telemon Formation, Figure 16a), collected only 200 m from the mapped contact with ignimbrites of the Silver Hills Volcanics (S24°1’7.2” , E145°57’47.1”). The Scartwater Formation contains less quartz than the correlative Telemon Formation (73 and 84 vol%, respectively). The Mt Hall Formation has the highest quartz content of Cycle 2 across the entire basin, with up to 99 vol% quartz framework grains (average 87 vol%). The overlying Raymond Formation shows an increased proportion of detrital feldspar and lithic grains in comparison with the Mt Hall Formation.

The base of Cycle 3 records another change in sandstone composition, but much less pronounced than at the Cycle 1/Cycle 2 boundary. Cycle 3 formations show a wide range of compositions (Supplementary papers, Table A1, Appendix 2). Some Cycle 3 formations (Ducabrook and Natal) are compositionally indistinguishable from Cycle 2 and mostly plot within the recycled orogen field, while others are very distinct and plot in the continental block field (Bulliwallah Formation).

The stratigraphic base of Cycle 3, the Star of Hope Formation, shows relatively high compositional variability, spanning from quartz-feldspathic to quartz-lithic. The majority of quartz grains show the same features as Cycle 2 quartz grains: weakly undulose extinction and abundant inclusion trails. Although a small increase in the proportion of feldspar relative to underlying formations is evident, the Star of Hope Formation composition overlaps with Cycle 2 in having a high quartz content.

The overlying Bulliwallah Formation marks a more pronounced contrast in composition: it is compositionally immature and the least quartzose within Cycles 2 and 3 (on average 41 vol% quartz), and typically contains abundant, relatively unaltered feldspar and few lithic grains, except for two lithic-rich samples from Campaspe DDH-4. The formation shows greater detrital biotite and a lesser muscovite content compared with Cycle 2, and the sandstone grains are consistently poorly rounded. A slight change in quartz features can be detected: in addition to large grains showing undulose extinction and inclusion trails, typically approximately half of the quartz grains in the Bulliwallah samples show straight extinction and a clear, inclusion-free texture.
The Natal Formation marking the top of Cycle 3 is again relatively quartzose, although still contains a significant amount of plagioclase—up to 27 vol%. Quartz grains in the Natal sandstones are dominated by the undulose variety with inclusion trails, but a significant number of clear grains with straight extinction are also present. All grain types in the Natal Formation sandstones are typically very well rounded.

**Interpretation of detrital grain characteristics**
The source of the Cycle 1 sandstones is clearly volcanic, given the abundance of volcanic and volcaniclastic lithic grains and the detrital quartz grain properties. In contrast, the lithic-poor composition of all Cycles 2 and 3 sandstones, and their relative enrichment in quartz content overall points to a cratonic provenance. The detrital quartz properties such as undulose extinction and

![Diagram of lithostratigraphic logs from Campaspe DDH-3 (S20°43'16.2", E145°47'53.5") and DDH-4 (S20°44'28.1", E145°46'37.5") drill cores. Mud-to silt-grade rocks are shown in grey, sand-grade in yellow and gravel-grade in orange. Volcanic and volcanic-derived sedimentary rocks are shown in red. Q/F/L denote dominant grain framework component (quartz/feldspar/lithic grains).](image-url)
numerous fluid inclusion trails argue against volcanic sourcing, and instead indicate plutonic or vein origin (e.g. Basu, 1985; Folk, 1980; Krynine, 1946). This type of quartz dominates in all but the Bulliwallah Formation, which in addition to the common quartz (plutonic or vein), also contains an approximately equal proportion of volcanic quartz. The volcanic influence is also noticeable for the Natal Formation, based on the presence of volcanic quartz variety, although to a much lesser extent. The composite quartz variety observed rarely in several Cycles 2 and 3 samples, showing strong undulose extinction, is consistent with a metamorphic source.

The source(s) of feldspar in the Cycles 2 and 3 formations is more difficult to determine solely based on petrographic analysis, but it is likely basement-derived where associated with the common quartz. By contrast, the increased amount of feldspar in the Bulliwallah Formation may reflect volcanic sourcing, based on coexisting volcanic quartz, as well as the relatively good preservation of the feldspar grains, sometimes showing preserved euhedral faces. The lithic grains in the Cycle 2 and 3 sandstones are dominated by such lithologies as chert, metasedimentary rocks and siltstone, with few volcanic rock fragments (Supplementary papers, Table A2, Appendix 2), which is also consistent with the general cratonic sourcing.

Other grain types in the Cycles 2 and 3 detrital suites, even though only present in small numbers, may also be sandstone provenance discriminators. A notable example is muscovite that consistently appears in Cycles 2 and 3 sandstones. The origin of the muscovite is likely cratonic, as the mineral has not been observed in the volcanic or volcanic-derived sedimentary rocks of any part of the Drummond succession. The detrital heavy mineral assemblage of Cycle 2 is dominated by zircon and apatite, with minor rutile and magnetite. The zircon grains show a range of morphologies, from very well rounded to angular with euhedral faces preserved, which indicates a mix of sources, likely both proximal volcanic and distal plutonic.

**Paleocurrent data**

Paleocurrent data from the Drummond Basin available in the literature are very sparse and almost entirely limited to the Mt Hall Formation. The data from Olgers (1972) and Olgers, Douth and Eftekharnejad (1967) record sediment flow through the basin in a northerly and northwesterly trend across the south and the centre of the basin. Some more local variation in sediment transport direction in Cycle 2 is apparent at the northeastern margin of the basin, with sediment transport to the east, and some local transport southwards indicated for the area near the Scartwater station (Olgers, 1972; van Heeswijck, 2006).

Paleocurrent directions measured from sedimentary structures in this study are presented in Figure 17, and data collection procedures are detailed in Appendix 3. The majority of readings were taken from the Cycles 2 and 3 sandstones and conglomerates, although four readings were obtained from the Llanarth Volcanic Member (St Ann’s Formation) of Cycle 1. Paleocurrent directions measured in the southernmost part of the basin indicate northerly (Telemen Formation at Snake Range NP, Mt Hall Formation at Foyle Park) to northeasterly (Telemen Formation at Foyle Park, Mt Hall Formation at Snake Range NP, and Raymond Formation at Mt Beaufort Anticline) sediment transport directions. Two datasets at the western edge of the Anakie Inlier, Withersfield (Mt Hall Formation) and Old Banchory (Star of Hope Formation), show some deviation from this general trend. A more bimodal distribution of opposing NW and SE trends was recorded at the Withersfield location, although the NW trend remains dominant and consistent with readings from elsewhere in the southern basin. More variable directions are shown for the Cycle 3 Star of Hope Formation in the central part of the basin (e.g. Old Banchory). In the central part of the basin (Narrien and Pebbly Creek antilines, Figure 1), the paleoflow directions become more north/northwest oriented, potentially reflecting the basin axis, and are mostly...
Figure 14. QFL classification of the Drummond Basin formations grouped into each sedimentary cycle. Results for each thin-section were plotted separate ternary QFL diagrams, one with polycrystalline quartz grouped with all quartz (left-hand side), the other with polycrystalline quartz grouped with lithic fragments (right-hand side) (Dickinson & Suczek, 1979; Dickinson et al., 1983). Samples from this study are shown in colour, samples from Henderson et al. (1998; Cycle 1) and van Heeswijck (2006; Cycles 2 and 3) are shown in black.
consistent with the recordings of Olgers (1972). The general northerly trend continues up to Dawsonvale, north of which the paleocurrent patterns shift to more radial distributions, with the northernmost location (Dandenong) showing a prominent southerly trend.

**Conglomerate clast analysis**

In addition to paleocurrent measurements, maximum clast-size analysis was undertaken on the Mt Hall conglomeratic units, to assess general clast-size grading patterns across the basin and determine the dominant clast types. Pebble- and cobble-sized clasts were counted and characterised in terms of lithology using the best exposed outcrops at 16 locations across the basin. Clasts were divided into: (1) quartz (including chert) and (2) lithic clasts. The lithic clast group includes sandstone, siltstone (both extra- and intraformational clasts), tuff/ignimbrite, volcanic clasts (mostly rhyolite) and other indeterminate lithic clasts. Data-collection procedures are detailed in Appendix 3.

A decreasing clast-size trend is indicated from south to north across the basin (Appendix 3). Conglomerates from the southern part of the basin tend to have average maximum clast sizes >2 cm, while all samples from the north have values <2 cm. No correlation between clast size or composition and stratigraphic position within the Mt Hall Formation was found. While all of the Drummond Basin conglomerates are dominated by pebble-grade clasts, individual cobbles were present in places, notably at Laglan and Star of Hope stations. The largest observed clasts were of flow-banded rhyolite, 18 cm in diameter at Star of Hope station (S22°42′45.3″, E146°55′29.5″), and of ignimbrite, 16 cm in diameter at Laglan (S22°30′27.1″, E146°44′21.0″). The largest observed quartz clasts were 15 cm in diameter, observed at the Pebbly Creek tributary (S23°27′76.2″, E147°11′75.0″) and Withersfield (S23°27′09.3″, E147°26′53.8″).

Quartz clasts dominated the count in all studied locations, which is consistent with the associated Mt Hall sandstones being relatively quartz-rich. Four locations in the southernmost part of the basin—Snake Range NP, Foyle Park, Snake Range East Pit and Pebbly Creek tributary—show an elevated percentage of lithic clasts (>30 vol%) compared with the rest of the locations. However, the most quartz-rich conglomerate (97.5 vol% quartz) was also recorded from the south (Withersfield).

**Discussion**

**Cycle 1/Cycle 2 boundary and provenance change**

The field, petrographic and QFL data in this paper demonstrate that the lithological and provenance change between the Cycle 1 volcanics and Cycle 2 sedimentary rocks is pronounced and basin-wide (Figure 15). The top formations of Cycle 1 are characterised by thick-bedded to massive silicic ignimbrites and lavas (Henderson et al., 1998; Johnson & Henderson, 1991; Olgers, 1972), accompanied by sedimentary rocks derived from contemporaneous volcanism, as indicated by a high percentage of volcanic-derived lithic grains, little quartz, and by the quartz grains present displaying volcanic textures. Proximal, first-cycle sediment sourcing is further supported by poor rounding and sorting of Cycle 1 sandstones and conglomerates.

In contrast to Cycle 1, the Cycle 2 formations show a considerable increase in quartz content and decrease in the number of lithic or detrital feldspar grains, thus indicating a recycled orogen provenance and little volcanic influence. This is particularly evident for the Telemon and Mt Hall formations. The Cycle 2 sandstones are dominated by quartz grains showing textures consistent with a plutonic or vein origin. Considering the size of quartz clasts in the conglomerates (commonly 3–5 cm milky-white pebbles, and occasionally up to 15 cm cobbles, as observed in this study), a vein origin is indicated for many clasts. The few lithic grains present are dominated by basement rather than volcanic rock types. The compositional shift is further marked by the appearance of detrital muscovite in Cycle 2 rocks as a common detrital grain, which for this basin, is a likely proxy for a provenance change. As volcanic and clastic units of both Cycles 1 and 2 contain no muscovite, the mineral is likely to be derived from basement rather than local volcanic sources, which is consistent with the relatively quartzose character of the Cycle 2 sedimentary rocks. Excellent rounding of quartz pebbles in the conglomerates and good rounding of the Cycle 2 sandstone clasts indicate prolonged sedimentary reworking and abrasion of the material prior to deposition in the Drummond Basin. In this fluvial environment, the working is interpreted to arise through long transport.

Assessing the Cycle 1/Cycle 2 transition and its abruptness is hindered by lack of exposure of the direct contact. It can be inferred, however, that the transition is relatively abrupt in the southern part of the basin, based on: (1) the
virtual lack of siliciclastic sedimentary rocks in the top section of the Silver Hills Volcanics; (2) the juxtaposition of quartz-rich sedimentary rocks of the Telemon Formation (Figures 15 and 16); (3) the paucity of volcanic rocks in Cycle 2; and (4) a lack of evidence for interfingering of the two formations. The contrast is well reflected in the QFL diagrams. The zones of no outcrop between Cycle 1 and Cycle 2 likely indicate the presence of fine-grained rock types that erode easily and/or crop out poorly.

The shut-off of volcanism in the northern part of the basin did not happen as abruptly as in the south. The Scartwater Formation shows mixed cratonic and volcanic provenance, and volcanic-derived lithologies such as tuffs, ignimbrites and feldspathic–lithic sandstones interfinger with more quartzose sedimentary rocks typical of Cycle 2. The QFL data show a relatively high percentage of detrital feldspar and lithic fragments, some of which are volcanic clasts, in the Scartwater sandstones compared with the Telemon Formation. Thus, the northern part of the basin appears to record a more gradual transition from volcanic-dominated Cycle 1 to the craton-derived, more quartzose Mt Hall Formation, than the southern basin areas.

The persistence of a volcanic influence in the basal part of Cycle 2 in the north reflects the interplay between two factors: (1) the frequency and proximity of volcanic eruptions; and (2) proximity to supply of craton-derived sediment. It is possible that the supply of the craton-derived sediment was sudden and extensive across the whole area, but volcanism stopped more quickly in the south of the basin while continuing in the north. The southern basin was also more proximal to, and overwhelmed by, the base- ment-derived sediment supply, while the northern basin was more distal, and this allowed for a more interbedded characteristic to the succession. This is supported by the paleocurrent data and clast-size grading indicating sediment supply from the south for the Cycle 2 formations. The transition from the Telemon and Scartwater formations to the Mt Hall Formation records a pronounced coarsening-upward trend (e.g. at Dandenong and Reklaw Park), peaking with pebble quartz conglomerate dominating the main part of the Cycle 2 succession.

The character of the provenance shift is inconsistent with being driven by paleoenvironmental change. Provenance changes induced by climate tend to be more gradual than observed in the Drummond Basin (e.g. Köhler et al., 2008; Sun, 2005; Sun & Zhu, 2010). No clear evidence is present to support any fundamental climate change in the region of the basin and over the basin history.
Paleoenvironmental indicators such as red beds and rare plant fossils of *Lepidodendron* and *cordaitalean* trees, are persistent throughout the Drummond succession and indicate tropical, oxidative, terrestrial depositional environment both below and above the change. A stable tropical position of northeastern Gondwana at the time of deposition in the Drummond Basin is also evident from paleogeographic and tectonic reconstructions (e.g. Domeier & Torsvik, 2014; Roberts & Engel, 1980; Rowley et al., 1985). A climatic shift can, therefore, be ruled out as a driver for the Cycles 1–2 provenance change, alternatively suggesting a far-field tectonic influence as a more likely possibility.

**Apparent cessation of volcanism during Cycle 2**

Contrary to earlier studies that concluded contemporaneous volcanic activity had terminated at the end of the deposition of Cycle 1 and was absent throughout the deposition of Cycle 2 (e.g. Henderson & Blake, 2013; Olgers, 1972), this study identified primary volcaniclastic rocks in outcrop across the basin (Reklaw Park, Snake Range East Pit, St Ann’s, and Scartwater) and in the Campaspe drill holes (first reported by Kerrison, 2013, from Campaspe DDH-1). We interpret, therefore, that rift-related volcanism in the basin area did not completely shut off but continued through Cycle 2 sedimentation. During deposition of Cycles 2 and 3, however, the volume of volcanic products decreased significantly compared with Cycle 1. Additionally, the thin beds and fine grain size of the volcaniclastic rocks suggest greater distance from the source. Volcanic rocks of Cycle 1 have been interpreted to be vented from proximal sources within the basin itself and potentially from outside the basin along its eastern margin (Henderson et al., 1998; Johnson & Henderson, 1991). The change in volcanic facies in Cycle 2 records a shut-off of the proximal intrabasinal volcanism but may reflect the continuation of volcanism more remote and further east of the basin (e.g. Bryan et al., 2003, 2004). Considering that these thin tuff and ignimbrite horizons occur within a thick sedimentary succession and are commonly overlain by high-energy erosional facies, it is suspected that volcanic activity was more frequent than the preserved record suggests, where only the thicker intervals have been preserved.

The presence of products of explosive volcanism within Cycle 2 suggests that the provenance change at the Cycle 1/Cycle 2 boundary may have been caused by a sudden supply of siliciclastic material, rather than by cessation of volcanic activity at a regional scale. It is possible that rift-related volcanism did not strictly stop but was punctuated and overwhelmed by a sustained influx of coarse-grained sediment of recycled orogen provenance, sourced from outside the basin, as suggested by the paleocurrent data.

**Cycle 2/Cycle 3 boundary**

The Star of Hope Formation reportedly marks the beginning of Cycle 3, a separate sedimentary cycle characterised by a resumption of intrabasinal volcanism and return to volcanic-related sedimentation similar to Cycle 1 (Henderson & Blake, 2013; Johnson & Henderson, 1991; Olgers, 1972; van Heeswijck, 2006). In contrast, the observations in this study show no marked change in depositional processes for the Star of Hope Formation compared with Cycle 2 formations, no change in conglomerate grain...
composition or detrital quartz features, and only a minor shift in sandstone grain composition (Figures 11, 14 and 15; Appendix 2). Regional variability is indicated by more compositionally and texturally immature sandstone in the north (Campaspe DDH-2) compared with the rest of the basin—the same trend as recorded in the Mt Hall and Raymond formations. Overall, the Star of Hope Formation is still dominated by siliciclastic sedimentation, and where volcanic influence is minor, thus providing little evidence for the formation to mark the Cycle 2/Cycle 3 boundary.

The slightly more feldspathic character of the Star of Hope Formation is transitional to the Bulliwallah Formation that marks a more pronounced compositional change (Figures 13, 14 and 15). The considerable increase in the proportion of relatively well-preserved plagioclase at the base of the Bulliwallah Formation indicates a renewed volcanic contribution to sedimentation. This is supported by plagioclase being a common phenocryst phase in the Cycle 3 primary volcaniclastic rocks. The provenance shift is further supported by: (1) more angular grain shapes compared with Cycle 2; (2) the appearance of a significant amount of volcanic quartz in the detrital mode; and (3) volcaniclastic horizons frequently interbedded with the sedimentary rocks of the Bulliwallah Formation. Despite this volcanic contribution, the formation still contains large amounts of common quartz and detrital muscovite, and the lithic fragments are dominated by basement lithologies, with only minor volcanic rocks. This points to a mixed provenance, rather than a reversal to exclusively or predominantly volcanic sourcing.

The Natal Formation, marking the top of the Drummond succession in the northern basin, differs significantly from the Bulliwallah Formation in that it is dominated by more quartzose, coarse-grained, erosionally based rocks. These observations are at odds with conclusions made by Olgers (1972), who described the formation as being a fine-grained, low-energy facies. It must be noted, however, that interpretation of the Natal Formation in this paper is based on drill-core observations only, while Olgers (1972) examined field exposures. Unlike the underlying formation, interbedded volcaniclastic horizons are absent in the Natal Formation. The sparsity of a volcanic influence is also reflected in the fact that the Natal Formation sandstones typically contain >80 vol% quartz with predominantly common quartz and only minor volumes of volcanic quartz. The sandstones show not only high compositional maturity, but also textural maturity evident from excellent rounding of quartz grains and minor matrix.

A conflicting QFL dataset for Cycle 3, showing quartz-lithic and feldspar-poor sandstone compositions, was presented by van Heeswijck (2006). The analysed samples, however, were not specifically correlated to stratigraphic formations. Van Heeswijck (2006) concluded that the relative enrichment in more unstable framework grain components (feldspar and lithic fragments) recorded for ‘Cycle 3’ reflects reduced chemical weathering driven by a climatic shift. It is unclear whether the climate change is inferred for the Drummond Basin or the sediment source area. Moreover, the compositional shift is not pronounced, with only part of the Cycle 3 samples showing an increased percentage of lithic fragments compared with Cycle 2, and therefore additional information on sediment sourcing is required to conclude any climate influence.

Observations from the Cycle 3 formations in this study are at odds with the interpretation currently available in the literature that Cycle 3 marks a resumption of widespread volcanism within the basin (Henderson & Blake, 2013; Johnson & Henderson, 1991; Olgers, 1972). Our results show that the Star of Hope, Natal and Ducabrook formations are dominated by relatively quartz-rich sedimentation derived from mixed continental block and recycled orogen-type sources and that contemporaneous volcanic contributions were minor and no more pronounced than in Cycle 2 (Figure 18). The quartz-rich, basement-derived sedimentation in the Drummond Basin was, therefore, more long-lived than previously thought, and once established, was not significantly disrupted by volcanism.

### Formation thicknesses

Basal strata of Cycle 2 show regional thinning from south to north, accompanied by an overall fining trend. These observations are consistent with previous studies (Henderson & Blake, 2013; Olgers, 1972). In contrast, Mt Hall and Raymond formations show significant variability in stratal thickness across the basin.

Even though a full lateral coverage of the basin area was not achieved owing to limited access to exposures and shortage of subsurface data, this study demonstrated...
significant variations in the thicknesses of the Mt Hall and Raymond formations. The Mt Hall Formation is thin in all southern locations but thickens northwards to a maximum thickness of >1082 m in the central part of the basin at Springvale (Figure 7). This trend is consistent with that described by Henderson and Blake (2013) and Olgers (1972), although the maximum thickness of 3000 m reported from an unspecified northern location appears unlikely based on profiles logged in this study and their proximity to mapped formation contacts. It is possible that the formation thickens further north; however, no complete Mt Hall profile was able to be examined in this study for the central or northern basin.

The Raymond Formation shows a similar pattern, with relatively small thicknesses in southern locations (e.g. Omega, Pebble Creek tributary), and the highest thicknesses in this study recorded in the central part of the basin (Springvale, Old Banchory 1). Insufficient data are available on the thickness of the Raymond Formation from the northern basin areas to recognise any thickening/thinning trends, although notably, the formation is relatively thin in the Campaspe DDH-1 drill hole, possibly owing to the proximity to the basin margin (Figure 8).

Similar to the Mt Hall and Raymond formations, the Star of Hope Formation is at least locally, significantly thinner than reported in the literature (Henderson & Blake, 2013; Olgers, 1972; van Heeswijck, 2006). The Mt Hall, Raymond and Star of Hope formations share similar thickness variability across the basin, while the overlying Bulliwallah, Natal and Ducabrook formations are reported to have more consistent thicknesses (van Heeswijck, 2006). The thickness variability has been reported to be caused by deposition on highly irregular topography, resulting from faulting associated with rifting (Davis & Henderson, 1996; Henderson et al., 1998; Johnson & Henderson, 1991; van Heeswijck, 2006). This explanation is at odds with the seismic data presented in these papers and by de Caritat and Braun (1992) and Fenton and Jackson (1989) who concluded that the faults were associated exclusively with the rifting phase of basin development, i.e. Cycle 1, and did not propagate into Cycle 2. The limiting of faulting to Cycle 1 is further supported by evidence of the onset of thermal subsidence with the deposition of Cycle 2 (de Caritat & Braun, 1992). It is clear from seismic imaging (Davis & Henderson, 1996; Henderson et al., 1998; Johnson & Henderson, 1991; van Heeswijck, 2006) that the faults cutting through the Cycles 2 and 3 formations are post-depositional, indicated by a lack of changes in thickness on both sides of faults, and sheet-like geometry of seismic facies. If any rift-related topography were still present towards the end of the deposition of Cycle 1, it would have been likely subdued by the volcanic and reworked pyroclastic accumulation.

The fact that the formation thicknesses appear to be thinner in the south of the basin than in the north appears inconsistent with the paleocurrent and conglomerate clast-size analysis that indicate that the southern margin was more proximal to the sediment source. A likely explanation is that the southern areas were bypassed during sedimentation, while a larger depocentre was present in the centre of the basin and possibly in the north. It is possible that initially there was a thicker sedimentary blanket in the southern area, but that material was later remobilised further into the basin. It is also possible that the formation thicknesses were influenced by post-depositional deformation in the basin. Folding and faulting of the Drummond sequence during the Kanimblan and Hunter–Bowen orogenies may have resulted in selective uplift and erosion, leading to apparently reduced thicknesses in the southern areas.

**Implications for Cycles 2 and 3 sediment sources**

A feature of the Drummond Basin is the extent of the coarse-grained quartz-rich sedimentary rocks preserved across the entire basin (~470 km N-S and ~100 km E-W; 47,000 km² of known exposure). The widespread sedimentation, particularly recorded by the Mt Hall and Star of Hope sandstones and conglomerates, is unusual in its volume and extent and poses a problem regarding sediment sourcing. Data presented here do not unequivocally point to a specific sediment source, but they do provide clear information pertaining to the type of source regions, and the directions of sediment transport. The relative maturity, general paucity of volcanolithic fragments and detrital feldspar, as well as the sparsity of primary volcanic horizons in Cycle 2 and most of the Cycle 3 formations, point to a cratonic source. This, coupled with paleocurrent data, rule out an intrabasinal and/or eastern margin volcanic source. The paleocurrent and conglomerate clast-size data imply that the southern end of the basin is the more proximal area in terms of sediment input. The paleoflow patterns for the northernmost part of the basin are partially consistent with sediment transport to the SE and NE reported by van Heeswijck (2006). Much more complex patterns than previously described are here revealed for this part of the basin, with multiple constituent directions. Additional facies analysis of the basin successions would assist in further interpreting the paleocurrent datasets.

While the specific cratonic source terrain(s) for the Cycles 2 and 3 successions currently remain unknown, several potential regions can be excluded based on the results presented here. The paleocurrent and petrographic data are consistent with two possible source regions: the Thomson Orogen west of the Drummond Basin (previously suggested by Kerrison, 2013 and van Heeswijck, 2006), and the Alice Springs Orogen (e.g. Haines, Hand, & Sandiford, 2001). Sediment supply from either of the two terrains is not straightforward. Sourcing from the intraplate Alice Springs Orogen poses a problem of long-distance transport required. However, the contemporaneity of basement uplift and exhumation of the Alice Springs Orogen (orogenic activity peaked during the Mississippian; e.g. Bradshaw & Evans, 1988; Gibson, Duddy, Ambrose, & Marshall, 2005; Haines et al., 2001; Maidment, 2005; Maidment, Williams,
& Hand, 2007; Wells & Moss, 1983) and the deposition of the Cycles 2 and 3 formations in the Drummond Basin is striking. Furthermore, far-field synorogenic sedimentation in several basins has been linked to the Alice Springs Orogeny, demonstrating that the event had an impact over an extensive area (e.g. Haines et al., 2001; Maidment, 2005; Maidment et al., 2007). Since no prominent topography was present in the vicinity of the Drummond Basin at the time of the deposition, far-field cratonic sources such as the Alice Springs Orogen need to be considered. Constraining the exact provenance for the Drummond Basin Cycles 2 and 3 succession requires a multi-method detrital geochronology analysis.

Conclusions

The observations presented in this paper have several implications relevant to understanding the stratigraphy of the Drummond Basin and regional tectonics in eastern Australia during the early Carboniferous. A pronounced basin-wide change in sediment composition occurs at the boundary of Cycles 1 and 2. The compositional contrast reflects a provenance change from proximal products of silicic volcanism to cratonic-derived siliciclastic sedimentation. However, the contemporary rift-related volcanism did not completely shut off during the accumulation of Cycle 2 as previously reported but the location of the volcanism became more distal to the sites of sedimentation within the basin.

While the division of the Drummond Basin stratigraphy into sedimentary cycles has validity for Cycles 1 and 2, Cycle 3 is less obvious in recording a return to consistently volcanic-related sedimentation. The new observations presented here reveal that ‘Cycle 3’ records only a minor change in detrital grain composition, and that a contemporary volcanic influence did not, in fact, increase significantly after the deposition of Cycle 2. Hence, we recommend that the distinction of ‘Cycle 3’ requires revision (Figure 18).

The thickness of Cycle 2 is highly variable across the basin, especially for the Mt Hall Formation, but still represents a substantial volume of sediment entering into the basin. The distinctive coarse-grained, relatively quartz-rich sedimentation of Cycle 2, as well as the Star of Hope Formation, is unusual in its volume and extent. The paleocurrent data and regional grading patterns indicate that the sediment was transported into the basin from the southern/southwestern margin, implying extrabasinal sediment supply and long-distance (>500 km) transport. More complex patterns of current directions of sediment transport are indicated in the northern part of the basin.

While the specific source terrain(s) for the Cycles 2 and 3 formations remain unknown, extrabasinal cratonic source region(s) undergoing substantial erosion are required. A plausible driver would be the intraplate Alice Springs Orogeny, which would reflect a far-field tectonic influence on sedimentation in the Drummond Basin.

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