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Stratigraphic and igneous relationships west of Yass, eastern Lachlan Orogen, southeastern Australia: subsurface structure related to caldera collapse?

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Stratigraphic and igneous relationships west of Yass, eastern Lachlan Orogen, southeastern Australia: subsurface structure related to caldera collapse?

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Running Title: Volcanic subsidence – Lachlan Orogen

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Volcanic rocks are widespread in middle Silurian to Lower Devonian rocks of the Lachlan Orogen in southeastern Australia. In the Yass–Canberra region, the Silurian succession consists of two S-type dominantly ignimbrite suites with the lower Hawkins/Goobarragandra and upper Laidlaw volcanics separated and overlain by clastic-carbonate intervals, and unconformably overlain by Lower Devonian silicic volcanic rocks. In the Talmo area, 30 km west of Yass, the Goobarragandra Volcanics are overlain by a clastic-carbonate succession of the Talmo Formation, which has a partly faulted boundary with the Lower Devonian Mountain Creek Volcanics containing rheomorphic welded ignimbrites. The contact of the Mountain Creek Volcanics and the Talmo Formation coincides with the margin of a prominent ovoid gravity low. Dip patterns in the Talmo Formation indicate two orientation domains divided by a northwest-trending faulted boundary. The domain to the southwest consists of gently northeast-dipping interbedded limestone and mudstone whereas the domain to the northeast has steep to moderate dips to the south and southeast with interbedded limestone and mudstone overlain by massive mudstone and quartz-rich turbidites. These contrasting domains are interpreted as a result of subsurface differential downsag, possibly a caldera, accommodated by downwarping in the adjacent Talmo Formation and accompanied by movements across a northwest-trending fault and potential ring faults.

KEYWORDS: caldera; downsag; ignimbrite; intrusions; limestone; structure; volcanic subsidence

Introduction

This paper examines stratigraphy, structure and relationships between igneous and sedimentary units in the Talmo area 30 km west of Yass in the Lachlan Orogen of southern New South Wales (Figures 1, 2). Limestone at Talmo was mapped as a sedimentary layer

within mid Silurian S-type volcanic rocks (Goobarragandra Volcanics) that are widely exposed in the region (Cramsie, Pogson, & Baker, 1978). An alternative interpretation, presented by Dadd (1998), was that sedimentary rocks around Talmo were blocks within ignimbrite, as was demonstrated for graptolitic black shale blocks in the Dinnertime Creek area 38 km west of Canberra (Figure 2). However, detailed geological mapping has established that a unit of interbedded limestone and siliciclastic rocks (Talmo Formation) overlies the Goobarragandra Volcanics and is partly faulted against the Lower Devonian Mountain Creek Volcanics. We interpret these relationships in the light of new regional maps, geophysical data and geochronology (Bodorkos et al., 2015; Colquhoun, Deyssing, Ballard, Hughes, & Troedson, 2017; Fraser et al., 2014; Geological Survey of New South Wales, 2016a, b, c, d; Thomas & Pogson, 2012). We infer that complex dip patterns in the Talmo Formation, in association with a northwest-trending fault and relationships between stratigraphic units, reflect subsurface subsidence associated with volcanic collapse. This is a significant issue for the regional geology as the influence of volcanic processes on subsurface structure has not previously been recognised and these relationships could have potentially been mistakenly attributed to either regional compressional or extensional deformation.

Regional setting

Rocks units of the eastern Lachlan Orogen in central and southern New South Wales were formed in three major intervals (Glen, 2005; Powell, 1984). The first interval is the Ordovician to Llandovery phase dominated by widespread turbidite deposition, Macquarie Arc volcanism, and the overlapping Benambran Orogeny. The second interval has common silicic volcanism, plutonism, and marine sedimentation in the mid Silurian to Early Devonian. Within this interval, basin evolution was complex with some areas characterised by deep-marine settings, including the Hill End Trough and Ngunawal Basin (Cas, 1983; Powell, 1984; Bain, et al., 1987), and other regions characterised by episodic subaerial volcanic activity and interspersed shallow to deeper marine sedimentation (e.g. the Yass Syncline, Figure 2, Thomas & Pogson, 2012). The third interval was marked by deposition of dominantly fluvial Upper Devonian units and shallow marine incursions followed by the Kanimblan deformation, which had widespread but variable effects throughout the Lachlan Orogen (Fergusson, 2017; Glen, 2005; Powell, 1984).

The Silurian succession in the Yass region consists of the Douro Group containing the lower Hawkins and the upper Laidlaw volcanics and the former is considered to be laterally equivalent to the Goobarragandra Volcanics farther west on the basis of similar age, rock types and S-type geochemistry (Thomas & Pogson, 2012) (Figure 3). A region of silicic volcanic units referred to herein as the Canowindra–Tumut–Canberra volcanic zone (Figure 1), is characterised by widespread Wenlockian to lower Ludlovian S-type ignimbrites and associated plutons (Wyborn, Chappell, & Johnston, 1981). The Canowindra–Tumut–Canberra volcanic zone has a NNW length of >400 km and a maximum deformed width of at least 100 km. It is comparable in scale to the Taupo Volcanic Zone in the North Island of New Zealand (Cas & Jones, 1979; Wilson et al., 1995). Subaerial pyroclastic rocks are interbedded with and overlain by shallow to locally deep-marine sedimentary units (Pogson, 2012).

Evidence for the locally significant Bindian deformation is strongest in the Tumut Zone, in contrast to the Yass district where milder contractional deformation caused an unconformity between the lowest Devonian Elmside Formation, at the top of the mainly upper Silurian

sedimentary succession (Hattons Corner Group), and the overlying Lower Devonian volcanic rocks (Black Range Group of Colquhoun & Pogson, 2012a; Fergusson, 2017). Lower Devonian intermediate to silicic volcanic rocks are preserved in synclinal structures including the Yass Syncline and the Taemas–Black Range Synclinorium (Figure 2). The Lower Devonian Black Range Group, including the Mountain Creek Volcanics, represents another major phase of silicic volcanism and was followed by shallow marine limestone and fluvial deposition of the upper Pragian to Emsian Murrumbidgee Group (Figure 3) (Colquhoun & Pogson, 2012b).

In the Yass–Goulburn region, regional deformation responsible for formation of the Yass Syncline and Taemas–Black Range Synclinorium has been considered to be part of the Tabberabberan Orogeny by Thomas & Pogson (2012) (Figure 2). Alternatively, Hood and Durney (2002) suggested that regional deformation in the Yass region was Kanimblan and post-dated Upper Devonian units that form a northern continuation of the Taemas–Black Range Synclinorium in the Koorawatha Syncline (Figure 2). This view was challenged by Packham (2003) but further supported by Durney and Hood (2003). The Talmo area lies within an unnamed syncline west of the Long Plain Fault along which, farther south, Silurian volcanic and plutonic rocks have been thrust east over the mainly Emsian Devonian Hatchery Creek Group (Hunt & Young, 2012) in the Wee Jasper Syncline adjacent to the Taemas–Black Range Synclinorium (Figure 2). A significant feature of these regional folds, where the succession contains competent volcanic units, is that they have gentle plunges and this is well illustrated by common gentle north dips around the southern closure of the Yass Syncline (Colquhoun & Cameron, 2012). In contrast, well-bedded sedimentary units lacking competent volcanic units (e.g., the Murrumbidgee Group) have complicated structural patterns with refolded folds and overprinted stylolitic cleavages (Hood & Durney, 2003).

Stratigraphy

The geology of the Talmo area is shown in Figure 4 and a cross-section is given in Figure 5. The stratigraphy is shown in the stratigraphic column in Figure 6. Two lineaments are identified in the Talmo area (Figure 7a-c) from magnetic and radiometric data (Geological Survey of New South Wales, 2016a, b, c) with the western lineament adjacent to a northwest-trending fault marking notable changes in stratigraphy and structure across it. An ovoid negative gravity anomaly nearly 9 km long in a northwest-southeast direction underlies the Devonian Mountain Creek Volcanics (Geological Survey of New South Wales, 2016d) (Figure 7d) suggestive of a lower density rock mass at depth.

Goobarragandra Volcanics

The Goobarragandra Volcanics lie west of the Taemas–Black Range Synclinorium. It is part of the Douro Group and equivalent to the mid Silurian Hawkins Volcanics (Colquhoun, Pogson, Simpson, & Blevin, 2012). Most of the unit is composed of massive dacitic ignimbrite that is gray-green. It contains abundant phenocrysts and crystal fragments of quartz and plagioclase around 1 cm across and smaller crystals of biotite <2 mm across. Biotite is typically altered to chlorite and plagioclase is commonly altered to sericite. The matrix consists of quartz and feldspar. Rare perlitic cracks were found by Solomons (1999) indicating that the matrix was originally glassy and welded (Figure 8a). Blocks of massive limestone up to 50 m across are present (Dadd, 1998). The unit is characterised by broken

and fractured crystals (Figure 8b) consistent with a pyroclastic origin (Dadd, 1998). More rarely elsewhere in the Goobarragandra Volcanics, the matrix shows fluidal foliation (Colquhoun et al., 2012, photograph 99). One locality with steeply plunging columnar joints was reported by Guy (1999) within the Talmo area ($148^{\circ}36'59.2''\text{E}$ $34^{\circ}54'18.1''\text{S}$). Dacitic ignimbrites of the Goobarragandra Volcanics have little in the way of orientation data apart from columnar joints, which are consistent with gentle dips (Colquhoun et al., 2012), as have been found in the equivalent Hawkins Volcanics (Pogson, Cameron, Colquhoun, Simpson, & Blevin, 2012).

Southwest of the northwest-trending fault (Figure 4), the Goobarragandra Volcanics consists of crystal-rich dacitic ignimbrite with two lenses of mudstone and massive volcanoclastic sandstone (Figure 8c). The lower mudstone/sandstone unit is at least 70 m thick whereas the upper lens is up to 100 m thick. The mudstone is well-bedded and the sandstone locally contains accretionary lapilli up to 4 mm across in thin graded layers (<3 cm thick) whereas other sandstone beds have mixed volcanic and carbonate grains (Solomons, 1999). Local micro-cross lamination in thin sandstone layers is consistent with traction transport (Solomons, 1999). These interlayered units of mudstone/sandstone have relatively gentle dips to the northeast (Figure 4); graded beds indicating upright younging. Overall dip measurements are consistent with a gentle northeast dip of the Goobarragandra Volcanics, which therefore underlies the Talmo Formation locally to the east and northeast. The base of the Goobarragandra Volcanics is not exposed in the Talmo area.

Talmo Formation

The Talmo Formation is a succession of limestone/marble, interbedded mudstone and calcareous layers, and mudstone and interbedded quartz sandstone. It is named after the property “Talmo” at $148^{\circ}36'50''\text{E}$ $34^{\circ}53'52''\text{S}$ and is exposed in the valley and surrounding ridges of the upper reaches of Limestone Creek, but it is typically covered by alluvium in the creek itself. The unit is recorded in the Australian Stratigraphic Units Database as the “Talmo Limestone”. It is clear from previous work (Cramsie et al., 1978; Thomas & Pogson, 2012) that the unit contains widespread mudstone and some quartz sandstone in addition to limestone and is therefore named as the Talmo Formation in preference to the “Talmo Limestone”. A thickness of over 1200 m is indicated (Figures 5, 6) based on the typical steep to moderate dips to the south and southeast across the eastern part of the unit. The unit is divided into: a lower succession (880 m thick) of mudstone, interbedded limestone beds and lenses of massive limestone, and an upper succession of laminated/bedded mudstone, and variable quantities of quartz sandstone (>350 m thick; Figure 6). Only part of the lower succession occurs west of the northwest-trending fault (Figure 4). No single type section is nominated but representative exposures of the lower limestone and mudstone are present between $148^{\circ}35'2.3''\text{E}$ $34^{\circ}53'38.2''\text{S}$ and $148^{\circ}35'14.8''\text{E}$ $34^{\circ}54'38.2''\text{S}$, and representative exposures of the upper mudstone and interbedded quartz sandstone are exposed in a tributary of Limestone Creek between $148^{\circ}35'37.5''\text{E}$ $34^{\circ}54'49.4''\text{S}$ and $148^{\circ}35'40.1''\text{E}$ $34^{\circ}54'49.4''\text{S}$ (Figure 4).

Most of the lower succession consists of interbedded greenish-gray/dark gray/black mudstone layers 2 to 20 cm thick and recessive limestone beds ~5 to 20 cm thick (Figure 8d). Many limestone beds are nodular. Massive limestone also forms mappable lenses up to 250 m thick. In the absence of associated breccias and indicators of discordance, these are interpreted as probably allodapic limestone and shelf bioherms respectively. Much of the limestone and

mudstone is weakly to locally strongly contact metamorphosed; limestone has recrystallised to form fine- to medium-grained granoblastic marble. Cramsie et al. (1978) referred to the non-carbonate layers interbedded with the limestones as “tuffs” but we have found no evidence that they are of volcanic origin. Limestones are locally fossiliferous containing crinoids, tabulate corals, pentamerid brachiopods, stromatoporoids and bryozoans (Pickett, 1982; Sherwin, 1968). The fossil faunas are poorly preserved in the unit and only a general Silurian age (probably Wenlock to Ludlow) has been determined (Colquhoun et al., 2012). Skarns occur locally near intrusions (Figure 4) and include zoned skarn with an outer layer of wollastonite and an inner layer of wollastonite and vesuvianite. Massive skarns contain grossular-rich garnet, epidote, wollastonite, and vesuvianite and minor altered plagioclase. Quartzose sandstone occurs on the western side of the quartz porphyry intrusion east of upper Limestone Creek (Smsm, Figure 4).

The upper succession consists mainly of mudstone that is poorly exposed and has no distinguishable features apart from containing scarce crinoids. Within this succession are interbeds of quartz sandstone and mudstone (Figure 8e); some intervals of quartz sandstone are up to 5 m thick. The quartz sandstone is fine-grained with abundant subangular to angular quartz, aligned muscovite flakes, and accessory tourmaline and plagioclase. It is notable that volcanic rock fragments are absent. Locally, layers with turbidite characteristics, including Bouma sequences, are developed; grading and micro-cross laminated layers indicate younging to the south.

Overall, the depositional setting of the Talmo Formation is inferred to reflect a shallow marine to deeper water transition up section, but the widespread contact metamorphism in the lower part of the succession has hindered identification of sedimentary structures preventing a more detailed assessment of depositional environments.

The contact between the Goobarragandra Volcanics and the Talmo Formation has been difficult to resolve given areas of poor exposure, overlying alluvium, and the extent of microgranitoid intrusions (Figure 4). In the domain northeast of the northwest-trending fault most of the Talmo Formation dips away from the Goobarragandra Volcanics, however, locally adjacent to the contact bedding dips are steep and atypically strike at a high-angle to the contact (Figure 8f). At location E (148°35'12.7"E 34°54'3.1"S) beds dip to the southeast away from topographically lower volcanic rocks indicating that the Talmo Formation overlies the Goobarragandra Volcanics as shown in cross-section AB (Figure 5). In contrast, in the domain southwest of the northwest-trending fault the contact between the units is discordant to bedding within the Talmo Formation (Figure 4). The Talmo Formation is covered by the Mountain Creek Volcanics (Figures 4, 5).

Mountain Creek Volcanics

The Mountain Creek Volcanics is the lowest unit of the Lower Devonian Black Range Group. Around Yass the Black Range Group unconformably overlies the Silurian to lowest Devonian succession (Colquhoun & Pogson, 2012a). In the Talmo area, the northwest-trending fault divides the Mountain Creek Volcanics into two domains: a western domain with an irregular contact between the Mountain Creek Volcanics and the adjacent Silurian units, and an eastern domain with a relatively straight contact that farther east curves to the SSE subparallel to the eastern magnetic lineament (Figure 4). The stratigraphy of the

Mountain Creek Volcanics is distinctive in each domain on either side of the northwest-trending fault.

A lower discontinuous unit of massive boulder conglomerate has a maximum thickness of 20 m and occurs at two locations at the base of overlying volcanic rocks (Figure 4). The conglomerate has clasts of dacite, mudstone, sandstone and limestone (Figure 9a). Limestone clasts are finely recrystallised and similar to the limestone of the Talmo Formation. The dacites are identical to those of the Silurian crystal-rich Goobarragandra Volcanics. The largest limestone boulder observed is >1 m across but most clasts are around 10 cm across. The sandstone matrix is poorly sorted, coarse- to very coarse-grained and contains clasts of limestone, quartz, plagioclase and volcanic rock fragments altered to chlorite/sericite. The clast composition of these rocks is consistent with derivation from the underlying Talmo Formation and Goobarragandra Volcanics.

The dominant unit in the eastern domain (Dld on Figure 4) is a uniform, dark-coloured, dacitic rock with a minimum thickness of 300 m and a maximum thickness of 600 m. The rock has broken phenocrysts 1 to 3 mm across of dominantly plagioclase with minor quartz and an altered ferromagnesian mineral in a dark gray matrix. Plagioclase has been altered to sericite and the ferromagnesian mineral replaced by chlorite and sericite. The matrix consists of feldspar and quartz with grains <0.5 mm across. The rock has a well-developed planar and locally lenticular foliation (Figure 9b-d) interpreted to result from welding and compaction of shards and pumice. The lenticular foliation is most obvious on weathered surfaces and the fragments range from 1 cm up to 50 cm in length. The foliation is generally northeast striking having steep to gentle dips to the southeast; common variations indicate that the foliation is internally folded within the unit. Smaller flow folds up to 20 m across have been observed (Figure 9c) but have erratic orientations of axial planes. The dacitic rock contains rare fragments >15 mm of feldspar porphyry with rounded to subrounded shapes. Columnar joints have been recognised at two locations to the southeast of the map area (148°36'24.9"E 34°55'50.6"S and 148°38'22.9"E 34°55'58.5"S; Guy, 1999). On the basis of compacted fluidal lenses, fragmental nature, welded bands and columnar joints, unit Dld (Figure 4) is a subaerial pyroclastic flow deposit, and is interpreted as an ignimbrite that has been subjected to rheomorphism with gravitationally induced downslope flow causing folding of the foliation.

In the eastern part of the area, 2 km south of "Talmo", the contact between the dacitic ignimbrite of the Mountain Creek Volcanics and underlying Goobarragandra Volcanics strikes NNW and dips gently WSW. Farther west, the contact curves to the southwest and has a relatively straight trend and the contact with the Talmo Formation is steeply dipping at locality F (Figure 4; 148°35'46.8"E 34°54'42.2"S) where it crosses a locally horizontal ridgeline. Here, the contact must be faulted with the southeast side downthrown relative to the northwest side (Figure 5). To the northeast and southwest of locality F (Figure 4) the contact is obscured along the base of a steep slope and is covered by abundant float of dacitic ignimbrite. The dacitic ignimbrite is conformably overlain southeast of the map area by black shale and coarser volcanoclastic rocks of the upper Black Range Group (Figure S1) (Thomas and Pogson, 2012).

In contrast to the eastern domain, the stratigraphy of the Mountain Creek Volcanics in the western domain is more varied. Several units were mapped by Solomons (1999), but contacts are difficult to locate due to the steep topography and scrubby vegetation. Thus the Mountain Creek Volcanics in this domain is largely left undivided on Figure 4. Most of the unit consists

of pinkish to purplish fine feldspar phenocrysts predominantly < 2 mm, but up to 4 mm across, of plagioclase, pyroxene and biotite. Most phenocrysts are strongly altered; feldspar has been replaced by sericite and calcite, and ferromagnesian minerals replaced by chlorite, epidote, calcite and sericite. In places phenocrysts are lacking and the rocks are aphanitic. The matrix/groundmass is finely recrystallised and includes common quartz, but quartz phenocrysts are rare. Compositionally these rocks are more silica-rich than the dacitic ignimbrite, as shown by the poor soil development on the former, and are probably rhyodacitic and rhyolitic rocks. These volcanic rocks are either massive, contain flow banding typical of banded rhyolites, or more commonly have flattened pumice(?) fragments typical of ignimbrites with rare welded glass shards in thin section (Figure 9d). Other minor clastic rocks are present including well-bedded mudstone and volcanic breccia (unit Dlb on Figure 4) and conglomerate with limestone clasts.

In the western-most parts of the unit, flow foliation and bedding within the clastic unit (Dlb) dip towards the contact (Figure 4) indicating that locally the contact is an inferred fault and not an angular unconformity as is found farther east in the western domain. Thus, overall in this domain the contact is considered to reflect a combination of poorly exposed faults and farther east, where the topographically higher Mountain Creek Volcanics overlies the topographically lower Talmo Formation around locality G (Figure 4), an angular unconformity.

Intrusions and quartz veins

The largest intrusion is a massive microgranodiorite (Dg) in the eastern part of the area (Figure 4). It occurs along the contact between the Goobarragandra Volcanics and the Mountain Creek Volcanics and is flat-lying with an irregular basal contact at an elevation of 570 m (± 15 m). Farther to the northwest, the intrusion cuts across the Talmo Formation and at its western extremity consist of several small pods intruded into the Talmo Formation. The main mass has a tabular shape with a maximum thickness of 100 m. It forms tors and is pink-orange, green-gray to light gray/white. The rock is fine- to medium-grained and is holocrystalline with grains typically 0.5 to 2 mm across. It has a microgranitic texture with plagioclase, quartz, common interstitial micrographic intergrowths and altered ferromagnesian minerals (Figure 9e). Sericite alteration has affected plagioclase; and the ferromagnesian minerals are replaced by chlorite, epidote, calcite and pumpellyite.

Another intrusion is the ridge-capping quartz porphyry located mainly on the eastern side of upper Limestone Creek (Dp, Figure 4). This is an irregular mass that intrudes the Talmo Formation and partially encloses quartzose sandstone on its western side. It is massive porphyry with large phenocrysts of quartz (1–10 mm), plagioclase (2–5 mm) and lesser aggregates of biotite in a gray holocrystalline groundmass. Quartz is the most abundant phenocryst. Chloritic alteration of biotite and sericitic alteration of plagioclase are widespread. This unit is similar in composition to the gray dacitic porphyritic ignimbrite of the Goobarragandra Volcanics except that it is clearly cross-cutting and intrusive into limestone of the Talmo Formation (Figure 4) and lacks broken crystals (Guy, 1999). Its relationship to the microgranodiorite is not known due to the lack of exposure along the short mapped contact between them.

In the southwest of the area, several small locally cross-cutting igneous masses occur along the contact of the Mountain Creek Volcanics with the Talmo Formation and Goobarragandra

Volcanics in and adjacent to Limestone Creek (Figure 4). These intrusions are pinkish porphyritic dacitic rocks containing abundant igneous and sedimentary xenoliths 0.5 cm to 1 m in diameter derived from the adjacent units and include dacitic crystal-rich ignimbrite, mudstone and sandstone. The intrusions have quartz and plagioclase phenocrysts in a crystalline groundmass and as for other intrusions in the area are typically altered including chlorite (replacing biotite), muscovite and epidote. Additionally, some intrusive flow banded rhyolite with local skarn development in limestone and calc-silicate rocks of the Talmo Formation occurs along the contact (Figure 4).

Several dykes are large enough to map and have widths of up to 10 m and lengths up to 400 m (Figure 4). The dykes are massive plagioclase (1–5 mm) porphyries; the groundmass of the dykes contains quartz, altered feldspar and chlorite-altered biotite.

Large quartz veins have been mapped including a prominent line of northwest to westerly discontinuous quartz veins in the Goobarragandra Volcanics in the northwest of the area (Figure 4). Larger areas with massive quartz blocks up to 3 m across occur near a large area of no outcrop in the south adjacent to the northwest-trending fault. The Mountain Creek Volcanics nearby also commonly contain quartz veins (Figure 9f). The adjacent northwest-trending creek bed is wide, contains abundant alluvium and has no bedrock exposure; features consistent with it being part of a fault as shown on Figure 4. Areas with common quartz veins have also been mapped by Guy (1999) to the southeast in the Mountain Creek Volcanics; they border on the area in Figure 4 and are associated with the eastern lineament.

Structure

The northwest-trending fault divides the Talmo Formation into two dip domains. In the southwest domain in lower Limestone Creek, bedding dips mainly gently to the northeast apart from some steep dips adjacent to several dykes (Figure 4). Northeast of the fault, the beds strike east-west and curve to the northeast-southwest farther west; most dips in the Talmo Formation are either moderate or steep to the SSE and southeast (Figures 4, 5). Local folds within the Talmo Formation are shown by large variations in strike and dip of beds in the northern part of the Talmo Formation 2.5 km west of Talmo homestead (Figure 4). These variations are present around the microgranodiorite intrusion but it is not clear how they are related to it, since it was difficult to map out the contact in this area due to the presence of many small intrusions and a highly irregular contact. No cleavage occurs in the rocks of the Talmo Formation despite the presence of mudstones and limestones, which elsewhere in the region contain spaced cleavage related to folds (Hood & Durney, 2002). The Talmo Formation was most likely strain hardened by the low-grade contact metamorphism of the unit making these rocks resistant to subsequent ENE–WSW shortening.

In the Douro Group, interbedded sedimentary units generally provide useful structural information on the orientation of the massive volcanic units (Colquhoun et al., 2017). The mudstone/sandstone unit in Limestone Creek (Smms) has gentle dips consistent with the low-angle dip of the Goobarragandra Volcanics. In detail, the bedding orientations in this unit are nearly perpendicular to the strike of the contact with adjacent dacitic ignimbrite (Figures 4, 10). Dips in this unit are also steeper than the dip of the contact as indicated by its relationship to topography (Figure 10). Primary depositional dip in the underlying sandstone-mudstone unit could account for this anomaly. In contrast, the upper sandstone-mudstone lens

to the north of Limestone Creek has an exposed conformable lower contact with the underlying dacitic porphyry (Figure 4).

The steeper dips encountered in the northeastern domain of the Talmo Formation contrast to the gentle dips of the overlying Mountain Creek Volcanics. Within the volcanic rocks, flow foliation has various orientations reflecting contortions developed during rheomorphic flow of ignimbrites and at variance to the gentle dips of basal contacts in parts of the mapped area (Figure 4).

The pattern of faulting in the Talmo area is difficult to resolve given gaps in exposure but the following constraints apply. The mapped contact between the upper Talmo Formation and the Mountain Creek Volcanics at location F (Figure 4) is a steeply dipping fault (see above); the Mountain Creek Volcanics are downthrown to the southeast (Figure 5). The same contact farther to the southwest is offset along a northwest-trending valley containing abundant alluvium and is interpreted as a steeply dipping fault affected by apparent sinistral offset along the western lineament (Figure 4). This structure is poorly exposed but is associated with quartz veins in the basal Mountain Creek Volcanics (Figure 9f) and adjacent Talmo Formation. Differential rotation along this northwest-trending fault accounts for the contrasting dip domains in the Talmo Formation with greater rotation in the northeastern domain compared to the southwestern domain (Figure 4). In the southwestern part of the area, the contact in lower Limestone Creek between the Goobarragandra Volcanics and the Mountain Creek Volcanics is an inferred near-vertical fault that accounts for the oblique structural measurements (Figure 4). This fault has been intruded by small masses of undeformed dacitic porphyry that therefore postdated faulting. In the area 1 km southwest of “Talmo” homestead (Figure 4), the microgranodiorite sill (Dg) is also undeformed implying that it has intruded along a faulted(?) contact between the Talmo Formation and the Goobarragandra Volcanics (Figure 4).

Discussion

Regional correlations

Substantial growth in the numbers of U–Pb zircon ages for igneous rocks in the Lachlan Orogen of New South Wales (e.g. Bodorkos et al., 2015), in addition to the major revisions of paleontological ages for rock units on the Goulburn 1:250,000 geological sheet (Thomas & Pogson, 2012) and for the Southern Tablelands region more generally (Percival & Zhen, 2017), has enabled correlations of the regional stratigraphy with rock units in the Talmo area (Figure 3). The Goobarragandra Volcanics has no U–Pb zircon ages, but its age is well constrained by the equivalent Hawkins Volcanics and the Young Granodiorite, which has intruded it, giving an age of around lower Wenlock (433–430 Ma, Figure 3). We suggest that the overlying Talmo Formation is probably equivalent to the Yass and Yarralumla formations in the Yass Syncline and Canberra region, respectively, and therefore lower to mid Wenlock (Figure 3). Stratigraphic and paleogeographic analysis by Link (1971) for the Yass Formation indicated a north-south trending shoreline migrating eastward consistent with the deepening farther west evident in the Talmo Formation. The Talmo Formation is in a similar stratigraphic position to the Glen Bower and Boambolo formations that are sandwiched between the Hawkins and Laidlaw volcanics 20 km SSW of Yass (Figure 2). The Mountain Creek Volcanics have a U–Pb age of 420 ± 3 Ma (Black, 2006) determined for a sample collected 1.5 km SSW of the southwestern corner of the map area in Figure 4 from near the

base of the succession (148°33'2.3"E 34°56'24.3"S). This age is consistent with ages determined for equivalent and overlying units in the Yass Syncline and the Taemas–Black Range Synclinorium as shown in Figure 3.

Geological history and structural interpretation

The predominant early geological event in the Talmo study area was eruption of the widespread dacitic ignimbrites of the Goobarragandra Volcanics. Megabreccia at the Dinnertime Creek locality west of Canberra is consistent with eruption of these ignimbrites during caldera collapse (Dadd, 1998). However, apart from isolated massive limestone blocks, we have not observed abundant large clasts forming megabreccia at Talmo. Source eruption sites for the Goobarragandra Volcanics remain unidentified which is not surprising given the extent of overlying rocks and the difficulty of resolving paleo-topography.

The Goobarragandra and Hawkins volcanics are compositionally grouped with the Bullenbalong Supersuite plutons including the Young Granodiorite (Thomas & Pogson, 2012; Wyborn et al., 1981; White et al., 2001). Wyborn et al. (1981) reported that the phenocryst assemblage in the dacitic ignimbrites of the Goobarragandra Volcanics has been related to temperatures of 700° to 750°C and to have equilibrated in magma chambers at a relatively high level in the crust. This contrasts to the Hawkins Volcanics where the magmas (crystal mush) rose from much greater depths (5 to 6 kb, i.e. depths in excess of 20 km, Wyborn et al., 1981). The Goobarragandra Volcanics is intruded over large areas by the 429–428 Ma Young Granodiorite (Figures 2, 3) and it is possible that these plutonic rocks were not necessarily the source magma of the volcanic rocks but represent later batches of compositionally similar magma that have risen and been emplaced within the pre-existing volcanic pile. This phenomenon is well documented by Hildebrand, Hoffman, Housh and Bowring (2010) for well-exposed volcanic-plutonic associations in the Wopmay Orogen of northwestern Canada.

The presence of limestone blocks within the Goobarragandra Volcanics and the more widespread limestone and shallow marine units interbedded with the Hawkins Volcanics, including the overlying Yanawe Formation, show that volcanism was taking place near sea level (Thomas & Pogson, 2012). The turbidites higher in the section of the Talmo Formation imply deepening of the upper part of the succession potentially caused by the eastward marine transgression in the equivalent Yass Formation (Link, 1971).

A major problem is to explain the unusual structural pattern within the Talmo Formation. Fold plunges associated with regional folds affecting the volcanic-dominated parts of the succession, including the Yass Syncline and parts of the Taemas–Black Range Synclinorium, are gently plunging to either the north or south as is evident from orientation data on the geological maps of Colquhoun et al. (2017) and Colquhoun & Cameron (2013). However, the moderate to steep dips of the Talmo Formation in the northeastern domain imply a synclinal hinge plunging 60° to the south (Figures 4, S1). It is therefore considered unlikely that this pattern was caused by regional folding in the Middle Devonian or Carboniferous.

The Talmo area has an orthogonal fault system with northwest and northeast striking faults along the northern margin of the Mountain Creek Volcanics in the Talmo area (Figure 4). The northwest-trending fault has formed an accommodation fault allowing differential rotation of the dip domains in the Talmo Formation, as well as enabling compartmentalised vertical

subsidence of the Mountain Creek Volcanics. Thus the apparent sinistral offset of the Mountain Creek Volcanics contact is also a result of accommodation along this fault, rather than any actual strike-slip displacement, and is analogous to a transfer fault in an extensional setting (Gawthorpe & Hurst, 1993). This implies synchronous formation of these faults and the offsets along them must have predated the associated igneous intrusions (Figure 4); unfortunately no radiometric ages are available for these rocks to constrain the absolute timing of faulting.

Caldera hypothesis

Our preferred explanation for these relationships is that the anomalous dips in the northeastern domain of the Talmo Formation reflect down-sagging in the subsurface at the margin of a caldera associated with explosive eruptions during formation of the Mountain Creek Volcanics (Figure 11). Development of a hypothesis of caldera collapse for this part of the Lachlan Orogen is challenging given that much of the map distribution of units outside the Talmo area reflects regional deformation with major fold structures, as evident in Figure 2. Elsewhere in the Lachlan and New England orogens caldera collapse structures have been recognised in rock assemblages postdating regional deformation, including the calderas of the Central Victorian Magmatic Province (Cas, O'Halloran, Long, & VandenBerg, 2003; VandenBerg et al., 2000), the Coombadjha Volcanic Complex in the southern New England Orogen (McPhie, 1986) and the Bindook Group in the eastern Lachlan Orogen, the northern part of which has been resistant to subsequent regional deformation (Fergusson, 1980).

Caldera development is well described in the literature with a summary provided by Cole, Miller and Spinks (2005) following pioneering work by Lipman (1984, 2000). We propose a basic outline of caldera development following these authors and relate the various stages to those potentially found in the Talmo area:

- (1) Pre-collapse volcanism: this stage is not recognised in the Talmo study area. The Goobarragandra/Hawkins/Laidlaw volcanics predate development of the Mountain Creek Volcanics by ~11 Ma and represent an earlier unrelated phase of volcanic activity (Figure 3).
- (2) Caldera collapse: this was presumably associated with explosive eruptions that formed the Mountain Creek Volcanics and accompanied downsag of the Talmo Formation in the northeastern domain. Initial subsidence is consistent with the conglomerate at the base of the Mountain Creek Volcanics, which contains clasts indicating derivation from the northwest implying a paleoslope to the southeast. Downsag accounts for the steep to moderate southerly to southeasterly dips that are anomalous in the regional structure. Downsagging associated with caldera collapse was piecemeal as indicated by the northwest-trending fault that has resulted in contrasting structure of the northeastern and southwestern domains of the Talmo Formation (Figures 4, 11). In the southwestern domain, downsag is significantly less well developed implying accommodating fault slip along the northwest-trending fault. It is unclear if these inferred faults developed earlier than the hypothetical caldera and were reactivated during collapse; alternatively, they may have accompanied caldera formation.
- (3) Post-collapse magmatism: numerous small intrusions occur along the western contact of the Mountain Creek Volcanics and older units in Limestone Creek, as well as the ring-like microgranodiorite sill and the plagioclase porphyry (Figure 4), and are potentially a product of magmatism associated with the hypothetical caldera margin.

- (4) Hydrothermal activity: this can occur throughout caldera development and in the Talmo area is potentially consistent with thick quartz veins, stockworks and skarns developed in association with the northwest-trending magnetic lineaments (Figure 4).

Calderas commonly have an association with gravity lows (Hunt, 1992) and additional support for the caldera collapse hypothesis comes from the oval-shaped gravity low shown on the isostatic gravity map of New South Wales (Geological Survey of New South Wales, 2016d) (Figure 7d). The outline of this gravity low is shown on Figures 2 and S1 and its northern part is located adjacent to the northern boundary of the Mountain Creek Volcanics. The cause of this gravity low is unknown. It is clear that the younger Burrinjuck Granite (Figure 2; Thomas & Pogson, 2012) cross-cuts the western part of this anomaly and is unrelated to it.

Where widespread post-volcanic deformation is recognised, including much of the Lachlan Orogen of southern New South Wales, distinguishing between compressional/extensional structures caused by tectonic regimes as opposed to structures generated by subsurface collapse during caldera formation can be problematic. We suggest that the Talmo study area contains an example of structure potentially related to a complicated sub-surface pattern arising from volcanic collapse rather than other causes.

Conclusions

The volcanic and sedimentary succession in the Talmo area 30 km west of Yass in the Lachlan Orogen of southern New South Wales has well preserved relationships between Silurian and Lower Devonian rock units and intrusions. The oldest unit in the succession, the mid Silurian Goobarragandra Volcanics, was previously considered to contain abundant blocks of limestone, mudstone and quartz turbidites in a megabreccia potentially related to a caldera structure (Dadd, 1998). We have found that the Goobarragandra Volcanics are overlain by a sedimentary unit (Talmo Formation) of interbedded limestone and mudstone overlain by mudstone with interbedded quartz turbidites consistent with deepening of the succession. Following an inferred hiatus potentially as long as 11 Ma, volcanism was renewed with eruptions of the Lower Devonian Mountain Creek Volcanics. We consider that this later phase of volcanism was related to a hypothetical northern margin of a caldera in the Talmo area marked by faulted contacts, and post-dated by numerous intrusions. Collapse at the surface was balanced in the subsurface by formation of accommodation faults and downsagging of a domain defined by steep to moderate dips in the Talmo Formation that are otherwise anomalous in the regional structural setting. A gravity low is developed at the site of the proposed caldera. The anomalous structure of the Talmo Formation is thus attributed to a subsurface response to volcanic processes rather than reflecting either regional contractional or extensional deformation.

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References

- Abell, R. S. (1991). *Geology of the Canberra 1:100 000 Sheet area, New South Wales and Australian Capital Territory*, 116 pp. Bureau of Mineral Resources Bulletin 233.
- Bain, J. H. C., Wyborn, D., Henderson, G. A. M., Stuart-Smith, P. G., Abell, R. S., & Solomon, M. (1987). Regional geological setting of the Woodlawn and Captains Flat massive sulphide deposits, NSW, Australia. In: *Proceedings of the Pacific Rim Congress 87*, pp. 25–28. Australasian Institute of Mining and Metallurgy, Melbourne.
- Basden, H. (1990). *Geology of the Tumut 1:100,000 sheet 8527*, 275 pp. Sydney, NSW: Geological Survey of New South Wales.
- Belousova, E. A., Jiménez, J. M. G., Graham, I., Griffin, W. L., O'Reilly, S. Y., Pearson, N., Martin, L., Craven, S., & Talavera, C. (2015). The enigma of crustal zircons in upper-mantle rocks: Clues from the Tumut ophiolite, southeast Australia. *Geology*, 43, 119–122.
- Black, L. P. (2005). SHRIMP U–Pb zircon ages obtained during 2004/05 for the NSW Geological Survey. Sydney, NSW: Geological Survey of New South Wales, Geological Survey File, GS2005/745.
- Black L.P. (2006). SHRIMP U–Pb zircon ages obtained during 2005/06 for NSW Geological Survey projects. Sydney, NSW: Geological Survey of New South Wales, Geological Survey File, GS2006/821.
- Bodorkos, S., Blevin, P. L., Eastlake, M. A., Downes, P. M., Campbell, L. M., Gilmore, P. J., Hughes, K. S., Parker, P. J., & Trigg, S. J. (2015). New SHRIMP U–Pb zircon ages from the central and eastern Lachlan Orogen, New South Wales: July 2013–June 2014, 158 pp. Canberra, ACT: Geoscience Australia, Record GS2015/0002. Maitland, NSW: Geological Survey of New South Wales, Record 2015/02.
<http://dx.doi.org/10.11636/Record.2015.002>
- Bodorkos, S., Blevin, P.L., Simpson, C.J., Gilmore, P.J., Glen, R.A., Greenfield, J.E., Hegarty, R. & Quinn, C.D. (2013). New SHRIMP U–Pb zircon ages from the Lachlan, Thomson and Delamerian orogens, New South Wales: July 2009–June 2010, 124 pp. Canberra, ACT: Geoscience Australia Record, 2013/29. Maitland, NSW: Geological Survey of New South Wales Report, GS2013/0427.
- Cas, R. A. F. (1983). A review of the palaeogeography of the Lachlan Fold Belt, southeastern Australia. *Geological Society of Australia Special Publication*, 10, 103 pp.
- Cas, R. A. F., O'Halloran, G. J., Long, J. A., & VandenBerg, A. H. M. (2003). Middle Devonian to Carboniferous late to post-tectonic sedimentation and magmatism in an arid continental setting. In W. Birch (Ed.), *The Geology of Victoria* (pp. 157–193). Geological Society of Australia, Victorian Division.
- Cas, R. A. F., & Jones, J. G. (1979). Paleozoic interarc basin in eastern Australia and a modern New Zealand analogue. *New Zealand Journal of Geology and Geophysics*, 22, 71–85.

- Cole, J. W., Milner, D. M., & Spinks, K.D. (2005). Caldera and caldera structures: a review. *Earth Science Reviews*, 69, 1–26.
- Colquhoun, G. P., Deyssing, L., Ballard, J. C., Hughes, K. S., & Troedson, A. L. (2017). New South Wales Zone 55 East Seamless Geology dataset, version 1 [Digital Dataset]. Geological Survey of New South Wales, Maitland.
- Colquhoun, G. P., & Cameron, R. G. (2012). *Yass Special 1:50,000 Geological Sheet (part 8628)*. Maitland, NSW: Geological Survey of New South Wales.
- Colquhoun, G. P., & Pogson, D. J. (2012a). Black Range Group (Db). In O. D. Thomas & D. J. Pogson (compilers), *Goulburn 1:250 000 geological sheet SI/55-12, 2nd edition, explanatory notes*, (p. 926–936). Maitland, NSW: Geological Survey of New South Wales.
- Colquhoun, G. P., & Pogson, D. J. (2012b). Murrumbidgee Group (Dm). In O. D. Thomas & D. J. Pogson (compilers), *Goulburn 1:250 000 geological sheet SI/55-12, 2nd edition, explanatory notes*, (pp. 980–989). Maitland, NSW: Geological Survey of New South Wales.
- Colquhoun, G. P., & Pogson, D. J. (2012c). Hattons Corner Group (Sh). In O. D. Thomas & D. J. Pogson (compilers), *Goulburn 1:250 000 geological sheet SI/55-12, 2nd edition, explanatory notes*, (pp. 559–565). Maitland, NSW: Geological Survey of New South Wales.
- Colquhoun, G. P., Pogson, D. J., Simpson, C.J., & Blevin, P.L. (2012). Goobarragandra Volcanics (Sdn). In O. D. Thomas & D. J. Pogson (compilers), *Goulburn 1:250 000 geological sheet SI/55-12, 2nd edition, explanatory notes*, (pp. 445–455). Maitland, NSW: Geological Survey of New South Wales.
- Cramsie, J. N., Pogson, D. J., & Baker, C. J. (1978). *Geology of the Yass 1:100,000 sheet 8628*, 85 pp. Sydney, NSW: Geological Survey of New South Wales.
- Dadd, K. A. (1998). Origin and significance of megabreccia blocks in the Silurian Goobarragandra Volcanics, southeastern New South Wales. *Australian Journal of Earth Sciences*, 45, 315–321.
- Durney, D. W., & Hood, D. I. A. (2003). Reply Sequence and kinematics of multiple deformation around Taemas Bridge, Eastern Lachlan Fold Belt, New South Wales, *Australian Journal of Earth Sciences*, 50, 829–833.
- Fergusson, C. L. (2017). Mid to late Paleozoic shortening pulses in the Lachlan Orogen, southeastern Australia: a review. *Australian Journal of Earth Sciences*, 64, 1–39.
- Fergusson, J. (1980). Yerranderie crater: a Devonian silicic eruptive centre within the Bindook Complex, New South Wales. *Journal of the Geological Society of Australia* 27, 75–82.
- Fraser, G. L., Gilmore, P. J., Fitzherbert, J. A., Trigg, S. J., Campbell, L. M., Deyssing, L., Thomas, O. D., Burton, G. R., Greenfield, J. E., Blevin, P. L., & Simpson, C. J. (2014). New SHRIMP U–Pb zircon ages from the Lachlan, southern Thomson and New England orogens, New South Wales: February 2011–June 2013, 217 pp. Canberra, ACT: Geoscience Australia, Record 2014/53. Maitland, NSW: Geological Survey of New South Wales, Report GS2014/0829. <http://dx.doi.org/10.11636/Record.2014.053>
- Gawthorpe, R. L., & Hurst, J.M. (1993). Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. *Journal of the Geological Society, London*, 150, 1137–1152.
- Geological Survey of New South Wales, (2016a). *Total magnetic intensity RTP of New South Wales 1:1,500,000*. Maitland, NSW: Geological Survey of New South Wales.
- Geological Survey of New South Wales, (2016b). *First vertical derivative of TMI map of New South Wales 1:1,500,000*. Maitland, NSW: Geological Survey of New South Wales.

- Geological Survey of New South Wales, (2016c). *Ternary radioelement map of New South Wales 1:1,500,000*. Maitland, NSW: Geological Survey of New South Wales.
- Geological Survey of New South Wales, (2016d). *Isostatic gravity map of New South Wales 1:1,500,000*. Maitland, NSW: Geological Survey of New South Wales.
- Geoscience Australia (2007). Geoscience Australia SHRIMP U–Pb Geochronology Interim Data Release July 2007.
https://d28rz98at9flks.cloudfront.net/65358/65358_geochron_20070731.zip
- Glen, R. A. (2005). The Tasmanides of eastern Australia. In A. P. M. Vaughan, P. T. Leat, & R. J. Pankhurst (Eds.), *Terrane processes at the margins of Gondwana* (pp. 23–96). London, UK: Geological Society of London Special Publication, 246.
- Guy, S. T. (1999). Silurian-Devonian volcanic rocks near Burrinjuck Dam, New South Wales. BSc Hons thesis, University of Wollongong (unpublished).
- Hildebrand, R. S., Hoffman, P. F., Housh, T., & Bowring, S. A. (2010). The nature of volcano-plutonic relations and the shapes of epizonal plutons of continental arcs as revealed in the Great Bear magmatic zone, northwestern Canada. *Geosphere*, 6, 812–839.
- Hood, D. I. A., & Durney, D. W. (2002). Sequence and kinematics of multiple deformation around Taemas Bridge, eastern Lachlan Fold Belt, New South Wales. *Australian Journal of Earth Sciences*, 49, 291–309.
- Hunt, J. R., & Young, G. C. (2012). Depositional environment, stratigraphy, structure and paleobiology of the Hatchery Creek Group (Early–?Middle Devonian) near Wee Jasper, New South Wales. *Australian Journal of Earth Sciences*, 59, 355–371.
- Hunt, T. M. (1992). Gravity anomalies, caldera structure, and subsurface geology in the Rotorua area, New Zealand. *Geothermics*, 21, 65–74.
- Kemp, A. I. S., Hawkesworth, C. J., Paterson, B. A., Foster, G. L., Kinny, P. D., Whitehouse, M. J., Maas, R., & EIMF (2008). Exploring the plutonic–volcanic link: a zircon U–Pb, Lu–Hf and O isotope study of paired volcanic and granitic units from southeastern Australia. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 97, 337–355.
- Link, A. G. (1971). The stratigraphic development of the Yass Basin, New South Wales. PhD thesis, Australian National University (unpublished). <https://openresearch-repository.anu.edu.au/handle/1885/10973>
- Lipman, P. W. (1984). The roots of ash flow calderas in western North America: windows into the tops of granitic batholiths. *Journal of Geophysical Research*, 89B, 8801–8841.
- Lipman, P. W. (2000). Calderas. In: Sigurdsson, H. (Ed.), *Encyclopaedia of Volcanoes*. Academic Press, San Diego, pp. 643–662.
- Lyons, P., & Percival, I. G. (2002). Middle to Late Ordovician age for the Jindalee Group of the Lachlan Fold Belt, New South Wales: conodont evidence and some tectonic problems. *Australian Journal of Earth Sciences*, 49, 801–808.
- McPhie, J. (1986). Evolution of a non-resurgent cauldron: the Late Permian Coombadjha Volcanic Complex, northeastern New South Wales, Australia. *Geological Magazine*, 123, 257–277.
- Owen, M., & Wyborn, D. (1979). *Geology and geochemistry of the Tantangara and Brindabella 1:100 000 Sheet areas, New South Wales and Australian Capital Territory*. Canberra, ACT: Bureau of Mineral Resources Bulletin, 204.
- Packham, G. H. (2003). Discussion Sequence and kinematics of multiple deformation around Taemas Bridge, Eastern Lachlan Fold Belt, New South Wales. *Australian Journal of Earth Sciences*, 50, 827–829.

- Percival, I. G., & Zhen, Y. Y. (2017). Précis of Palaeozoic palaeontology in the Southern Tablelands region of New South Wales. *Proceedings of the Linnean Society of New South Wales*, 139, 9–56.
- Pickett, J. (1982). *The Silurian system in New South Wales*, 264 pp. Sydney, NSW. Geological Survey of New South Wales, Bulletin 29.
- Pogson, D. J. (2012). Douro Group (Sd). In O. D. Thomas & D. J. Pogson (compilers), *Goulburn 1:250 000 geological sheet SI/55-12, 2nd edition, explanatory notes*, (p. 427–444). Maitland, NSW: Geological Survey of New South Wales.
- Pogson, D.J., Cameron, R.G., Colquhoun, G.P., Simpson, C.J., & Blevin, P.L. (2012). Hawkins Volcanics (Sdh). In O. D. Thomas & D. J. Pogson (compilers), *Goulburn 1:250 000 geological sheet SI/55-12, 2nd edition, explanatory notes*, (p. 456–468). Maitland, NSW: Geological Survey of New South Wales.
- Pogson, D. J., & Watkins, J. J. (1998). *Bathurst 1:250 000 Geological Sheet SI/55-8: explanatory notes*, (pp. 430). Sydney, NSW: Geological Survey of New South Wales.
- Powell, C. McA. (1984). Ordovician to earliest Silurian: marginal sea and island arc. Silurian to mid-Devonian—dextral transtensional margin. Late Devonian and Early Carboniferous: continental magmatic arc along the eastern edge of the Lachlan Fold Belt. In J. J. Veevers (Ed.), *Phanerozoic earth history of Australia* (pp. 290–340). Clarendon Press, Oxford, UK: Geological Sciences Series, 2.
- Sherwin, L. (1968). *Report on fossils from the Yass 1:100,000 sheet (Goulburn 1:250,000)*, 3 pp. Sydney, NSW. Geological Survey Report GS1968/394. Geological Survey of New South Wales.
- Solomons, M. D. (1999). The Silurian-Devonian geology of the Talmo area, southwest of Yass, New South Wales. BSc Hons thesis, University of Wollongong (unpublished).
- Stuart-Smith, P. G., Hill, R. I., Rickard, M. J., & Etheridge, M. A. (1992). The stratigraphy and deformation history of the Tumut region: implications for the development of the Lachlan Fold Belt. *Tectonophysics*, 214, 211–237.
- Thomas, O. D., & Pogson, D. J. (2012). *Goulburn 1:250 000 geological sheet SI/55-12, 2nd edition, explanatory notes*, (pp. 1931). Maitland, NSW: Geological Survey of New South Wales.
- VandenBerg, A. H. M., Willman, C. E., Maher, S., Simons, B. A., Cayley, R. A., Taylor, D. H., ... Radojkovic, A. (2000). *The Tasman Fold Belt System in Victoria*, (pp. 462). Melbourne, Vic: Special Publication, Geological Survey of Victoria.
- White, A. J. R., Allen, C. M., Beams, S. D., Carr, P. F., Champion, D. C., Chappell, B. W., Wyborn, D., & Wyborn, L. A. I. (2001). Granite suites and supersuites of eastern Australia. *Australian Journal of Earth Sciences*, 48, 515–530.
- Wilson, C. J. N., Houghton, B. F., McWilliams, M. O., Lanphere, M. A., Weaver, S. D., & Briggs, R. M. (1995). Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. *Journal of Volcanological and Geothermal Research*, 68, 1–28.
- Wyborn, D., Chappell, B. W., & Johnston, R. M. (1981). Three S-Type volcanic suites from the Lachlan Fold Belt, southeast Australia. *Journal of Geophysical Research*, 86, 10,335–10,348.

Figure Captions

Figure 1. Paleogeographic features of the eastern Lachlan Orogen of southeastern New South Wales and eastern Victoria. The Canowindra–Tumut–Canberra volcanic zone is located between the two dotted black lines.

Figure 2. Regional geology of the Canberra and Yass region and includes the southern Cowra Trough. Simplified and modified from the digital map of Colquhoun et al. (2017). Cenozoic units and most faults are not shown. The gravity anomaly is from the isostatic gravity map of NSW (Geological Survey of New South Wales, 2016a). Location of Dinnertime Creek area is shown where Dadd (1998) identified a megabreccia composed of Upper Ordovician blocks of graptolitic siltstone in the Goobarragandra Volcanics. Abbreviations: BG–Burrinjuck Granite, CV–Canowindra Volcanics, GBF/BF–Glen Bower Formation and Boambolo Formation, KS–Koorawatha Syncline, LPF–Long Plain Fault, TBRs–Taemas–Black Range Synclinorium, WJS–Wee Jasper Syncline, YF–Yass Formation, YS–Yass Syncline.

Figure 3. Correlation chart based on data compiled from each zone for: (1) the Tumut Trough (Basden, 1990; Stuart-Smith et al., 1992), (2) the Talmo area and Taemas–Black Range Synclinorium (Thomas & Pogson, 2012; this study), (3) Yass Syncline (Percival & Zhen,

2017; Thomas & Pogson, 2012), and (4) Canberra (Abell, 1991). U–Pb zircon ages from volcanic and plutonic rocks mainly determined by SHRIMP, and abbreviations: Tumut Trough; Blowering Formation (430 ± 2 Ma, 434 ± 3 Ma, Black in Geoscience Australia, 2007), Cootamundra Group (416 ± 3 Ma, Black in Geoscience Australia, 2007), Frampton Volcanics (420 ± 2 Ma, Black in Geoscience Australia, 2007; 428 ± 6 Ma, Stuart-Smith et al., 1992), Gocup Granite (411 ± 5 Ma, Stuart-Smith, Hill, Rickard, & Etheridge, 1992), GuG–Gundibindyal Granite (418 ± 2 Ma, Bodorkos et al., 2015), Kimo Diorite (420 ± 3 Ma, Fraser et al., 2014), MCG–Mishurley Creek Granite (419 ± 2 Ma, Black in Geoscience Australia, 2007), North Mooney Complex (427 ± 3 Ma, Bodorkos et al., 2013, with leucogabbro 431 ± 5 Ma, and plagiogranite 429 ± 5 Ma, Belousova et al., 2015), YaG–Yammatree Granite (418 ± 2 Ma, Bodorkos et al., 2015); Talmo–Taemas; Mountain Creek Volcanics (420 ± 3 Ma, Black, 2006), Young Granodiorite (429 ± 2 Ma near Young, Lyons & Percival, 2002, Black in Geoscience Australia, 2007; 428 ± 3 Ma from northeast of Tumut, Belousova et al., 2015), WCG–Willawong Creek Granite (419 ± 3 Ma, Black, 2005); Yass Syncline; BoF–Boambolo Formation, GBF–Glen Bower Formation, Hawkins Volcanics (438 ± 3 Ma and 434 ± 3 Ma, Black, 2005, from lower in the unit, and 430 ± 4 Ma higher in the unit, Kemp et al., 2008), Laidlaw Volcanics (from near Yass, 433 ± 3 Ma and 431 ± 3 Ma, Black, 2005, 2006), PA–Pilleuil Andesite (420 ± 3 Ma, Black, 2005), YF–Yass Formation.

Figure 4. Geological map of the Talmo area 30 km west of Yass (see Figure 2 for location). Locations of the western and eastern lineaments are drawn from the magnetic intensity maps of New South Wales (Geological Survey of New South Wales, 2016a, b).

Figure 5. Cross-section ABCD across the Talmo area (see Figure 4 for location).

Figure 6. Stratigraphic column for the eastern domain of the Talmo area. Key to symbols in Figures 4 and 5.

Figure 7. Extracts from geophysical maps of New South Wales for the regions centred on the mapped Talmo area (white rectangles). In (a) to (c) the two magnetic lineaments are shown by red lines. (a) Total magnetic intensity map (reduced to the pole) (Geological Survey of New South Wales, 2016a). (b) First vertical derivative of total magnetic intensity map (reduced to the pole) (Geological Survey of New South Wales, 2016b). (c) Ternary radioelement map (Geological Survey of New South Wales, 2016c). (d) Isostatic gravity map (Geological Survey of New South Wales, 2016d).

Figure 8. (a) Perlitic cracks in dacitic ignimbrite of the Goobarragandra Volcanics ($148^{\circ}33'42.6''\text{E}$ $34^{\circ}54'18.4''\text{S}$). (b) Fractured quartz phenocrysts in dacitic ignimbrite of the Goobarragandra Volcanics, cross-polarised light ($148^{\circ}34'5.4''\text{E}$ $34^{\circ}53'59.6''\text{S}$). (c) Well bedded mudstones of the lower sandstone/mudstone lens in the Goobarragandra Volcanics, looking southwest ($148^{\circ}33'36.1''\text{E}$ $34^{\circ}55'20.8''\text{S}$). (d) Interbedded mudstone and nodular limestone of the Talmo Formation in the valley of upper Limestone Creek, looking east ($148^{\circ}35'25.7''\text{E}$ $34^{\circ}54'11.8''\text{S}$). (e) Interbedded quartz sandstone and mudstone in the upper Talmo Formation, looking west ($148^{\circ}35'40.1''\text{E}$ $34^{\circ}54'45.2''\text{S}$). Unless shown, the scale in each photograph is indicated by the geological hammer, 33 cm long, circled in (c). (f) General view of hillside north of limestone Creek showing blocky outcrops of microgranodiorite (Dg) intrusive into the Talmo Formation (Smlm). Dashed white line shows contact. Scene is located 1.8 km WSW of Talmo homestead (Figure 4) around $148^{\circ}35'43''\text{E}$ $34^{\circ}53'59''\text{S}$.

Figure 9. (a) Limestone clast in boulder conglomerate at the base of the Mountain Creek Volcanics ($148^{\circ}35'29.6''\text{E}$ $34^{\circ}55'30.8''\text{S}$). (b, c) Weathering enhanced flow foliation in dacitic ignimbrite of the Mountain Creek Volcanics ($148^{\circ}35'46.7''\text{E}$ $34^{\circ}54'44.1''\text{S}$). (d) Flow foliation in matrix of rhyolitic ignimbrite of the Mountain Creek Volcanics formed by ductile deformation of shards ($148^{\circ}34'25.9''\text{E}$ $34^{\circ}55'17.1''\text{S}$). (e) Microgranodiorite containing altered plagioclase (p), micrographic intergrowths (m), quartz (q) and altered ferromagnesian minerals (fm) ($148^{\circ}36'17''\text{E}$ $34^{\circ}53'58''\text{S}$). (f) Dacitic ignimbrite with quartz veins ($148^{\circ}35'10.5''\text{E}$ $34^{\circ}55'13.5''\text{S}$). Unless shown, the scale in each photograph is indicated by the geological hammer (33 cm long).

Figure 10. Cross-section HI across the mudstone-sandstone unit within the Goobarrangandra Volcanics in lower Limestone Creek. The cross-section is drawn perpendicular to the strike of the Smms unit as indicated by the intersection of the upper contact and topography. Bedding in the Smms unit has an apparent dip of 18° to the NNW and in this section is only slightly discordant to the upper contact with the dacite. See Figure 4 for location.

Figure 11. Block diagram showing the postulated caldera margin along the northern contact of the Mountain Creek Volcanics (not shown) during their eruption. The caldera has been segmented along northwest-striking faults allowing greater downsagging in the northeastern

domain of the Talmo Formation. The present-day level of erosion has reduced the extent of the Talmo Formation shown in this block diagram. Abbreviations: cgte–conglomerate, EML–eastern magnetic lineament, GV–Goobarrangandra Volcanics, TF–Talmo Formation, WML–western magnetic lineament.

Supplementary Figure Caption

Figure S1. Map simplified and reinterpreted from part of the digital seamless geological map of NSW Zone 55East (Colquhoun et al., 2017) showing the negative gravity anomaly, surface geology (Cenozoic units omitted), and location of south-plunging syncline in the Talmo Formation. The upper Black Range Group includes the Kirawin Formation and Sugarloaf Creek Formation underlying the limestones and clastic rocks of the Murrumbidgee Group. The inferred caldera must have extended beyond the outline of the gravity anomaly to at least encompass the downsagged rocks of the Talmo Formation in the domain between the western and eastern lineaments.