Structure of the Upper Devonian Merimbula Group, Lachlan Orogen, Southeastern Coastal New South Wales

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The Upper Devonian Merimbula Group (NSW South Coast) is dominated by northerly-trending folds developed at several scales and indicative of buckling. In the northern area (west of Nowra), moderately to gently dipping limbs of the Budawang Synclinorium are exposed. In upper Ettrema Creek, distinct thin-bedded graded sandstone-mudstone are affected by abundant mesoscopic folds. Farther south, the southern Budawang Synclinorium along Bumbo Creek consists of three map-scale folds with locally common mesoscopic folds of upright, open folds and angular monoclinal folds. The western contact with the underlying Adaminaby Group is repeated by a steep fault. The southern end of the Budawang Synclinorium is a simple, upright, open syncline, with a faulted western limb. In the Pambula area (north of Eden), the eastern Bald Hills anticline is an upright, gentle fold whereas the western Box Range syncline has a wide flat-lying keel with common angular monoclines. Shortening is greatest in the southern Budawang Synclinorium (35%) and is 19-20% west of Nowra and 12% or less in the Pambula area. Locally, rigid granitic basement has resulted in reduced shortening in the overlying Merimbula Group.

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KEYWORDS: deformation, folds, Merimbula Group, Upper Devonian.

INTRODUCTION

The Upper Devonian Merimbula Group consists of fluvial and shallow marine sedimentary rocks exposed along the NSW South Coast region in the Lachlan Orogen, a component of the Tasman Orogenic Belt (Figs 1 and 2; McIlveen, 1975; Powell, 1983, 1984; Dunstone and Young, 2019). From 15 km west of Narooma (Fig. 3), the Merimbula Group lies within the Budawang Synclinorium that continues 170 km northwards where it is overlain by the southern Sydney Basin (McIlveen, 1975). South of Narooma, the Merimbula Group occurs in several discontinuous belts including widespread exposures around Eden (Fig. 3). The Merimbula Group unconformably to conformably overlies the Eden-Comerong-Yalwal Volcanic Zone (ECYVZ), which is northerly trending, 320 km long, up to 20 km wide and consists of Middle to Upper Devonian basaltic and rhyolitic lava flows, pyroclastic and sedimentary rocks (McIlveen, 1975; Dadd, 1992).

Both the Merimbula Group and underlying ECYVZ have been affected by north-trending folds, faults and related structures that formed during the Kanimblan Orogeny in the Carboniferous (Powell, 1983, 1984; Cooper, 1992). Structure of the Merimbula Group has been described for coastal headlands around Eden by Rixon et al. (1983), and in brief to more detailed descriptions of structural profiles through the Upper Devonian units in the Shoalhaven River – Ettrema Creek area (Cooper, 1992), the region northwest of Moruya (Rickard et al., 1983; Duff et al., 1985), and the Yadboro Creek area (Powell, 1983). From these studies the Upper Devonian Merimbula Group was determined to have been affected by shortening up to 40% (Fergusson, 2017) accommodated by upright, open to gentle folds and what Rixon et al. (1983) termed “mega kink folds” but are referred to as angular monoclines in this work because the term “megakinks” in relation to other structures has been widely used in the South Coast region (Powell et al., 1985).

Various interpretations have been given for the overall structure of the Upper Devonian sedimentary succession along the NSW South Coast. In a study in the southern Budawang Synclinorium reported

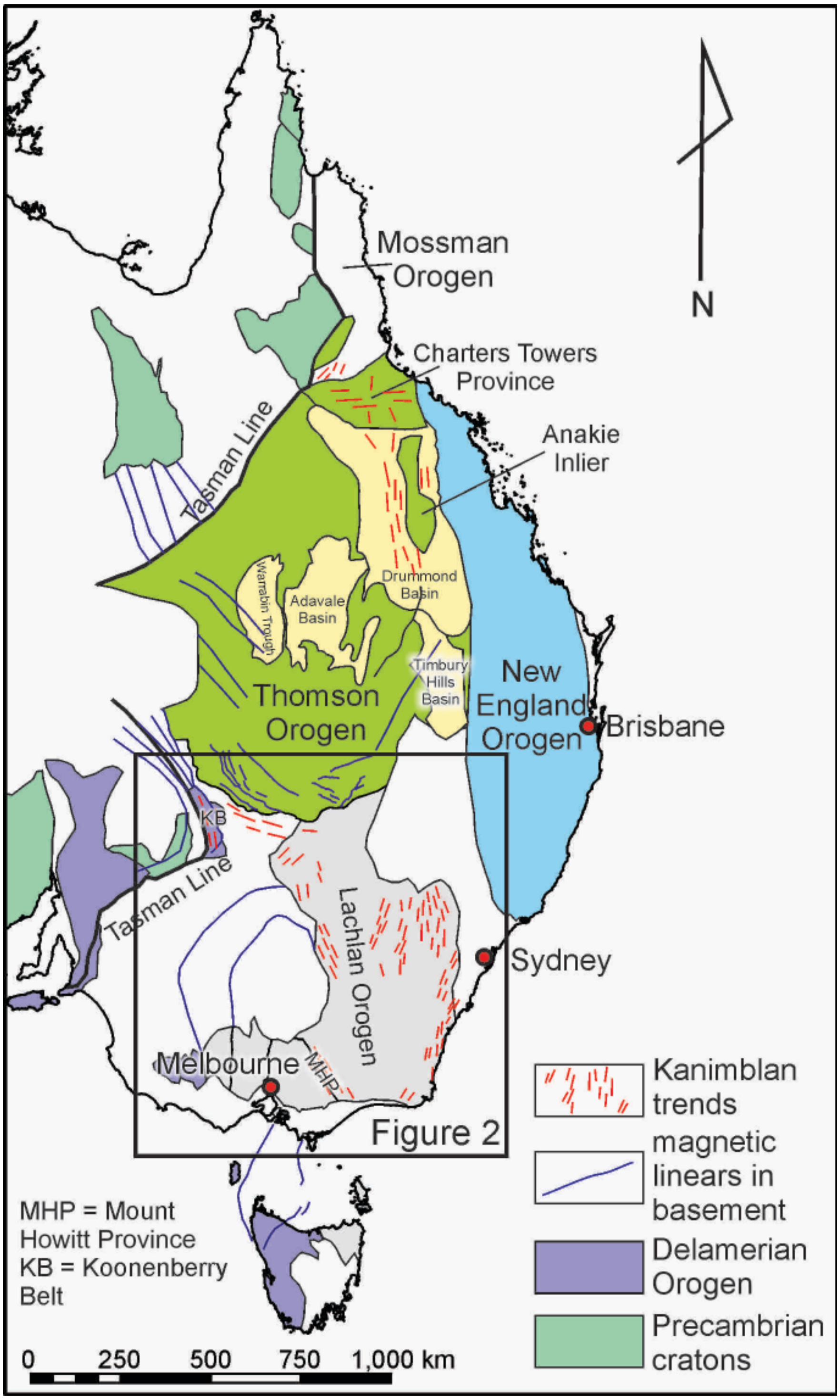

Figure 1. Map of the Tasman Orogenic Belt (Tasmanides) of eastern Australia showing the Devonian-Carboniferous sedimentary basins covering the Thomson Orogen in Queensland and structural trends (red lines) formed by the Carboniferous Kanimblan Orogeny (modified from Fergusson and Colquhoun, 2022).

by Glen and Lewis (1990; see also Glen, 1992; Lewis et al., 1994) it was proposed that the structure was controlled by a thrust system with internal imbrication rather than being a "simple fold structure as is generally portrayed". High-angle to moderately dipping contraction faults are found in and bounding the Upper Devonian Merimbula Group (Rixon et al., 1983; Cooper, 1992). The role of so-called "mega kink folds" (i.e. angular monoclines) was emphasized in the accounts of Rixon et al. (1983) and Cooper (1992). The present paper presents structural data from three different areas of the NSW South Coast (Bumbo Creek, upper Ettrema and Danjera creeks ~22 km west-southwest of Nowra, and the Pambula

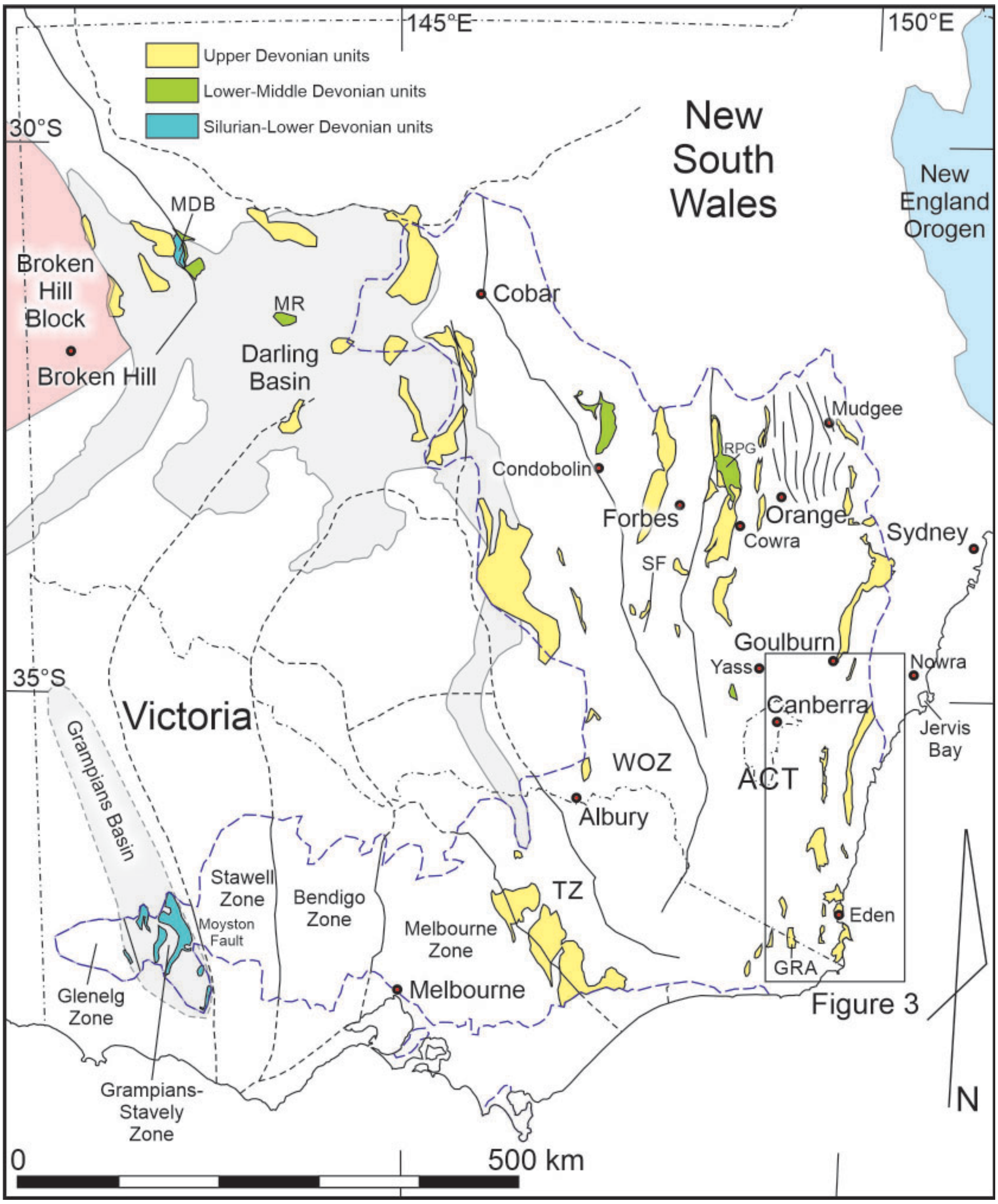

Figure 2. Map of the Lachlan Orogen showing the main areas of upper Lower to Upper Devonian fluvial and shallow-marine strata, upper Silurian to Devonian dominantly fluvial strata in the Darling Basin (mainly in the subsurface), and fluvial to shallow-marine strata of the Grampians Group in western Victoria. Only the Upper Devonian units in the eastern Melbourne Zone are considered to extend into the Lower Carboniferous. Structural trends are shown in the northeastern Lachlan Orogen. Abbreviations: ACT, Australian Capital Territory; GRA, Genoa River area; MDB, Mt Daubeny Basin; MR, MacCullochs Range; RPG, Rocky Ponds Group (silicic volcanics); SF, Springdale Fault; TZ, Tabberabbera Zone; WOZ, Wagga–Omeo Zone. Modified from Fergusson (2017). See Fig. 1 for location.

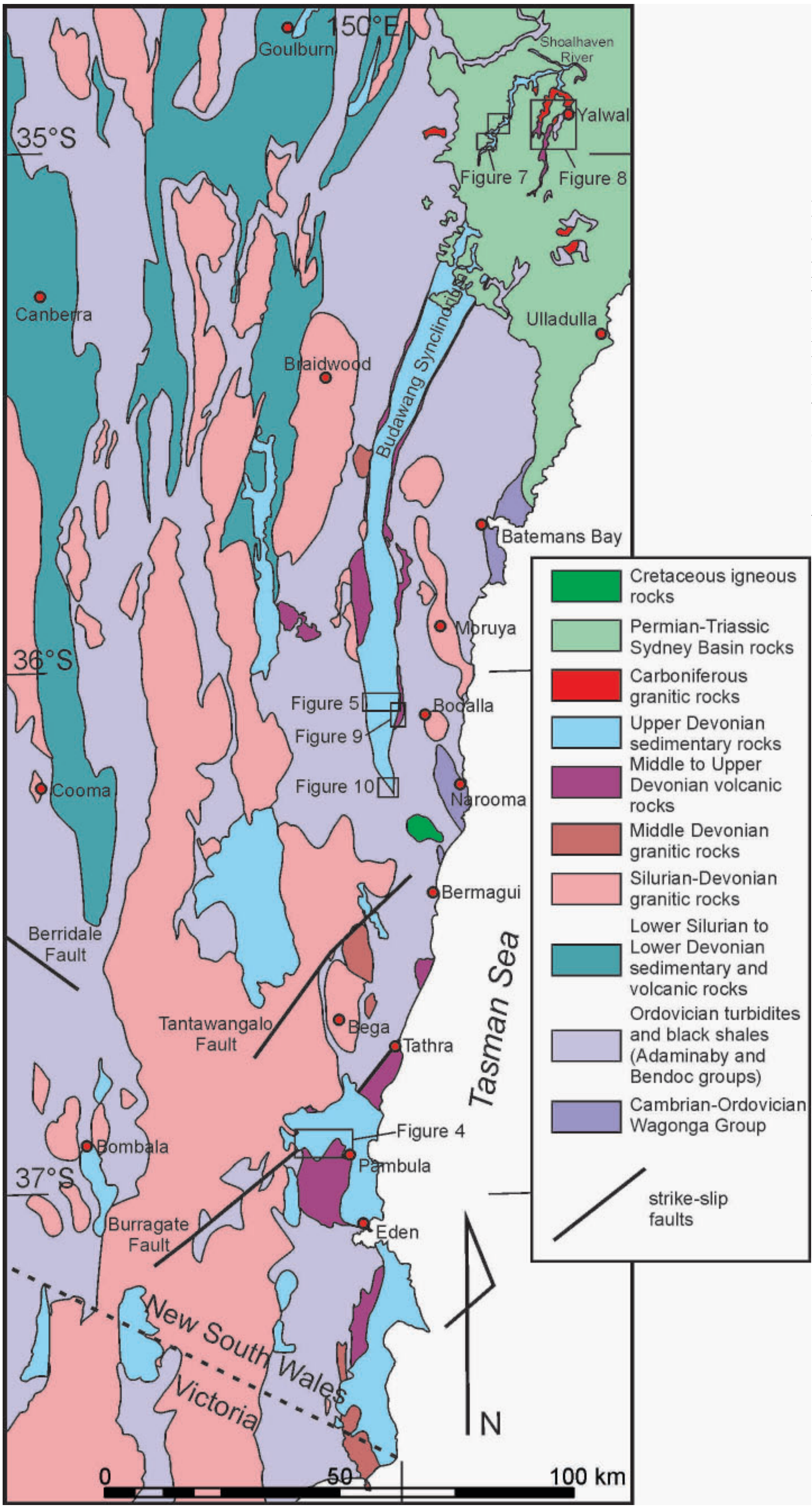

Figure 3. Geological sketch map of the pre-Cenozoic rocks of the NSW South Coast region south of Jervis Bay. Simplified and reinterpreted from the MinView web site (https://minview.geoscience.nsw.gov.au/). See Fig. 2 for location.

district) with the aim of determining the orientations and styles of structures in the Upper Devonian Merimbula Group. The roles of mesoscopic and map-scale folding caused by buckling in addition to fault-related folding are also considered.

GEOLOGICAL SETTING

The early to late Paleozoic Lachlan Orogen (or Fold Belt) is in the central part of the Tasman Orogenic Belt in southeastern Australia (Fig. 1) and lies west of the early Paleozoic to early Mesozoic New England Orogen which has had a long history of convergent plate margin tectonics (Jessop et al., 2019). In the Late Devonian to Carboniferous a well-developed east-facing active continental margin was developed with volcanic arc, forearc basin and subduction complex tectonic elements (Scheibner and Basden, 1998) and indicates a backarc tectonic setting for inboard components of the Tasmanides including the Lachlan Orogen and basinal successions in Queensland overlying the Thomson Orogen (Glen, 2005; Jell, 2013). During the Middle to Late Devonian these inboard elements were affected by igneous activity including in the Lachlan Orogen (e.g. the Mt Howitt Province in central Victoria, the Dulladerry Volcanics in central NSW, the ECYVZ) and widespread fluvial to shallow marine sedimentation (Powell, 1984; Scheibner and Basden, 1998; Jell, 2013). These successions have been related to initial rifting in a backarc setting in Queensland (Jell, 2013) but are considered to have formed in a backarc compressional setting in the Mt Howitt Province of the Lachlan Orogen (O'Halloran and Cas, 1995).

In the early Carboniferous, widespread backarc contractional deformation affected the Lachlan Orogen with deformation extending across NSW to the north and east of Broken Hill with the general magnitude of shortening decreasing from east to west and southwestwards (Powell, 1984; Fergusson, 2017). Deformation has involved the development of regional anticlines and synclines in addition to some thrust faults and has been referred to the Kanimblan Orogeny in southeastern Australia (Packham, 1969). The timing of deformation is constrained by the intrusion of the Carboniferous Bathurst-type intrusions with an age range of 341–314 Ma (Meakin and Morgan, 1999; Jeon and Williams, 2018). In contrast weak contractional deformation in Queensland has occurred in the mid to late Carboniferous (Jell, 2013). The deformation timing overlaps with the Alice Springs Orogeny of central Australia (Haines et al., 2001) and shows that East Gondwana was undergoing widespread contractional deformation related to the active margin.

STRATIGRAPHY

The NSW South Coast region south of the Permian-Triassic Sydney Basin is dominantly underlain by highly deformed Lower to Middle Ordovician turbidites (Adaminaby Group), overlying Upper Ordovician black shales (Bendoc Group), and in the Narooma and Batemans Bay areas, the Wagonga Group of mid Cambrian to Ordovician age (Fig. 3). These rock units are intruded by widespread granitic plutons of the Early Devonian Bega and Moruya batholiths. Extending from the Shoalhaven River in the north to Gabo Island in the south is the Middle to Upper Devonian ECYVZ and associated granitic intrusions (Collins et al., 1982; Dadd, 1992) and collectively these igneous rocks extend up to 45 to 25 km west of the coastline (Fig. 3). Basalts are most abundant in the Eden-Pambula district whereas silicic volcanic rocks, mainly rhyolitic lavas, are more abundant elsewhere in the ECYVZ (Fergusson et al., 1979; Dadd, 1992).

The Merimbula Group in the Eden area unconformably overlies the ECYVZ and has been divided into three formations by Steiner (1975): the Twofold Bay Formation at the base consisting of conglomerate (the Wolumla Conglomerate Member) and overlying red beds (quartzose sandstone and mudstone), the overlying Bellbird Creek Formation of interbedded sandstone and mudstone containing shallow-marine fossils, and the overlying Worange Point Formation of red beds (conglomerate, sandstone and mudstone). The Twofold Bay Formation and Worange Point Formation were deposited in alluvial fan to fluvial environments and the Bellbird Creek Formation in a shallow marine setting (Steiner, 1972). South of Eden, Lewis et al. (1994) named the Ben Boyd Formation based on the detailed sections mapped by Taylor and Mayer (1990), although the latter attributed these rocks to the upper Worange Point Formation. The Ben Boyd Formation was considered to have a higher mudstone content than the underlying Worange Point Formation by Lewis et al. (1994). In the Pambula district, the Merimbula Group was left undifferentiated on the Bega 1:250,000 geological map (Lewis and Glen, 1995) but was divided by Steiner (1975) into the threefold subdivision (Twofold Bay Formation, Bellbird Creek Formation and Worange Point Formation) that is followed in this work (Fig. 4).

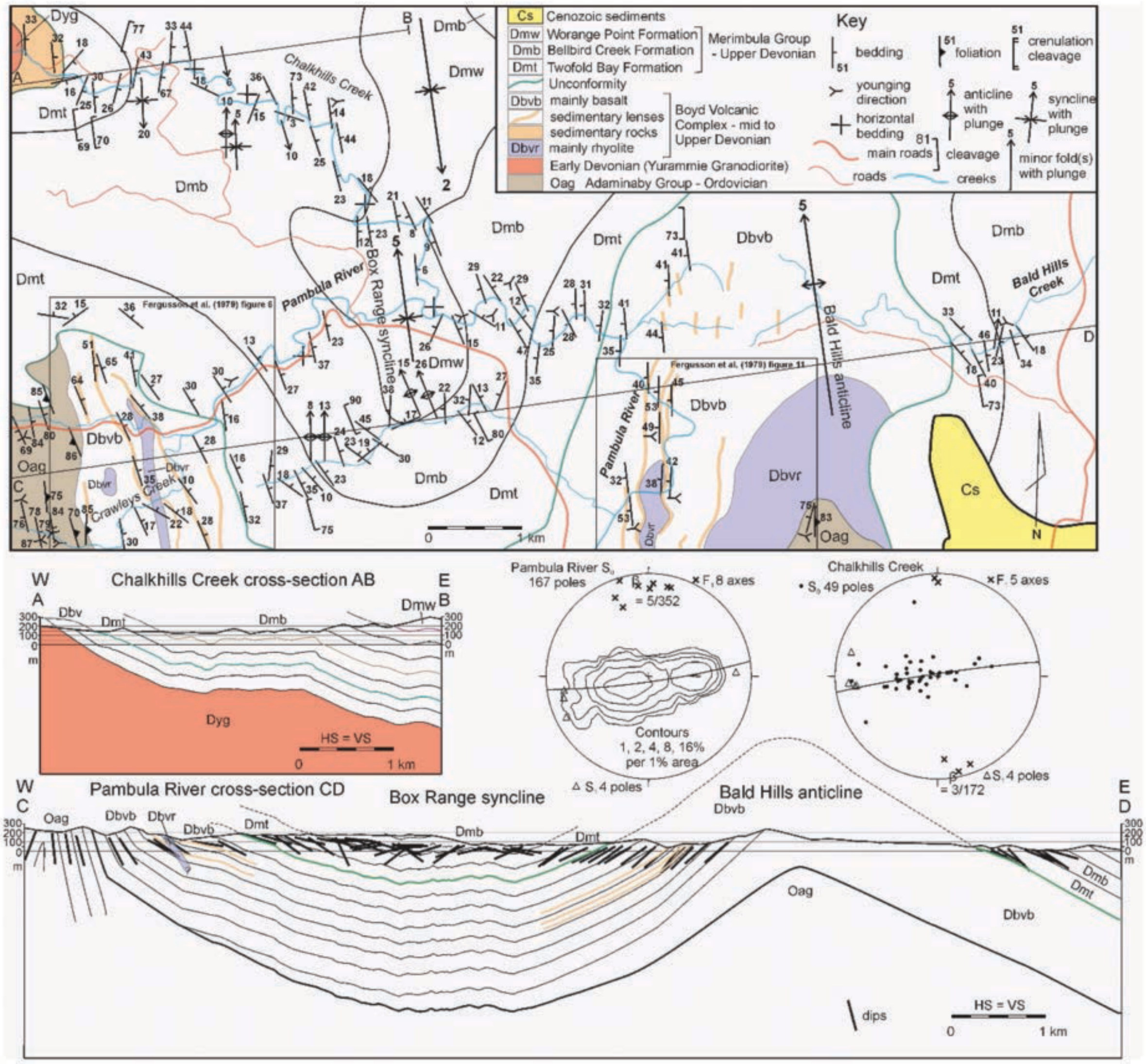

Figure 4. Map and cross-sections of the Pambula district (for location of map see Fig. 3). Contacts of the Twofold Bay and Bellbird Creek formations follow Steiner (1975). Geology shown in the rectangles (lower left and lower middle part) are from figures 6 and 11 respectively in Fergusson et al. (1979). Representative structural measurements are shown only (the full data set is available for this and other maps from the author on request). Equal-area stereonets with orientation data (bedding - S0, cleavage - S1, and F1 fold axes) for the Pambula River and Chalkhills Creek areas. On cross-sections: HS = VS, horizontal scale = vertical scale.

In the southern Budawang Synclinorium, Steiner's units have been mapped along Bumbo Creek (Fig. 5). On the Bega 1:250,000 geological sheet in the southern Budawang Synclinorium the Ben Boyd Formation was distinguished from the Worange Point Formation and furthermore the distribution of rock units has been used to indicate structural complications due to a hypothesized thrust system with a décollement below the entire succession (Glen and Lewis, 1990; Lewis et al., 1994; Lewis and Glen, 1995). However, in the mapped areas reported herein, the Ben Boyd Formation has not been recognized either because it could not be distinguished from the remainder of the Worange Point Formation or because the succession did not extend above the top of the Worange Point Formation. Additionally, Dunstone and Young (2019) disputed the stratigraphic and structural interpretations presented by Glen and Lewis (1990) on both paleontological and stratigraphic grounds.

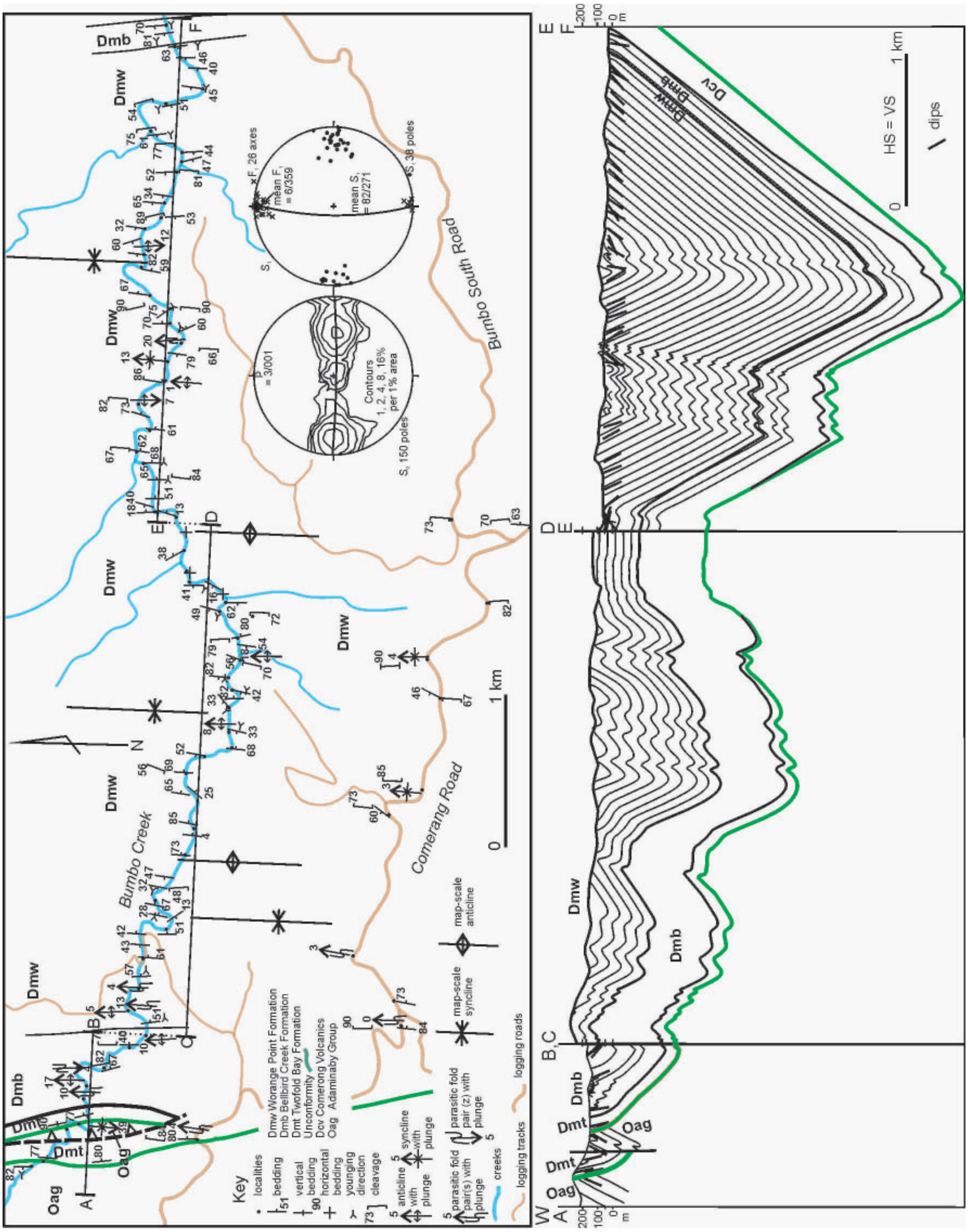

Figure 5. Map and cross-section of the traverse across the Budawang Synclinorium along Bumbo Creek (for location of map see Fig. 3). Along this traverse the Merimbula Group has been divided into the Twofold Bay, Bellbird Creek and Worange Point formations (following Steiner's 1975 mapping in the Eden district). Note that the Twofold Bay Formation is only found along the western limb of the synclinorium and is duplicated by a steeply dipping reverse fault. Equal-area stereonets show orientation data for bedding (S0), cleavage (S1), and F1 fold axes.

Figure 6. Photograph of the angular unconformity between the overlying flat-lying Permian succession of the Sydney Basin and the underlying Upper Devonian Merrimbula Group dipping to the east at 30-40°E. Photograph taken at 150°10'57.46"E 34°59'37.68"S and looking south to the eastern side of the gorge ~1 km to the south. Ettrema Creek gorge here has a depth less than 400 m below the plateau surface.

In upper Ettrema Creek and Danjera Creek, the Middle to Upper Devonian rocks are unconformably overlain by the Permian Shoalhaven Group (Fig. 6). The contact of the Merimbula Group with the Ordovician Adaminaby Group is not exposed in upper Ettrema Creek (Fig. 7), but it is exposed in Cooee Creek 9.5 km north-northeast from the junction of Ettrema and Tullyangela creeks, where it is a steeply west-dipping fault with the Ordovician rocks thrust over the Merimbula Group (Cooper, 1992). The Upper Devonian succession is well exposed in Ettrema Creek gorge but is left undifferentiated in this work. The succession contains Frasnian limestone in Jones Creek (Pickett, 1972; McIlveen 1975; MinView web site, 2023) and the presence of fossil shell beds (Fig. 7) indicates that much of the succession is most likely equivalent to the Bellbird Creek Formation, which was mapped by Cooper (1992) in lower Ettrema Creek. Within the section between the junction of Myall and Ettrema creeks upstream to 500 m below the junction of Jones and Ettrema creeks (Fig. 7b) is abundant thin-bedded sandstone and mudstone with graded bedding in addition to the thick-bedded fossil shell beds. Elsewhere in upper Ettrema Creek, thickly bedded cross-bedded sandstone interbedded with mudstone dominate the Merimbula Group.

In the Danjera Creek area, most of the Devonian succession is dominated by the Middle to Upper Devonian Yalwal Volcanics (Fig. 8). The contact of the Yalwal Volcanics with the overlying Merimbula Group is difficult to resolve because in upper Bundundah and Strike creeks a succession of red beds (conglomerate, sandstone and mudstone) contains a few basaltic lava flows but overall is dominated by sedimentary rocks and has a basal conglomerate overlying the flow-banded rhyolite exposed in Rhyalite Saddle and down the ridge east to Danjera Creek (Fig. 8). 15 km to the northeast in the Shoalhaven River, Cooper (1992) mapped basal conglomerate of the Twofold Bay Formation overlying the Grassy Gully rhyolite of the Yalwal Volcanics. Thus, either the basal Merimbula Group in upper Bundundah and Strike creeks contains local basaltic lava flows and overlies rhyolite of the Yalwal Volcanics, or the contact of the Merimbula

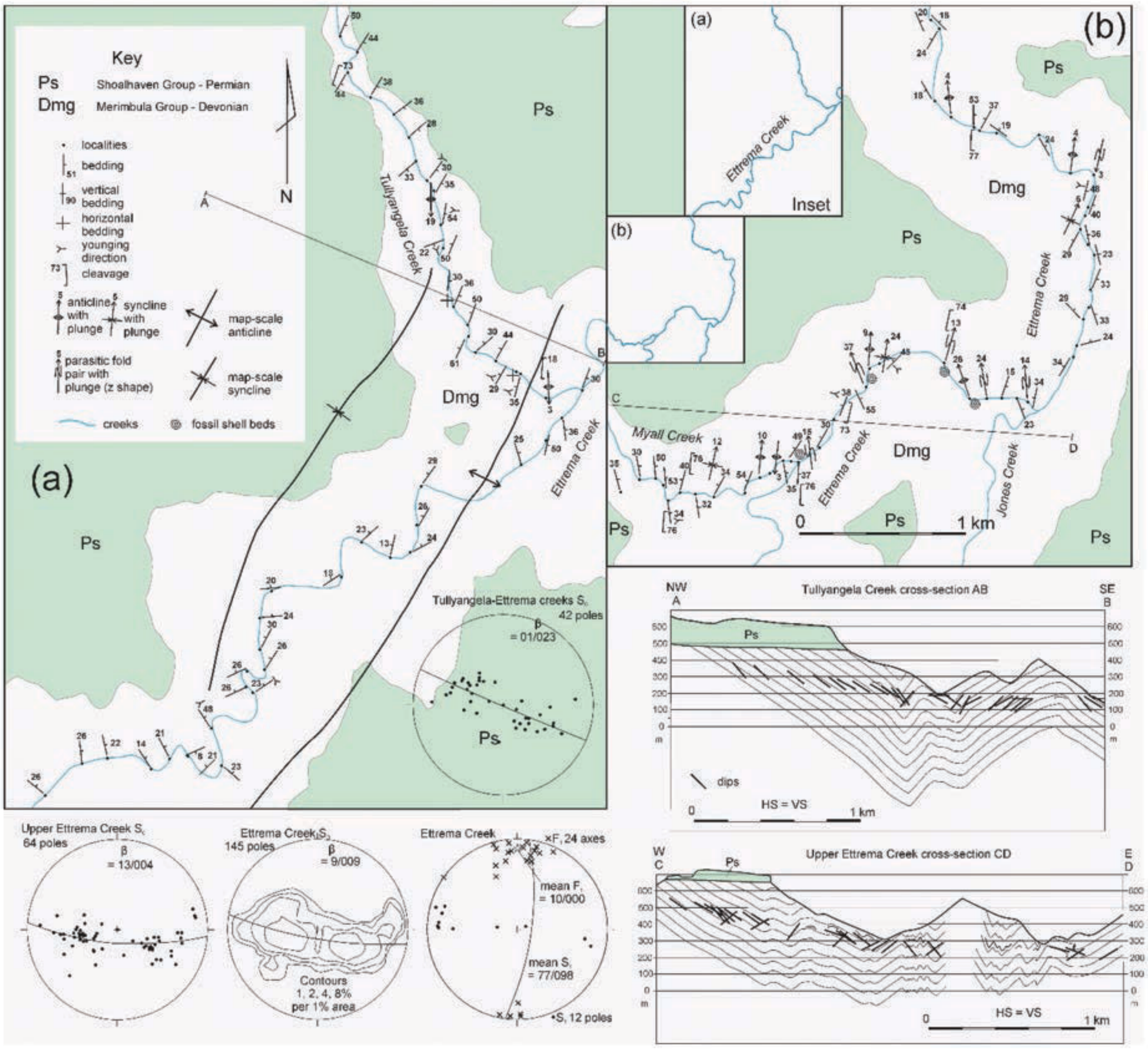

Figure 7. Map and cross-sections of the traverse along upper Ettrema Creek on the western limb of the Budawang Synclinorium (for location of map see Fig. 3). Inset shows locations of parts (a) and (b) along upper Ettrema Creek. Geological detail from the mapping reported herein; contacts of Permian units are from the MinView web site (https://minview.geoscience.nsw.gov.au/). Equal-area stereonets with orientation data (bedding – S0 and cleavage – S1) for Upper Ettrema Creek from Myall Creek downstream to 1 km downstream from the junction of Ettrema and Jones creeks (lower left), Tullyangela Creek to 2.75 km upstream from the junction of Ettrema and Tullyangela creeks on map (a), and all bedding and other data from the upper Ettrema Creek gorge.

Group is higher in the succession. On the MinView web site (after unpublished mapping in theses by Love, 1965, and Wall, 1965) the contact is shown in upper Bundundah Creek, but the basal Merimbula Group also contains a basaltic layer (lava or sill?). West and north of Yalwal, the Merimbula Group is intruded by the Bundundah Granite (Fig. 8), which has a U-Pb zircon age of 324.4 ± 3.2 Ma (Bodorkos et al., 2010). This zircon age constrains the timing of the deformation of the Upper Devonian succession to the early Carboniferous.

STRUCTURE

The Budawang Synclinorium is north-northeast-trending in the Yalwal-Ettrema Creek areas, swings southwards to a more northerly trend west of Moruya and has a north-northwest trend at its southern

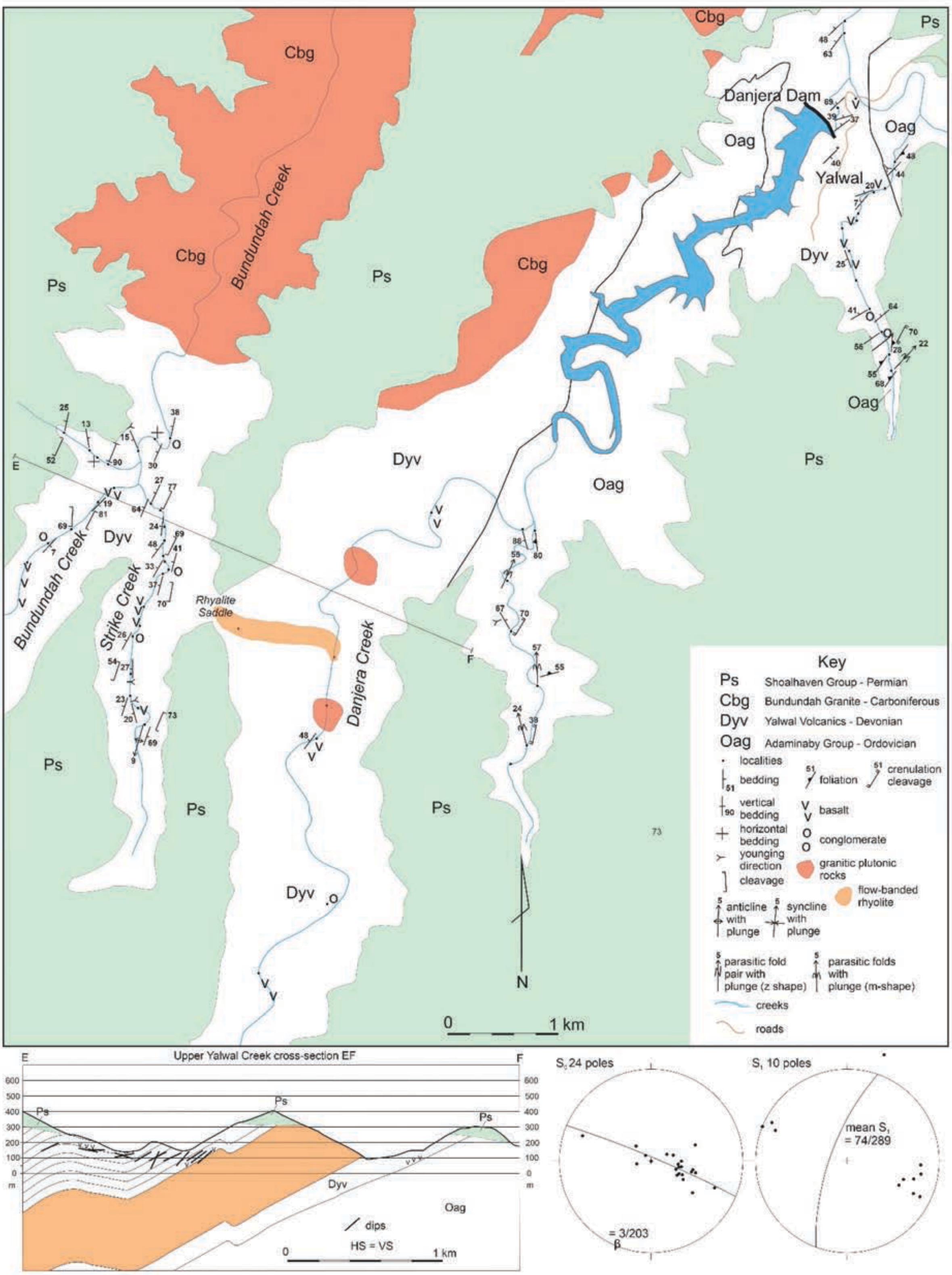

Figure 8. Map and cross-sections of the Yalwal and Danjera Creek area on the eastern limb of the Budawang Synclinorium (for location of map see Fig. 3). Geological detail from the mapping reported herein; contacts of main units are from the MinView web site (https://minview.geoscience.nsw.gov.au/). Equal-area stereonets with orientation data (bedding – S0 and cleavage – S1) for the Devonian rocks in upper Bundundah Creek, Strike Creek and upper Danjerra Creek (upstream from the reservoir at Danjerra Dam).

termination southwest of Bodalla (Fig. 3). South of the Budawang Synclinorium towards Bega, the Upper Devonian units are north-northwest-trending and around Eden are northerly trending (Fig. 3; Powell, 1983). Folds are generally open to gentle, upright and gently plunging. In this paper, the interlimb angle classification follows that of Van der Pluijm and Marshak (2004, 0-10° = isoclinal, 10-60° = tight, 60-120° = open, 120-180° = gentle).

Southern Budawang Synclinorium

The southern Budawang Synclinorium includes the Bumbo Creek traverse, the Comerang Mountain area, and the Reedy Creek area (Fig. 3). For the Bumbo Creek area, orientation data is shown on the map, cross-section and stereonets in Fig. 5. All folds are northerly trending with gentle plunges to the north and south (Fig. 5). A steeply dipping, spaced to slaty cleavage is developed in mudstones and is axial planar to mesoscopic folds. In Bumbo Creek, the Budawang Synclinorium consists of several map-scale anticlines and synclines (Fig. 5). The largest syncline is in the eastern part of the traverse and has an eastern planar west-dipping limb typically at 50-60°W. In this section, the relatively thin (~250 m) Bellbird Creek Formation directly overlies the Comerong Volcanics and a thick section (~1000 m) of the Worange Point Formation is preserved. The western limb of the syncline dips east at a similar angle to the eastern limb but contains a ~500 m wide zone containing several east-verging upright open mesoscopic anticlines and synclines. The map-scale anticline to the west has a relatively flat-lying ~500 m wide core containing several small-scale angular monoclines. To the west is a syncline with common mesoscopic folds that are upright and open with a subhorizontal enveloping surface. Farther west, an anticline with local flat bedding is present and then another syncline with common mesoscopic folds. The western limb of the synclinorium dips ~50-60°E and has west-verging mesoscopic (s-shaped, looking north) folds. The basal part of the succession (Twofold Bay Formation) is repeated by a steeply dipping fault that also affects part of the underlying Ordovician Adaminaby Group. Overall, shortening within the synclinorium attributed to folding in the Bumbo Creek cross-section is 35% [calculated using the standard formula for shortening, e.g. Ramsay (1967), $S = (l_o - l_1)/l_o$, where l_1 = deformed length, l_o = undeformed length]. South of Bumbo Creek the eastern syncline continues southwards west of Comerang Mountain where silicic volcanic rocks of the basal Comerong Volcanics are well exposed (Fig. 9).

At the southern end of the Budawang Synclinorium the structure is dominated by an open, north-northwest, gently plunging syncline with a steeply dipping axial plane (Fig. 10). In contrast to Bumbo Creek to the north, mesoscopic folds are relatively scarce, and the syncline has a rounded hinge. Shortening for cross-section KL is 35%, the same as for the Bumbo Creek cross-section. The western limb of the syncline is truncated by a poorly exposed, steeply dipping fault. It is considered steeply dipping as the fault is shown crossing topographic contours at a high angle.

Upper Ettrema Creek and Danjera Creek

Structural data for the upper Ettrema Creek gorge and the Yalwal-Danjera Creek area are given on the maps, cross-sections and orientation data in Figs 7 and 8. The western limb of the Budawang Syclinorium consists of a map-scale syncline-pair exposed in Tullyangela Creek and upstream ~2 km along Ettrema Creek towards the junction with Jones Creek (Fig. 7, cross-section AB). The folds are north-northeast-trending, sub-horizontally plunging, open and with steeply dipping axial planes (Fig. 7). In this area the succession is dominated by thick-bedded quartz sandstone with relatively thin mudstone interbeds, and mesoscopic folds are relatively uncommon. Rock cleavage is not developed. Shortening for cross-section AB (Fig. 7) is 19%, similar to 21-22% recorded for the cross-sections along the Shoalhaven River and lower Ettrema Creek (Cooper, 1992; Fergusson, 2017).

Farther upstream the structural trends are more northerly and folds are plunging gently to the north (Fig. 7). In the western part of Myall Creek, the western limb of the Budawang Synclinorium dips 30-40°E and is well exposed in Ettrema Creek gorge farther upstream (Fig. 6). To the east along lower Myall Creek and down Ettrema Creek to beyond the junction with Jones Creek, the structure forms an overall syncline (Fig.7, cross-section CD) equivalent to the syncline mapped farther downstream. This syncline contains abundant mesoscopic folds especially along Ettrema Creek in the thin-bedded sandstone and mudstone typical of this part of Ettrema Creek. These mesoscopic folds are upright, close to open, and have wavelengths of at least 5-20 m. Shortening for cross-section CD (Fig. 7) was calculated at 20%.

In upper Bundundah and Danjera creeks, the structures are north-northeast trending with a gentle plunge to the south-southwest (Fig. 8). The main structures are an anticline-syncline pair and overall strata dip west indicating the eastern limb of the

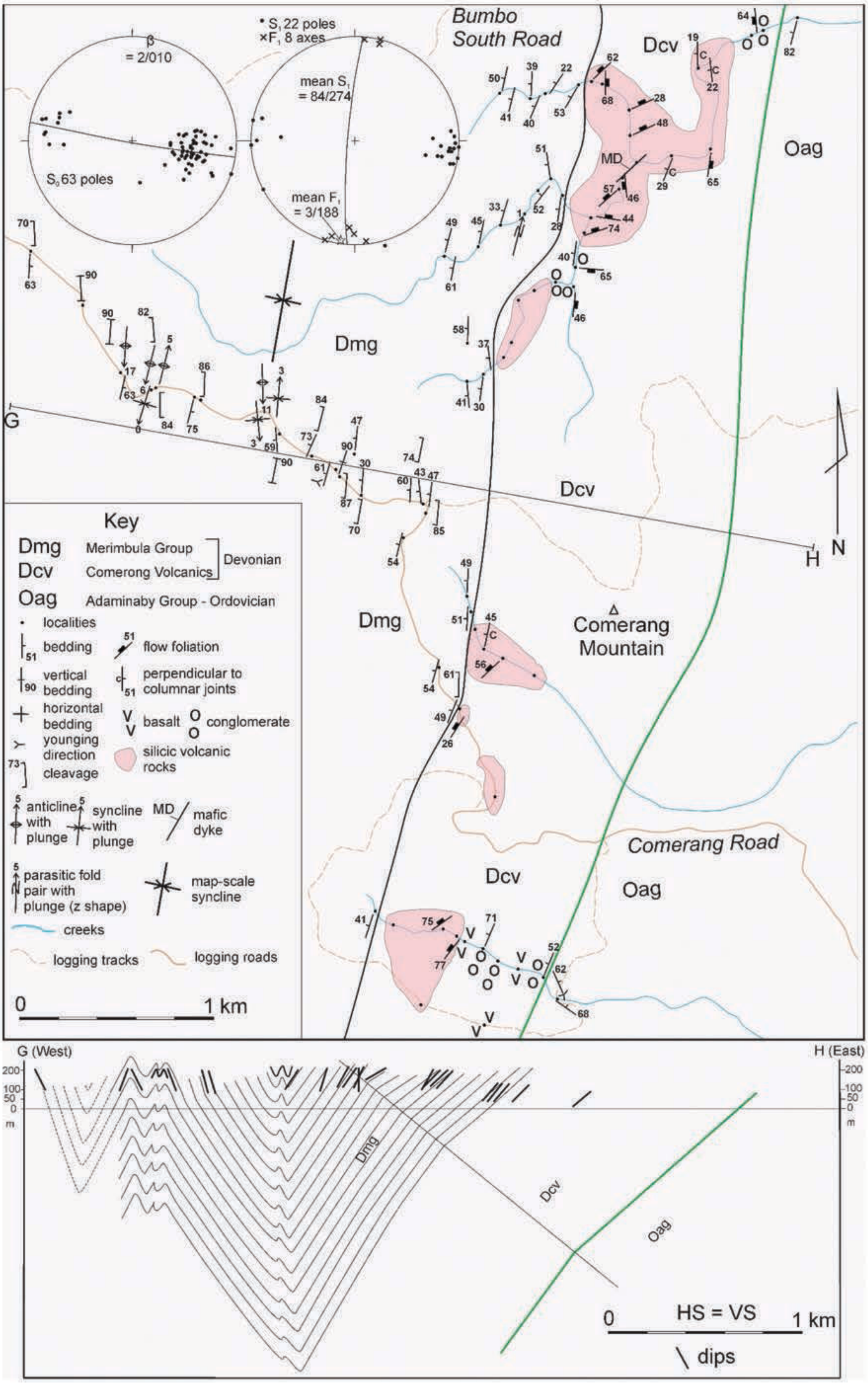
β = 2/010
S0 63 poles
S1 22 poles
F1 8 axes
mean S1 = 84/274
mean F1 = 3/188
Bumbo South Road
Dcv
Oag
Dmg
MD
G
H
N
Comerang Mountain
Comerang Road
Key
Dmg Merimbula Group
Dcv Comerong Volcanics
Devonian
Oag Adaminaby Group - Ordovician
localities
bedding
flow foliation
vertical bedding
perpendicular to columnar joints
horizontal bedding
basalt
conglomerate
younging direction
silicic volcanic rocks
cleavage
anticline with plunge
syncline with plunge
mafic dyke
parasitic fold pair with plunge (z shape)
map-scale syncline
creeks
logging tracks
logging roads
0
1 km
G (West)
H (East)
HS = VS
dips

Figure 9 (above). Map and cross-section of the Comerong Volcanics and overlying Merimbula Group along the eastern limb of the Budawang Synclinorium (for location of map see Fig. 3). Equal-area stereonets with orientation data (bedding - S0, cleavage - S1, and F1 fold axes). Stratigraphic unit abbreviations (on cross-section): Oag, Ordovician Adaminaby Group; Dcv, Devonian Comerong Volcanics; Dmg, Merimbula Group.

Budawang Synclinorium. The succession here contains more mudstone than to the west in Ettrema Creek and rock cleavage is more widely developed. Only a few mesoscopic folds occur. Shortening is only 11% considerably less than elsewhere in the Yalwal-Ettrema region and possibly reflects the adjoining competent Yalwal Volcanics.

Pambula district

The structure of the Pambula district has been locally investigated and reported by Fergusson et al. (1979) for two areas mapped in detail (Fig. 4). The structure of the Upper Devonian units has been described in detail for the coastal sections north and south of Eden (Rixon et al., 1983). In this account unpublished mapping undertaken in the Pambula district has enabled construction of two cross-sections (Fig. 4). Map-scale folds in the Pambula district are gently plunging to the north and south (Fig. 4). Most of the succession is gently dipping to flat lying (Fig. 4). The map-scale structures include the Box Range syncline in the west and the Bald Hills anticline in the east (Fig. 4). The Box Range syncline has a wide flat-bottomed hinge with the main limbs in the east and west dipping moderately to the west and east respectively (Fig. 4, cross-section CD). The wide hinge zone of the Box Range syncline contains many local angular monoclines (the "mega kink folds" of Rixon et al., 1983) as shown by localized steep dips amongst flat to gently dipping beds in addition to some upright, gentle minor folds. These structures are also evident in upper Chalkhills Creek in Fig. 4 cross-section AB. In contrast, the Bald Hills anticline is a gentle angular fold with the eastern planar limb dipping ~30°E and the western planar limb dipping ~40°E. Shortening for cross-section CD (Fig. 4) is 12% and much less for cross-section AB (6%). These values are consistent with the low level of shortening (10%) determined by Rixon et al. (1983) in the coastal outcrops north and south of Eden.

DISCUSSION

Variations in structural style are shown in the cross-sections arranged from north to south in the Merimbula Group in the South Coast region (Fig. 11). In the northern part of the Budawang Synclinorium the structure has a wide flat-lying synclinal zone with relatively moderately dipping outer limbs. Shortening is around 20% (Fergusson, 2017). In the Yadboro River cross-section the structure has changed to a relatively simple, rounded, open syncline (Powell, 1983) and shortening is 33%. This simple structure has been mapped southwards towards Moruya (Schmidt et al., 1986), but from there to the south beyond Bumbo Creek the structure of the synclinorium is more complicated with map-scale anticlinal and synclinorial zones as shown in the Bumbo Creek cross-section and to the northwest of Moruya (Rickard et al., 1983, plate 1, profile 5; Duff et al., 1985). Along the South Coast, shortening is greatest in the Bumbo Creek and Reedy Creek cross-sections (35%). At the southern termination of the Budawang Synclinorium the structure is again a simple rounded syncline but with a faulted western limb. Farther south in the Murrah State Forest area, the cross-section from Powell (1983) shows a map-scale syncline-anticline pair in the west that is offset along a high-angle (reverse) fault over a syncline in the east (Fig. 11h) and overall shortening is 20%. Around Eden, the structural style shows the least shortening with values of 6 to 12% with large areas of relatively flat-lying rocks exposed along the coastline but inland along the Pambula River a gentle map-scale anticline-syncline couple developed.

The variations in the wavelengths of upright mesoscopic to map-scale folds evident in the cross-sections (Fig. 11) are indicative of buckling as being a common fold mechanism during shortening (e.g. Navabi and Fossen, 2021). The thickness of layering has controlled the fold wavelengths as evident from the abundance of upright mesoscopic folds in the thin-bedded units in upper Ettrema Creek and the larger wavelength folds developed in Bumbo Creek, Ettrema Creek and the Pambula River cross-sections (Fig. 11). The development of angular monoclinal folds ("mega kink folds" of Rixon et al., 1983) in the Eden district and also elsewhere along the South Coast (e.g. lower Ettrema Creek, Bumbo Creek), as shown by locally steeply dipping beds, is suggestive of fault propagation folding related to offsets along thrust to reverse faults at depth (e.g. Eslev, 1991). Rixon et al. (1983) considered that these monoclinal folds could have developed from reactivation of normal faults formed previously during rifting associated

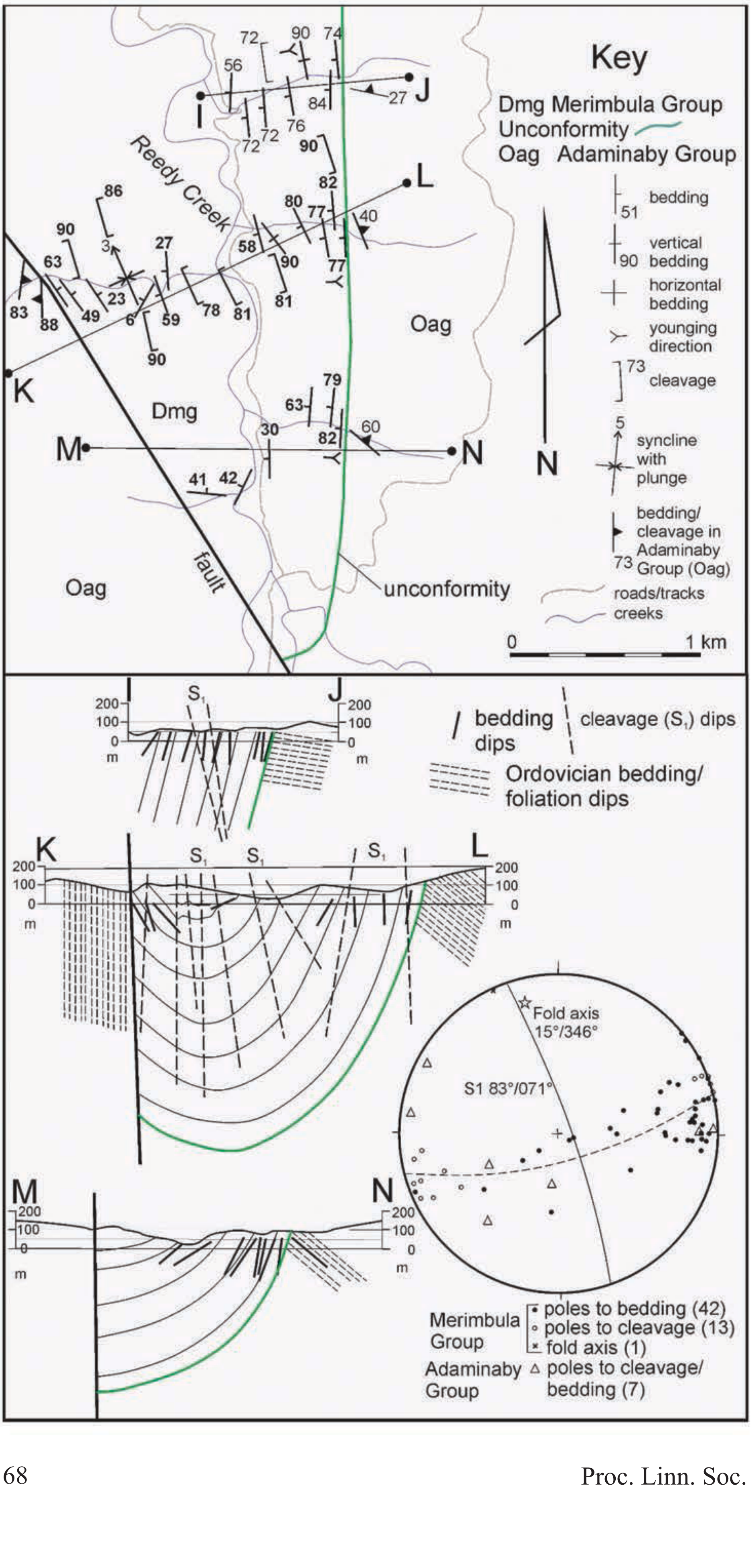

Figure 10. Map, cross-sections and equal-area stereonet of structural data from the southern termination of the Budawang Synclinorium along Reedy Creek (for location see Fig. 3).

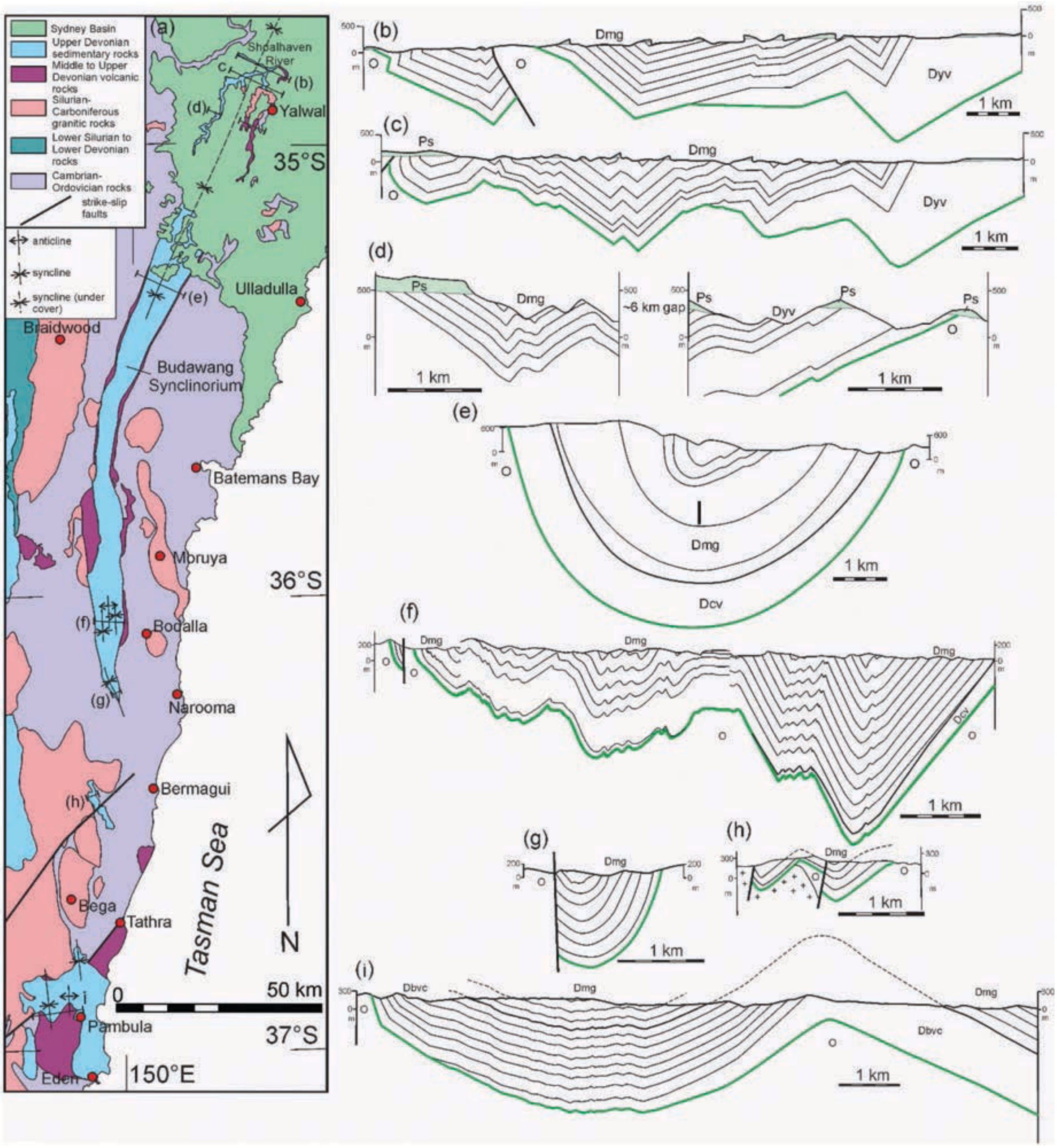

Figure 11. Summary map and cross-sections (all horizontal scale = vertical scale) showing the structure of Devonian units along the NSW South Coast region. Thicker green line is the sub-Devonian unconformity. Thicker black lines are faults and the contact between the Merimbula Group (Dmg) and the underlying volcanic units (Boyd Volcanic Complex – Dbvc, Comerong Volcanics – Dcv, Yalwal Volcanics – Dyv). Ordovician – O. (a) Simplified geological map of the NSW South Coast region modified from the MinView web site https://minview.geoscience.nsw.gov.au/. (b) Lower Shoalhaven River section (modified from Cooper, 1992). (c) Lower Ettrema Creek section (modified from Cooper, 1992). (d) Upper Ettrema Creek and Bundundah Creek sections (simplified from Figs 7 and 8). (e) Yadboro River section modified from Powell (1983, p. 33). (f) Bumbo Creek section simplified from Fig. 5. (g) Reedy Creek section simplified from Fig. 10. (h) Murrah State Forest section modified from Powell (1983, p. 34). Crosses indicate granodiorite. (i) Pambula River section simplified from Fig. 4.

with igneous activity in the Boyd Volcanic Complex. They provided an alternative explanation that these monoclinal folds had formed purely from horizontal shortening unrelated to deeper level faulting. Rixon et al. (1983) considered this consistent with indications of maximum compressive stress from vein and cleavage orientations, and thus indicative of horizontal shortening and possibly associated with décollements in the succession. Note that the suggestion of décollements within the succession was not supported by any field evidence and is unrelated to the proposition that a regional décollement underlies the entire Budawang synclinorium (Glen and Lewis, 1990).

The role of faulting associated with the Carboniferous deformation of the Merimbula and underlying Devonian volcanic units has been a problematic issue. The suggestion of major thrust tectonics presented by Glen and Lewis (1990) was not supported by Cooper (1992) and Dunstone and Young (2019). It should be apparent from the maps and cross-sections presented in this work, in particular the detailed traverse along Bumbo Creek (Fig. 5), that the Budawang Synclinorium is a synclinal zone with some areas containing uncommon high-angle to near-vertical reverse faults as in the Shoalhaven River, lower Ettrema Creek, Bumbo Creek and Reedy Creek. The map data presented herein (e.g. Figs 9 and 10) shows that where mapped, the basal eastern contact of the west-dipping Devonian succession is an unconformity with basal conglomerate overlying the Ordovician Adaminaby Group and not an east-dipping thrust as interpreted in the cross-sections in Glen and Lewis (1990). It should also be noted that the section line 3 (“Comerong Road”) in Glen and Lewis (1990), based on the widely scattered road cuts along the Comerang Road to the south of Bumbo Creek is broadly consistent to the structure portrayed by the more detailed mapping of the more widespread exposures in Bumbo Creek, apart from the stratigraphic interpretation and the resulting interpreted thrust faults.

Mapped faults are present along the western side of the southern Budawang Synclinorium (contra Dunstone and Young, 2019). In Bumbo Creek the steep topography and the mapped relationships indicate that this fault is steeply dipping but appears to die out southwards towards Comerang Road (Fig. 5). The basal conglomerate and part of the Adaminaby Group are repeated by this steeply dipping fault, but the steep dip indicates it is unlikely to be part of a “Jura-style” thin-skinned thrust complex as interpreted by Glen and Lewis (1990). Instead, it is interpreted as a deeper-seated “Laramide-type” structure as for the faults in the Shoalhaven River and lower Ettrema Creek sections (Cooper, 1992). Another possibility is that the steep dip of these faults reflects reworking of fault zones that formed during extension associated with the mid to Late Devonian volcanism during formation of the ECYVZ (e.g. Giordano and Cas, 2001). Block movements contemporaneous with deposition/igneous activity along a steep east-dipping fault bounding the Boyd Volcanic Complex were considered responsible for the angular unconformity on the western limb of the Box Range Syncline (Fig. 4; Fergusson et al., 1979). Farther north in the ECYVZ the volcanic succession is conformably overlain by the Merimbula Group (e.g. Yalwal and Danjera Creek area, Fig. 8; Comerang Mountain area, Fig. 9). Elsewhere in the Lachlan Orogen reverse faulting is associated with the western boundaries of synclines containing Upper Devonian successions (O’Halloran and Cas, 1995; Fergusson, 2017). An example being the Springdale Fault (80 km south-southwest of Forbes, Fig. 2), which a deep-seismic profile shows is a deep-seated reverse fault that shallows at depth (Glen et al., 2002; Fergusson, 2017).

The general pattern of shortening in the Kanimblan Orogeny in the Lachlan Orogen is that the intensity of deformation dies out gradually to the west and southwest (Powell, 1984; Fergusson, 2017). However, as shown by the variations in shortening along the South Coast, other factors must also influence the amount of shortening. These include the nature of the basement underlying the Upper Devonian sedimentary successions, basement-cover interaction, the thickness of the Upper Devonian succession and hence the likely depth of burial during the deformation. The generally low estimates of shortening for the Eden district (6-12%) was considered consistent with a shallow depth of burial (Rixon et al., 1983) given that the succession around Eden has a thickness of only 1370 m (Lewis et al., 1994) with no known overlying units prior to the Carboniferous deformation. Additionally, the variation in basement type also points to some control. For example, in the Chalkhills Creek cross-section basement is the Yurammie Granodiorite and shortening is only 6%, which is considerably less than the 12% for the Pambula River cross-section with a basement of the presumably less rigid Ordovician Adaminaby Group (Fig. 4). Elsewhere the Budawang Synclinorium generally has a basement of Ordovician Adaminaby Group and shows higher shortening than in the Eden district, although it is not clear why shortening would be higher in the southern Budawang Synclinorium than in the cross-sections west of Nowra.

It is difficult to generalize on the controls of shortening in these rocks as there are numerous potential variables. For example, shortening in the Murrah State Forest is 20% yet the basement in the western half of the cross-section is the Quaama Granodiorite and there is no obvious difference in shortening between this part of the cross-section and the eastern part where the Upper Devonian succession overlies the Ordovician Adaminaby Group. For plutonic basement, the thickness of the pluton will also be important, thinner sheet-like plutons will be more susceptible to map-scale folding than thicker sheets. In the Lachlan Orogen the thickness of most plutons is generally poorly known. One example is where a thin sheet-like shape (350 m thick) was determined for the Strathbogie batholith in central Victoria from field relationships (Phillips et al., 2022). Gravity surveys for plutons in the Bega batholith have indicated wedge to sheet shapes with thicknesses of 1 to 3 km (Richards and Collins, 1994) whereas elsewhere in the Lachlan Orogen geophysical data (gravity, seismic reflection profiles) indicate pluton thicknesses of 3 to 5 km or more (e.g. Cayley et al., 2011).

CONCLUSIONS

The early Carboniferous Kanimblan Orogeny has produced variations in shortening of 6 to 35% mainly produced by buckling, kink-like formation of angular monoclines and some reverse faulting of the Upper Devonian Merimbula Group in the NSW South Coast region. The structural style ranges from map-scale anticlines to synclines to sections with abundant upright, close to open, mesoscopic folds as well exposed in upper Ettrema Creek and parts of Bumbo Creek in the Budawang Synclinorium. Variations in the levels of shortening are difficult to explain but at least locally shortening seems to have been inhibited in areas with granitic basement to the Upper Devonian succession.

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