PROOF COVER SHEET

Author(s): J. R. Hunt and G. C. Young

Article title: Depositional environment, stratigraphy, structure and paleobiology of the Hatchery Creek Group (Early–?Middle Devonian) near Wee Jasper, New South Wales

Article no: TAJE_A_625447

Enclosures: 1) Query sheet
2) Article proofs

Dear Author,

1. Please check these proofs carefully. It is the responsibility of the corresponding author to check these and approve or amend them. A second proof is not normally provided. Taylor & Francis cannot be held responsible for uncorrected errors, even if introduced during the production process. Once your corrections have been added to the article, it will be considered ready for publication.

Please limit changes at this stage to the correction of errors. You should not make insignificant changes, improve prose style, add new material, or delete existing material at this stage. Making a large number of small, non-essential corrections can lead to errors being introduced. We therefore reserve the right not to make such corrections.

For detailed guidance on how to check your proofs, please see
<http://journalauthors.tandf.co.uk/production/checkingproofs.asp>.

2. Please review the table of contributors below and confirm that the first and last names are structured correctly and that the authors are listed in the correct order of contribution. This check is to ensure that your name will appear correctly online and when the article is indexed.

Sequence	Prefix	Given name(s)	Surname	Suffix
1		J. R.	Hunt	
2		G. C.	Young	

Queries are marked in the margins of the proofs.

AUTHOR QUERIES

General query: You have warranted that you have secured the necessary written permission from the appropriate copyright owner for the reproduction of any text, illustration, or other material in your article. (Please see <http://journalauthors.tandf.co.uk/preparation/permission.asp>.) Please check that any required acknowledgements have been included to reflect this.

- AQ1** Lindley (2002) does not appear to have been cited. Please check.
- AQ2** Please ensure that the figures are mentioned in strict ascending numerical order.
- AQ3** I have changed “ANU” to “Australian National University” for clarity – Please check.
- AQI** have added the remaining editors’ names in Harvey (2004) reference – Please check.
- AQ5** Miller reference – publisher name?
- AQ6** Nilsen reference – missing details?
- AQ7** “see for full details”? Please clarify and reword

How to make corrections to your proofs using Adobe Acrobat

Taylor & Francis now offer you a choice of options to help you make corrections to your proofs. Your PDF proof file has been enabled so that you can edit the proof directly using Adobe Acrobat. This is the simplest and best way for you to ensure that your corrections will be incorporated. If you wish to do this, please follow these instructions:

1. Save the file to your hard disk.

2. Check which version of Adobe Acrobat you have on your computer. You can do this by clicking on the “Help” tab, and then “About”.

If Adobe Reader is not installed, you can get the latest version free from <http://get.adobe.com/reader/>.

- If you have Adobe Reader 8 (or a later version), go to “Tools”/ “Comments & Markup”/ “Show Comments & Markup”.
- If you have Acrobat Professional 7, go to “Tools”/ “Commenting”/ “Show Commenting Toolbar”.

3. Click “Text Edits”. You can then select any text and delete it, replace it, or insert new text as you need to. It is also possible to highlight text and add a note or comment.

4. Make sure that you save the file when you close the document before uploading it to CATS using the “Upload File” button on the online correction form. A full list of the comments and edits you have made can be viewed by clicking on the “Comments” tab in the bottom left-hand corner of the PDF.

If you prefer, you can make your corrections using the CATS online correction form.

Depositional environment, stratigraphy, structure and paleobiology of the Hatchery Creek Group (Early–?Middle Devonian) near Wee Jasper, New South Wales

J. R. HUNT AND G. C. YOUNG*

Research School of Earth Sciences, The Australian National University, Canberra ACT 0200, Australia.

A revised depositional model of predominantly swampy rather than lacustrine conditions is proposed for the upper dark shales and mudstones (Corradigbee Formation) of the Hatchery Creek Group. The whole sequence is interpreted as a humid alluvial fan deposit, conformable on underlying limestones, with a total thickness of about 1800 m. Cyclic sedimentation probably resulted from climatic fluctuations much longer than seasonal events and may reflect Milankovitch cyclicity. The most recent Devonian time-scale calibrations indicate that much of the Hatchery Creek sequence could have been deposited during the Emsian, giving adequate time for subsequent folding during the Middle Devonian Tabberabberan episode. The Corradigbee Formation contains a unique fossil fish assemblage, not represented elsewhere in eastern Australia, but sharing features with Early Devonian faunas from Yunnan, China, and the Middle Devonian Aztec Siltstone fish fauna of Victoria Land, Antarctica. The first invertebrate fossils are recorded from the Hatchery Creek Group (freshwater gastropods, indeterminate arthropods). Abundant plant remains at some localities include lycopsids, some early leaf-like structures, and deep root systems preserved in paleosols, the earliest record of such features from Australia. The new data are inconsistent with Northern Hemisphere fossil evidence linked to a modelled dramatic drop in CO₂ levels and rise in O₂ during the Devonian Period, but comply with some other evidence that the first forests may have evolved somewhat earlier in East Gondwana than elsewhere.

KEY WORDS: Hatchery Creek Group, Emsian, humid alluvial fan, fish, freshwater gastropods, plants, root systems, paleosols, calcareous nodules.

INTRODUCTION

The Hatchery Creek Group (Hunt & Young 2010) is the uppermost part of a ~5 km-thick sedimentary sequence laid down largely during the Early Devonian in the Burrinjuck area of New South Wales (Young 2011). Previously named the 'Hatchery Creek Conglomerate,' the ~1800 m-thick sequence of non-marine strata forms an isolated outcrop of some 70 km² areal extent near Wee Jasper, about 50 km NW of Canberra (Figure 1). Most of its outcrop lies on the Brindabella 1:100 000 sheet (Owen & Wyborn 1979), with a small northern extension onto the Yass 1:100 000 sheet (Cramsie *et al.* 1978). A late Early Devonian (Emsian) maximum age limit for the base of the sequence is provided by an abundant invertebrate fauna in marine limestones of the underlying Murrumbidgee Group (Pedder *et al.* 1970). Within the Hatchery Creek sequence, numerous new fossil localities discovered in recent years have relevance to one of the major evolutionary events of the Devonian Period, namely terrestrialisation of the biota including the vertebrate transition onto land and the origin of the first forests, the latter considered 'nearly as important to the evolution of life and the atmosphere as the rise of microbial photosynthesis during the Archaean' (Berner 2005).

Originally, an assumed lithological similarity with the Hervey Group of central New South Wales led to the assessment that the 'Hatchery Creek Conglomerate' was Late Devonian in age, and separated by a disconformity or unconformity from the underlying limestones (Pedder 1967; Packham 1969; Pedder *et al.* 1970). However, a fossil fish assemblage described by Young & Gorter (1981) included forms such as the placoderm *Sherbonaspis hillsi* (Figure 4f), a close relative of the 'winged fish' first documented by Hugh Miller (1841) from classic Middle Devonian (Eifelian) Old Red Sandstone fish faunas of Scotland. This was the first discovery of such forms in the Southern Hemisphere. The Hatchery Creek fish locality was estimated at about 1900 m above the base of the sequence, suggesting that any disconformity with the underlying limestones was of short duration (Owen & Wyborn 1979; Young & Gorter 1981). The original mapping by Edgell (1949) had interpreted a conformable boundary between the Hatchery Creek sequence and the underlying limestones, and this is now supported by more recent work (Campbell & Barwick 1999; Hunt & Young 2010).

*Corresponding author: gavin.young@anu.edu.au

The lithological similarity between the 'Hatchery Creek Conglomerate' and the Hervey Group was based on the most accessible lower section, dominated by cycles of massive conglomerate and sandstone, but the fossil fish assemblage of Young & Gorter (1981) came from an upper finer sequence of siltstones and mudstones. Edgell (1949) identified this as a separate formation, and the recent stratigraphic revision by Hunt & Young (2010) separates this upper fine-grained sequence as the Corradigbee Formation, with the lower coarser sequence renamed the Wee Jasper Formation, both formations included within the Hatchery Creek Group (Figure 2).

A second fossil locality (plants), recorded on the geological map of Owen & Wyborn (1979), was investigated by Francis (2003), where fish were found in association. This locality (JF, Figure 1) is only slightly higher in the sequence than the original fish locality (WT, Figure 1), and in the same sedimentary cycle. A detailed field study of the Corradigbee Formation by Hunt (2005, 2008) produced numerous additional fossil localities. Fifteen fining-upward sedimentary cycles, comprising about 260 m of the Corradigbee Formation, were mapped on both sides of the axis of a broad syncline, a major structure not shown on the geological map of Owen & Wyborn (1979). As a result, their estimated thickness (2900+m for the entire sequence) is revised downward to about 1800 m (Hunt & Young 2010). The new results conform more closely with the first geological investigation (an unpublished honours thesis by Edgell 1949), rather than the published map of Owen & Wyborn (1979). The higher relief of the softer mudstone sequence in the central part of the outcrop has the effect of obscuring the syncline axis. This is a form of inverted topography resulting from relatively recent exhumation from beneath cover of Tertiary basalt, of which residual caps remain on the highest hills.

The revised stratigraphic thickness, sedimentation rates based on a new depositional interpretation as a humid alluvial fan, and new data on the fossil fish ages and isotopic calibrations of Devonian conodont zones, all now indicate that much (or all) of the Hatchery Creek Group could have been deposited during the Emsian stage of the Early Devonian. This has implications for the age of folding in the Burrinjuck area and gives added significance to the discovery of extensive plant remains including deep root systems in soil horizons within the Wee Jasper Formation, as documented and discussed below. Previously, modelling for past atmospheric CO₂ indicating very high levels in the Early–Middle Devonian has been linked to shallow root penetration and absence or only small leaves in the earlier forms of land plants, before a dramatic drop in atmospheric CO₂ to approach modern levels by the Late Devonian.

The data supporting these models derive almost entirely from the Northern Hemisphere, and evidence from Gondwana, the largest Paleozoic landmass, is poorly represented. The most dominant factor affecting atmospheric levels of both CO₂ and O₂ over the past 550 million years was the rise of vascular land plants, namely trees (Berner 2003, 2004), regarded as the primary cause of the steep increase in atmospheric O₂ between about 400 and 300 million years ago (Berner 2006; Berner *et al.* 2007).

The largest landmass (Gondwana) during the middle Paleozoic should be expected to contribute significantly to global data on final terrestrialisation of the biota. In this paper, we summarise new data on depositional environment, sedimentation rates, and faunal evidence for age of the Hatchery Creek Group, which was being deposited during this crucial time interval. The new age evidence has implications for age of folding in the Burrinjuck Devonian sequence. We illustrate some of the abundant new fossil plant remains recently discovered, and discuss new evidence from the Hatchery Creek Group relevant to atmospheric modelling based on Northern Hemisphere data. This is consistent with some other evidence (e.g. Retallack 1997) suggesting that forests may have evolved in Gondwana earlier than in the Northern Hemisphere. Full grid references and other geological data for 148 numbered localities are documented in the appendix of Hunt & Young (2010). All registered fossil material is housed in the ANU Palaeontological Collection, Canberra (Building 47, Research School of Earth Sciences).

DEPOSITIONAL ENVIRONMENT

Previously (Owen & Wyborn 1979; microfiche supplement, now converted to pdf), the lower part of the 'Hatchery Creek Conglomerate' was interpreted as a meandering stream deposit by with coarse basal beds probably indicating a high-energy environment and steep gradient. Extensive development of soil profiles suggested that areas were quiescent for long periods before later deposition, with well-developed vegetation extensively churning the sediments. The general red colour was taken to indicate a non-marine environment with deposition in desert-like climates with infrequent flooding (e.g. Van Houten 1973). However, Sheldon (2005) has suggested that red-coloured sediments in general do not indicate specific paleoclimatic conditions, the colour primarily being due to former good drainage.

The upward transition into finer-grained cycles was interpreted as a change to a lower-energy environment, with shallower gradient, and subdued relief in the source area (Owen & Wyborn 1979, M318). They interpreted grey to black sediments as short-lived episodes of

Figure 1 (a) Geological map showing the outcrop area of the Hatchery Creek Group near Wee Jasper, NSW, based on the Owen & Wyborn (1979) Brindabella 1:100 000 geological map. Detail is updated from Hunt & Young (2010, figures 1–3) to show stratigraphic type sections, with base of 16 fining upward cycles in the Hatchery Creek Group indicated by stippled/shaded lines running along strike. Fossil localities as discussed in the text are numbered as listed by Hunt & Young (2010, appendix). WT is the original fossil fish locality at 'Windy Top' described by Young & Gorter (1981). (b) Location of the Hatchery Creek Group outcrop (shaded area) in relation to Canberra (ACT), Yass (NSW), and Burrinjuck Dam.

Figure 2 Stratigraphic sections of the Hatchery Creek Group to show the two formations (a) and more detail of the upper Corradigbee Formation (b). Updated from Hunt & Young (2010, figures 2b, 3b).

Figure 3 Sedimentary structures observed in the Corradigbee Formation. (a) Rain drop impressions (white arrows) in red mudstone (locality 80). (b) Calcareous nodules (white arrows) aligned parallel to bedding (locality 128). (c) Details of three nodules from locality 128.

lacustrine deposition, on the evidence of lack of basal scour, minor basal conglomerates, and thick black mudstones representing quiet stages when no coarse material was deposited. Calcareous concretions indicated soil profile development on dried-out lake beds. On the evidence of unworn fish plates, unbroken plant remains and unworn quartz grains in the basal pebbly sandstones, Owen and Wyborn suggested little transport of bed load, the sediments therefore representing sheet deposition of the traction load in the earliest stages of decreasing high-energy flow. They envisaged the black mudstones to have been deposited from suspension during falling-flow stages, with periodic floods bringing in coarser material. The absence of ripples and sand laminae was attributed to highly weathered exposures. Shallow lakes of limited lateral extent could have resulted from wind ablation or by damming of shallow valleys by alluvium of tributary streams.

However, detailed fieldwork in the area of the present study (Figure 1b) has demonstrated the absence of laminar bedding in almost all outcrops of the grey-black mudstones. This is inconsistent with the lacustrine deposition model, and an alternative interpreta-

tion more consistent with the data is that the Hatchery Creek Group was deposited in a humid alluvial fan environment, similar to the modern alluvial fan of the Kosi River of northern India (Wells & Dorr 1987). Humid alluvial fans are large physiogeographic features in temperate and humid regions. Today they are widespread along the margins of several young mountain chains (e.g. Apennines, Alps, Himalayas), and exhibit evidence of meandering channels (Ori 1982), and a predominance of sandy sheet flood deposits, with pebble bearing material restricted to the proximal part of the fan (Kumar *et al.* 2004, p. 423). Nilsen (1985) described humid fans as deposited in streams of considerable magnitude, with the angle of alluvial fan surfaces rarely exceeding 10° , the main depositional agents being sheet floods, stream floods, and streams. The colour change from red beds of the Wee Jasper Formation up through red-purple mudstones and then predominant grey-black mudstones of the Corradigbee Formation indicates change from a well-drained system in the lower part, to swampy (rather than lacustrine) conditions in the Corradigbee Formation. This contrasts with some other Devonian alluvial fans documented in the literature, for example terminal fans in an arid environment described from Ireland (Sadler & Kelly 1993), or extensive lacustrine/fan delta deposits in the Middle Devonian Hornelen Basin of Norway (Pollard *et al.* 1982).

The lower Wee Jasper Formation shows characteristics of the apex of a fan system, the large beds of conglomerate forming extensive continuous beds presumably fed by a nearby mountain canyon system from a highland to the west, or perhaps northwest as suggested by decreasing grainsize along strike to the south in several cycles of the Wee Jasper Formation (Hunt & Young 2010). The sandstones, siltstones, and mudstones in the finer-grained Corradigbee Formation would represent a more distal part of the humid fan deposit, with erosion of the mountain front causing the fan apex to move further west from the site of deposition.

Within the Corradigbee Formation, resistant layers of uniform fine sandstone at the base of each cycle form extensive sheets traceable laterally over distances of 5+ km in the mapped area (Figure 1b; Hunt & Young 2010). These are interpreted as times when the fan system had vast flooding, with large movements of water to transport this coarser sediment, the fine sandstones deposited during flood events as sheet flows. Sheet flow rather than channel deposition is indicated by the lack of cross-bedding. Minor pebbly sandstones are evidence of small creeks that flowed down onto the plain. Thinner sandstones within cycles, interpreted as smaller flooding events, were observed to pinch out along strike. The alternating colour of the mudstones could indicate climatic or seasonal change, but alternatively may result from burial gleisation—the chemical reduction of iron oxides by anaerobic bacteria consuming organic matter, which can occur within a few thousand years of burial (Retallack 1991, 2001). Isolated occurrences of laminar bedding indicate very localised lake deposits, probably ephemeral as might be expected in a deltaic alluvial flat environment. The

Figure 4 Examples of new fossil fish discoveries in the Corradigbee Formation. (a) Prepared right lower jaw of an osteolepid lobe-finned fish (ANU V3133); inner (lingual) view showing tooth rows, fangs, and fossa for the adductor jaw muscle. (b) Body portion (articulated scales) of an osteolepid lobe-finned fish (latex cast of ANU V3228). (c) Tooth of an onychodontid lobe-finned fish from locality 134 (ANU V3523). (d) Denticulated lower tooth-plate of a phlyctaeniid arthrodire (ANU V3193) from locality 59. (e) Nuchal plate from the skull of an arthrodire placoderm close to *Coccoosteus* Miller, 1841 from the Old Red Sandstone of Europe (ANU V3365). (f) Prepared fronto-ethmoidal shield of an osteolepid lobe-finned fish (ANU V3339); ventral view showing the palate including the denticulate parasphenoid bone. (g) Posterior median dorsal plate of the placoderm fish *Sherbonaspis hillsi* (Young & Gorter 1981) (ANU V3197, right lateral view). (h) Reconstruction (left lateral view) of the placoderm *Sherbonaspis hillsi* (Young & Gorter 1981), which first established a pre-Late Devonian (?Eifelian) age for the Hatchery Creek sequence.

fossil plant material, abundant at certain levels in the formation, indicates a good vegetation cover adjacent to the sites of deposition.

Extensive paleosol development is indicated by calcareous nodule horizons in most of the cycles of the Corradigbee Formation (Figures 2b, 3b, c). These have not yet been studied in detail, but have the potential to provide important data on paleoclimate of East Gondwana for this crucial part of the geological column (Retallack 2001, 2005). Calcareous paleosols in the Aztec Siltstone of Victoria Land, Antarctica (McPherson 1979) include the 'Rosemary Paleosol' (Retallack *et al.* 1997), which has provided evidence for the oldest known soils to form in a forest environment (Retallack 1997). In a detailed analysis within the Devonian Catskill Formation, Retallack *et al.* (2009) used depth to carbonate nodule horizons

in paleosols and other parameters to suggest alternating subhumid and semiarid paleosol development linked to Milankovich 100 ka eccentricity periods. Retallack & Huang (2011) have used detailed studies of paleosol sequences to gain insights into the ecology and evolution of Devonian trees in New York ('Gilboa Forest'; Middle Devonian). There is good potential to apply a similar analysis to the Hatchery Creek sequence.

CYCLICITY AND RATES OF SEDIMENTATION

The basal sandstone layers in the Corradigbee Formation indicate repeated events initiating each cycle, and a strong cyclicity is also evident on a larger scale right to the base of the Hatchery Creek Group (and indeed into

Figure 5 Examples of fossil plants and invertebrates from the Corradigbee Formation. (a, b) Branched plant stems (ANU 46690, 691) from locality 062. (c) Enlargement of ANU 46691 showing preserved surface detail of plant stem. (d) Lycopsid plant stem from sandstone at locality 65 in Cycle G (ANU 60769). (e) Unidentified gastropod from locality 062 (ANU 46688). (f) Leaf-like structures showing a median vein (from locality 77). (g) Example of abundant plant stems at the same locality.

the underlying Murrumbidgee Group, with shale/limestone interbeds alternating with more massive limestones as constituent members of the Taemas Limestone).

Two important factors influencing alluvial sedimentation over geological time-scales are tectonism and climate. Tectonism was previously the preferred explanation for cycles and megacycles in sedimentary sequences, because such regularity in climatic fluctuations was considered unlikely. However, studies of modern fluvial systems suggest rather that climate and hydrology have been more significant deciding factors in determining stratigraphic form (Kelly & Sadler 1995, p. 20). The transition to non-marine sedimentation at the

base of the Hatchery Creek Group could be attributed to a global drop in sea-level (the 'Hatchery Creek regression' of Talent 1989). However, coarse basal clastics indicate proximity to a mountain front in a tectonically active setting, which would have masked the effect of any latest Emsian transgression, as indicated on the Euramerican sea-level curve (Johnson *et al.* 1996; Young 1996, p. 108; Mawson & Talent 2000).

Kelly & Sadler (1995) noted research in several Devonian continental basins suggesting that regular fluctuations in climate, perhaps related to orbital forcing, were probably more significant than previously assumed. Kelly (1992) had attributed smaller-scale (36, 55 m) and larger-scale (130 m) sedimentary cycles in the

Figure 6 Deep rooting structures of plants observed in the Wee Jasper Formation. (a) Root system at least 1.4 m deep in a fire trail cutting through a paleosol within Unit 3 at locality GR648604 6122399, Wee Jasper 1:25 000 topographic map 8627-4N (2nd edition). (b) detail of a root cast in an isolated block from near the same locality (see open squares, Figure 1a).

Late Devonian Munster Basin of southwest Ireland to 100 ka and 412 ka Milankovitch cycles respectively, with somewhat lesser thicknesses in the largely lacustrine Orcadian Basin (8, 40 m sedimentary cycles) attributed to 21 ka and 100 ka Milankovitch cycles. Marshall *et al.* (2007) have discussed the 80–90 lacustrine cycles in the Middle Devonian Stromness Group (Orkney) of the Orcadian Basin, indicating an alternation between wet

and dry conditions interpreted as 100 ka eccentricity cycles (the Eifelian–Givetian boundary estimated at 10–20 cycles below the top of the group). The cycles increase in average thickness from 5.25 m in the lower part to 12 m in the upper part (total thickness nearly 600 m). Marshall *et al.* (2007, p. 145) noted this interpretation was consistent with an Eifelian duration of 6–7 Ma, but not with the 4 Ma recently proposed by Kaufmann (2006). In contrast, in the condensed marine sequence of the Barrandian Basin, Chlupáč (2000) recorded bedding couplets or ‘bundles’ 30–50 cm thick with 250–380 cycles for the ‘Dalejan’ (approximates to the upper Emsian) with a total thickness of less than 200 m.

For the Devonian Munster Basin, Kelly & Sadler (1995) noted that a reliable time-scale to estimate sedimentation rates would greatly assist in separating out tectonic, climatic and other factors. Tertiary fluvial sedimentation rates in the Andean and Himalayan foreland basins calibrated by magnetostratigraphy have indicated that climate and hydrology were more important than tectonism, and the response of alluvial fan geometry and sedimentary style to these factors is a focus of recent research (Harvey 2004; Harvey *et al.* 2005; Quigley *et al.* 2007).

For non-marine basins in various tectonic settings, sedimentation rate (averaged over 10^6 years) has been estimated to vary between 0.1 and 0.6 mm/year (Miall 1978). Kelly & Sadler (1995) used available Devonian time-scale calibrations to estimate an average sedimentation rate of 0.4 mm/year for the Upper Devonian Munster Basin, giving about 50 000 years for a 20 m-thick cycle to accumulate. Since then, research integrating numerical dates with the Devonian conodont zonation have greatly improved precision in some parts of the Devonian time-scale, although the early Emsian–mid Eifelian is still relatively poorly constrained (Kaufmann 2006). Kaufmann placed the Emsian–Eifelian boundary at 392–391 Ma (about 397 Ma on the time-scale of House & Gradstein 2004), with a 408 Ma calibration for the lower Emsian, giving the Emsian the longest duration of any Devonian stage (17.2 Ma), with the *serotinus* zone perhaps lasting 5.5 Ma. Less reliable is the Middle Devonian duration, estimated at only about 8.2 Ma (cf. 15 Ma in Young 1996), which would require much greater sedimentation rates than the ranges mentioned above for some basins (e.g. 25+ km attributed to the Middle Devonian in the Hornelen Basin; Pollard *et al.* 1982).

For the Hatchery Creek sequence, sedimentation rates would be expected to decrease from the proximal to distal parts of the fan. Owen & Wyborn (1979, p M314–320) described numerous fining-upward cycles through the lower part of the Wee Jasper Formation (Hunt & Young 2010). Thickness variation between 1 and 20 m was assumed to depend on how much of the upper layers had been eroded by the overlying cycle. These coarser 20 m cycles would represent shorter durations than those in the Corradigbee Formation. A total thickness of 1800 m would represent 90×20 m cycles, and thus 4.5 Ma duration using an average sedimentation rate of 0.4 mm/year (Kelly & Sadler 1995). However, this estimate may not be appropriate, because the Munster Basin is interpreted as a terminal fan system deposited

in a semiarid environment (Sadler & Kelly 1993), with a higher sedimentation rate compared with the humid fan interpretation for the Hatchery Creek sequence. Calibration by magnetostratigraphy of an 1800 m section in a Miocene humid fan system of the Himalayan Foreland Basin (Kumar *et al.* 2004, figure 3) gives a somewhat lower average sedimentation rate (0.335 mm/year), and 60 000 years as the average time to accumulate a 20 m cycle. This gives about 5.4 Ma to accumulate the 1800 m of the Hatchery Creek sequence, which is less than Kaufmann's (2006) calibrated duration just for the *serotinus* conodont zone (Figure 7). Thus, the entire thickness of the Hatchery Creek Group could have been deposited during the Emsian on these estimates, and new faunal evidence from the Corradigbee Formation is consistent with this (see next section).

FOSSIL FAUNA

Edgell (1949) recorded a supposed 'orbiculoid brachiopod shell' as the first fossil found in the Hatchery Creek

Group, but this was later determined as a placoderm fish plate (Hills 1958) and was assigned to the antiarch *Sherbonaspis hillsi* by Young & Gorter (1981). Fish remains are the most common fossils, and have been found at many localities within Cycles C' through to I (Figure 2), mainly preserved in the mudstones, and more rarely in sandstone (observed only at the JF and WT localities *in situ*). Most remains are disarticulated, with good examples coming from localities 91 and 134 (cycles H and F respectively). However, they are excellently preserved, so any reworking (e.g. from nearby dried-out pools or billabongs) must have been minimal. At three localities (JF, 81, 120, Figure 1b), articulated placoderm armours, and an incomplete portion of articulated osteolepidid squamation (ANU V3228), were found in the mudstone, indicating a low energy environment, and probably rapid burial.

The fish fauna from the numerous new localities in the Corradigbee Formation now includes 16 named or identified taxa (see Table 1), but this is a minimum number since most of the new material has not been studied in detail. Since the original description, when

Figure 7 (a) Stages of the Devonian Period, with isotopic calibration (Ma) and conodont zonation (CZ) from Kaufmann (2006). Arrows on the left side summarise East Gondwana evidence from the Hatchery Creek Group discussed in the text: (i) deep root systems in the Wee Jasper Formation; (ii) leaf-like structures in the Corradigbee Formation. Arrows on the right side summarise the Laurussian (Euramerican) fossil record (N.Hemisph.) as discussed in the text for shallow plant roots (iii), first evidence of forests and deep root systems (iv), and true leaves associated with the spread of archaeopterid trees (v). Abbreviations for rock units in the Burrinjuck Devonian sequence (oldest to youngest) are: MCV, Mountain Creek Volcanics; KF, Kirawin Formation; MG, Murrumbidgee Group; HCG, Hatchery Creek Group. Conodont zones (CZ) as abbreviated are (oldest to youngest): *sulcatus*, *kindlei*, *pireneae* (Pragian), *kitabicus*, *dehiscens*, *gronbergi*, *nothoperbonus*, *inversus*, *serotinus*, *patulus* (Emsian), *partitus*, *costatus*, *kockelianus* (Eifelian). (b–c) Segments of Paleozoic atmospheric concentration curves for CO₂ and O₂ (after Berner 2006, figures 18–19; see for full details), with the Devonian Period indicated [DEV.], through which a dramatic drawdown of CO₂ (b) and corresponding increase of O₂ (c) is indicated.

Table 1 Faunal list for the Corradigbee Formation of the Hatchery Creek Group.**INVERTEBRATES****Arthropoda**

1. Indet. ?arthropod

Gastropoda

2. Indet. gastropod

VERTEBRATES**Agnatha****Thelodontida**3. *Turinia* sp. cf. *T. hutkensis* Blieck & Goujet (Young & Gorter 1981)**Gnathostomata****Acanthodii**4. *climatiid* gen. et sp. indet.5. ?*diplocanthiform* gen. et sp. indet.6. *Tareyacanthus* sp. cf. *T. magnificus* Valiukevicius (Burrow 2002)7. *Watsonacanthus*? sp. (Burrow 2002)**Osteichthyes (Sarcopterygii)**8. cf. *Kenichthys* [= '*Gyroptychius*' *australis* Young & Gorter 1981]9. *osteolepiform* gen. et sp. nov. 2 (Hunt 2008)10. *osteolepiform* gen. et sp. nov. 3 (Hunt 2008)11. ?*onychodontid* indet. (Hunt 2008)**Placodermi****Arthrodira incertae sedis**12. *Edgellaspis gorteri* Hunt & Young 2011**Arthrodira**13. *Denisonosteus weejasperensis* Young & Gorter 198114. cf. *Denisonosteus* sp. nov. (Hunt 2005)15. *coccosteomorph* cf. *Coccosteus* (Hunt 2008)**Antiarchi**16. *Sherbonaspis hillsi* Young & Gorter 198117. cf. *Sherbonaspis* sp. nov. (Hunt 2005)18. *Monarolepis verrucosa* (Young & Gorter) Young 1988

eight different fish were identified (Young & Gorter 1981, p. 87), Young (1988) reassigned the *Bothriolepis* species to the new genus *Monarolepis*, Burrow (2002, figure 20, p. 102) assigned acanthodian scales to two genera *Tareyacanthus* and *Watsonacanthus*, and Hunt (2005) identified a new actinolepid arthrodire, and possible second species of the arthrodire *Denisonosteus* and the antiarch *Sherbonaspis*. Hunt (2008) interpreted the osteolepiform material to comprise three taxa (genera), the originally described *Gyroptychius*? *australis* being close to the Chinese form *Kenichthys*. New osteolepid specimens illustrated here include a skull and lower jaw (Figure 4a, f), and the incomplete portion of articulated body scales (Figure 4b). Teeth 10–20 mm long (ANU V3509, 3523) from localities 120, 134 (Cycles I, F) may belong to an onychodontiform lobe-finned fish (Figure 4c). A denticulated toothplate from locality 59 (Figure 4d) belongs to a phlyctaeniid arthrodire like *Denisonosteus*. In addition, a coccosteid arthrodire very similar to the type *Coccosteus* from the Scottish Middle Devonian (Figure 4e), is represented by two nuchal plates and a possible suborbital (ANU V3365–67) from locality 138 (Cycle E). The antiarch *Sherbonaspis* (Figure 4g, h) is represented at numerous sites, many of which have also yielded thelodont agnathan scales (assigned to the early Eifelian *costatus* conodont zone by Turner 1997).

Bioturbation at various levels was recorded by Edgell (1949), Young (1969) and Owen & Wyborn (1979). Francis (2003, figure 27) illustrated trace fossils (ANU 49355) from the vicinity of Windy Top near the boundary between the two formations of the Hatchery Creek Group (Unit 4e, Wee Jasper Formation; open squares, Figure 1a). Here we report and illustrate the first invertebrate body fossils from the Hatchery Creek Group (Figure 5e). Numerous small gastropods (~2 mm across, a few larger, to 5 mm) were found in a bed of grey shale with plant remains at locality 062 (Figure 4e), in Cycle C'. They resemble an example figured by Landrum (1975, plate 32, figure 9) from the Early Devonian of the Darling Basin, western NSW, and among Middle Devonian (Eifelian) marine gastropods described from southeastern Alaska there are similarities in shape to *Euryzone* sp. of Blodgett *et al.* (2001, plate 1, figure 2). None of the marine gastropods described by Tassell (1982) from the underlying Murrumbidgee Group are similar, nor those (also marine) described from the Middle Devonian of Queensland by Cook (1997) and Cook & Camilleri (1997). From the associated abundant plant remains, and complete absence of any typical marine Devonian invertebrates throughout the Hatchery Creek Group, it is assumed that these new gastropods lived in freshwater, an are thus much earlier than the 'oldest freshwater snail' previously claimed from Australia (Cretaceous), as described by Keer *et al.* (2003).

Probable arthropod remains (ANU 60766–67) were collected from locality 91 (Cycle H), the same locality that has produced bones of a *Sherbonaspis*-like antiarch possessing median dorsal plates with dorsal spines (ANU V3200–3202). *Monarolepis* was also found at this locality, where both fish and arthropod remains were oriented perpendicular to the bedding. Some of the oldest known terrestrial arthropods from Gondwana occur in the Taemas area beneath the Murrumbidgee Group limestones (Edgecombe 1998).

Based on a very preliminary study, a faunal change might be present within the Corradigbee Formation, with the placoderm *Edgellaspis* and gastropods restricted to the lower part (Cycle C'), and the coccosteid arthrodire, spined antiarchs, and arthropod remains occurring only in the higher horizons (Cycles F–I). The distribution of all fossil material (plant, fish, arthropod, gastropod) through the Corradigbee Formation (in 11 of the 15 cycles) was summarised by Hunt & Young (2010, appendix).

AGE AND CORRELATION

Young & Gorter (1981, p. 89) gave three specific arguments supporting an Eifelian age for the Hatchery Creek fish assemblage: (1) Eifelian age for *Turinia hutkensis* in the Kush-Yulagh fauna of Iran; (2) Eifelian age for the oldest *Bothriolepis* species in China; (3) primitive features in the new species *Bothriolepis verrucosa*. They noted that this would mean very rapid sedimentation, of the same order as that recorded as a maximum for this part of the geological column (almost 4000 m for the Middle Devonian of East Greenland).

Taking the latter into account, a late Eifelian age was considered more likely. On that basis, Macrovertebrate Zone 3 (Hatchery Creek/??Cravens Peak fauna) was shown spanning the late Emsian–Eifelian boundary in the Australian macrovertebrate biozonation of Young (1996) and Young & Turner (2000), the next youngest non-marine assemblage being the Aztec fish fauna of Antarctica.

Subsequent research, and the new data presented here, now indicate that the Hatchery Creek fish assemblage may be older than previously thought. For recent updates on the Devonian micro- and macrovertebrate assemblages from East Gondwana see Burrow *et al.* (2010) and Young *et al.* (2010). There is now a revised older age for the Kush-Yulagh fauna of Iran indicated by an overlying Emsian conodont assemblage (Lelièvre *et al.* 1993, p. 165). In China, the earliest *Bothriolepis* occurrence is also now revised to Emsian (Zhu 2000), and close similarities have been noted between the Hatchery Creek osteolepid material and Chinese forms including *Kenichthys* (Chang & Zhu 1993; Chang & Yu 1997), which also comes from the Emsian (Zhu 2000). Of new additions to the fish fauna, the enigmatic placoderm *Edgellaspis* compares with various placoderms from the Early Devonian of China (Hunt & Young 2011). A possible second species of the asterolepid antiarch *Sherbonaspis* has a median dorsal spine like the well-known *Byssacanthus* from the Givetian of the Northern Hemisphere (Karatajūtė-Talimaa 1960). However, Otto (1999) described a similar spined antiarch from the Eifelian Brandenburg Group of the German Rhineland, so on available evidence there is no age significance to this new antiarch species. The arthrodire *Coccosteus* is a classic component of the Middle Devonian lacustrine deposits of Scotland, and the new examples from the Corradigbee Formation closely resemble the corresponding plates in *C. cuspidatus* in being shorter than broad, with the straight anterior margin seen in small individuals (Miles & Westoll 1968, figure 4). However, older small coccosteids are now recorded from the Eifelian of Germany, some plates of which have very similar ornament to our new material (Otto 1998, figure 6), and also in the Emsian of north Gondwana (e.g. Iran, Blicek *et al.* 1980), although nuchal plates have not been described from either region. Otto (1997) suggested an Eifelian first appearance for coccosteids in Scotland, Germany and the Baltic sequence. In summary, all new data for the Hatchery Creek fish assemblage are consistent with an Emsian–Eifelian age or show a close affinity with Emsian or older taxa in China and Iran.

As discussed by Young (2004, pp. 47–48), reassessment of some of the original conodont determinations of Pedder *et al.* (1970) from their highest productive samples in the underlying Murrumbidgee Group indicates a *serotinus* zone age (perhaps low in this zone; Basden 2001) for uppermost limestone horizons at Wee Jasper. This places the conformable base of the Hatchery Creek Group also in the late Emsian (*serotinus*–*patulus* conodont zones; Figure 7). Thus, the assumption that the base of the ‘Hatchery Creek Conglomerate’ must be Eifelian (Hood & Durney 2002, p. 293) is not supported by the fossil evidence. The Emsian–Eifelian is the least

well-constrained part of the Devonian time-scale (Kaufmann 2006), but current data indicate that the Emsian may be the longest stage (17.2 Ma; cf. 15.5 Ma in Young 1996), and the *serotinus* zone the longest conodont zone (5.5 Ma; cf. 4.5 Ma in Young 1996). As noted above, sedimentation rates do not preclude most or all of the Hatchery Creek Group being deposited during the Emsian.

TECTONIC SETTING AND AGE OF FOLDING

The Hatchery Creek Group forms part of the Goodradigbee Structural Block in the Gilgandra–Cowra–Yass Structural zone of the Lachlan Fold Belt (Scheibner & Basden 1998; Hood & Durney 2002). Owen & Wyborn (1979, pp. 14–16) tentatively assigned an interpreted disconformity at the base of the ‘Hatchery Creek Conglomerate’ to the Tabberabberan folding episode, this being the only evidence for it in the mapped area. Conglomerate deposition was attributed to uplift outside the mapped area, which they suggested must have occurred earlier than elsewhere, in the late Early Devonian. Deformation of the entire Devonian sequence was attributed to the Carboniferous Kanimblan fold episode in the absence of contrary evidence, but Owen & Wyborn noted the possibility that it could have been much older (Tabberabberan).

Hood & Durney (2002, p. 293) commented that the ‘structural relationship between the Taemas limestone and the Hatchery Creek Conglomerate is important when considering the age of the deformation in this area.’ Although the fossil fish assemblage documented by Young & Gorter (1981) indicated a probable Eifelian age and little if any time break at the base, the earlier assumption of a Late Devonian age persisted in some papers considering the structural framework on a regional scale. Thus, both Powell (1984) and Scheibner & Basden (1998) still included the ‘Hatchery Creek Conglomerate’ with the Hervey, Catombal, Cocoparra and Merimbula Groups within the general term ‘Lambie Facies.’ Under that interpretation, the limestone folding in the Taemas Synclinorium could be attributed to the Middle Devonian Tabberabberan event, as suggested earlier by Browne (1959). Hood & Durney (2002) reported on a detailed structural analysis in the area around Taemas Bridge and concluded there was no evidence for a Middle Devonian convergent or fold-forming deformation event, but only ‘mild topographic uplift’ to cause the change from marine to fluvial sedimentation at the base of the Hatchery Creek sequence. Their four proposed convergent folding events (D₁–D₄) were attributed to Carboniferous (Kanimblan) deformation, including the earliest (D₁), on the critical age evidence for the ‘Hatchery Creek Conglomerate.’

Hood & Durney (2002, p. 306) dismissed a theoretically possible Late Devonian age for their D₁ (i.e. after deposition of the Hatchery Creek Conglomerate and before deposition of the Hervey Group) on the absence of any evidence of discordance within the Upper Devonian succession. However, Young (2006a, p. 611) reported fossil fish evidence for an angular unconformity within the Hervey Group above the main Tabberabberan

hiatus on the Narromine 1:250 000 sheet in central NSW, as already documented for equivalent strata in Victoria (e.g. VandenBerg *et al.* 2000). Our conclusion that most or all of Hatchery Creek deposition could have taken place in the Emsian (see above) would give time for later deformation in the Middle Devonian, including one or more of the deformation events that Hood & Durney (2002) attributed to the Kanimblan folding episode.

In summary, the very coarse lithologies in the lower part of the Hatchery Creek sequence indicate significant tectonic activity, masking a latest Emsian marine transgression on the global sea-level curve for the Devonian. In addition, lithological differences are inconsistent with an interpretation that the Hatchery Creek Conglomerate was 'a short-term incursion of the fluvial facies of the Mulga Downs Group' as suggested by Packham (2003, p. 829; see also Branagan & Packham 2000, p.18). Our new evidence does not contribute to the question of whether the Middle Devonian 'Tabberabberan' episode involved only uplift, or uplift and folding, a point debated by Packham (2003) and Hood & Durney (2002). However, it is noted that some sections in central NSW are clearly continuous between volcanics and sediments of Middle Devonian age, and Upper Devonian Hervey Group (e.g. the Merriganowry Shale Member of the Dulladerry Volcanics on the Bathurst 1:250 000 sheet; see Young 1999; Young *et al.* 2000).

FOSSIL FLORA

Evidence of abundant plant remains at certain levels in the Hatchery Creek Group was recorded many decades ago, but was not widely known. Edgell (1949) first noted numerous poorly preserved and indeterminate plant stems, including plant material ('wood') suggesting vascular land plants. Owen & Wyborn (1979), in their microfiche supplement, noted root casts, extensive bioturbation and rare wood tissue in the red siltstones at the top of the conglomeratic cycles within the Wee Jasper Formation. Owen & Wyborn (1979, p. M317) recorded the upper dark grey to black mudstones to contain plant remains described as 'vascular plants ... stems up to 10 cm long and possible leaf impressions.' Francis (2003, figure 24) illustrated possible lycopod impressions from near Unit 4b of the Wee Jasper Formation (ANU 49351; GR482 202) and branching stems (Francis 2003, figure 26; ANU 49356) from slightly higher (Unit 4e) at about GR4815 2005 (both along the Windy Top Trail type section of the Wee Jasper Formation; see Hunt & Young 2010; open squares, Figure 1a).

The lowest plant horizon in the Corradigbee Formation observed during the fieldwork for this study was in Cycle B', and the highest in Cycle J (Figure 2). Plant material was found in both sandstone and mudstone lithologies, and can be grouped into four general types, as illustrated in Figure 5. ANU 60769 from the basal sandstone of Cycle G at locality 65, and similar material from locality 139 (basal sandstone of Cycle F) shows leaf scar patterns indicative of lycopsids (lycopods), well known from the Upper Devonian of eastern Australia (e.g. *Leptophloeum australe*; White 1986). Some of the oldest known lycopods (*Baragwanathia*) come from the

Silurian and Early Devonian of Victoria (for discussion of their anomalous early age see Rickards 2000; Gensel 2008). The closely spaced leaf scars in our material (Figure 5d) is reminiscent of the form earlier called '*Protolapidodendron*' from the Middle Devonian (e.g. White 1986, figure 90), also recorded from black shales of the Bunga Beds on the New South Wales south coast (Young 2007). Our illustrated example is the largest from locality 65, and shorter pieces are also common in the sandstone at locality 139.

Other plant material was found in mudstones of the following cycles (locality numbers in parentheses): Cycle A (77), B (159), D (74, 106), E (60, 61, 63), F (3, 138), H (17, 121, 150), I (96), and J (86). Small stems, so far found only at locality 63, exhibit unequal (pseudomonopodial) branching to form a main stem or axis as occurs in the 'trimerophytes' known from similar-aged rocks elsewhere (e.g. Kasper & Andrews 1972). The largest branched specimen measures 30 mm in length (Figure 5a, b). The stems show small hair-like striations and a diamond-shaped pattern, which seems regular and therefore part of the plant structure, although possibly an artefact of preservation (Figure 5c). One example (Figure 5b) shows three branches in different planes. No fruiting bodies have been found, which are required for proper determination of such material (B. Meyer-Berthaud, pers. comm. 2005). There are some superficial similarities to *Zosterophyllum* from South China illustrated by Hao *et al.* (2007), but these are considerably older, and this genus has not been recorded from rocks younger than early Emsian according to Edwards *et al.* (2000), whereas generally similar material from the Middle Devonian is referred to *Psilophyton* and related taxa (B. Meyer-Berthaud, pers. comm. 2005).

A third plant type is the most common, occurring in all the other mudstone localities listed above. They are flat strap-like ribbons with longitudinal veins (Figure 5g), 10–20 mm wide, and some up to 30 cm long. Of interest are some pointed leaf-like examples observed at locality 156 with a dark central line (?median vein Figure 5f), perhaps a nematophyte like *Mosellophyton* from Germany (Schaarschmidt 1974; G. Retallack, pers. comm. 2011). The fourth plant type comprises impressions of straight unbranching stems, occasionally preserved as three-dimensional pencil-like segments, generally less than 10 mm diameter and up to 30 cm long, with 8–10 coarse longitudinal ribs along their surface. They occur with the ribbon-like 'leaves' at several localities, and could be stems of the same plant.

In addition to the abundant plant remains of the Corradigbee Formation, there is also evidence of well-established vegetation from the underlying Wee Jasper Formation. Poorly preserved plant remains found by Francis (2003) were mentioned above. Root casts and rare wood tissue in paleosols were noted in the original Brindabella 100K sheet mapping by Owen & Wyborn (1979), but these fine-grained upper parts of the conglomerate cycles are generally very poorly exposed on the western escarpment of the Wee Jasper valley owing to cover of conglomerate scree. At that time there was only one relatively well exposed section through the lower part of the Hatchery Creek Group (Owen &

Wyborn's designated type section up the Cave Creek Road; see Figure 1). New exposures were examined in road cuttings for a fire trail installed during the 2003 bushfires in the area, and provide significant new evidence of the Devonian vegetation cover for this part of the sequence. One of the best examples of an *in situ* deep root system with a penetration depth of at least 1.4 m was observed within Unit 3 of the Wee Jasper Formation and is shown in Figure 6a. Numerous root traces observed in siltstone float (Figure 6b) at this and other localities indicate extensive development of such features in the fine-grained upper parts of the conglomerate cycles, the lowest occurrence observed so far being in the upper part of Unit 1 (open squares, Figure 1a). These are remarkably old examples of deep rooting structures in the fossil record, the significance of which is discussed in the next section.

In summary, the evidence from both formations of the Hatchery Creek Group indicates a well-established terrestrial vegetation in this part of East Gondwana already by late Emsian–Eifelian time.

PALEOBIOLOGY

Terrestrialisation, from a human perspective at least, was one of the most significant transformations in the history of the Earth's biota. A low land vegetation supporting an already diverse terrestrial fauna was in place by the Early Devonian, at a time of very high atmospheric CO₂ (reconstructed in excess of ten times modern levels; Figure 7b). With the establishment of arborescent vascular plants (the first forests) in the Middle Devonian, the land surface for the first time showed a resemblance to that of today. Deposition of the Hatchery Creek sequence was taking place during that crucial transformation, so it is worth noting that we have recorded the oldest Devonian paleosols and deep root systems, perhaps the oldest leaves, and the oldest freshwater snails known so far from the Australian geological record.

Various papers have discussed the relationship between terrestrialisation of the flora, increased chemical weathering in vegetated soils, and atmospheric changes in CO₂ and O₂ during the Devonian. Earliest roots in the fossil record (Early Devonian) are 3 mm diameter and up to 30 mm long, and shallow dichotomous branching roots 90 cm long are known from the Emsian (Elick *et al.* 1998; Raven & Edwards 2001). Soil penetration remained shallow (less than 20 cm depth) during the Middle Devonian, and only deepened to 80–100 cm with the spread of archaeopterid trees in the Late Devonian (Algeo & Scheckler 1998). Recently Mintz *et al.* (2010) have documented slightly older 1 m deep root systems in the Appalachian basin (USA). However, Retallack (1997) had already reported stout root traces (up to 11 mm diameter) penetrating 1.5 m into paleosols in the Aztec Siltstone of Antarctica that he interpreted as the oldest known forest soils. As noted above the Aztec fish fauna is slightly younger than the Hatchery Creek fish assemblage, but they share some unique characteristics (e.g. co-occurrence of turiniid thelodonts and early bothriolepid antiarchs), faunal associations

not seen outside East Gondwana (e.g. Young 1989). The fact that we can now document similar, but slightly older, deep rooting structures in the Hatchery Creek Group is thus not surprising. Retallack & Huang (2011) have recently discussed the size of Devonian trees, suggesting that large plants co-evolved earlier in more humid climates, for example in the Emsian–Eifelian of Germany and Spitzbergen, and thus in the same age range as our new occurrences.

Most reconstructions of Paleozoic atmospheric composition show very high CO₂ levels at the start of the Devonian Period (~4000 ppmv), associated with high tropical air temperatures, before a dramatic drop in CO₂ during the Late Devonian (e.g. Osborne *et al.* 2004, figure 1), when large (megaphyll) leaves first become common in the fossil record (end of the Devonian and Early Carboniferous). Regarding the evolution of leaves, Beerling *et al.* (2001) proposed that in the Early Devonian the very high atmospheric CO₂ would have been inimical to megaphyll leaves, which only became viable as CO₂ fell to approach modern levels in the Late Devonian–Early Carboniferous. Environmental barriers to leaf evolution involving evaporative and convective cooling, leaf size and density of stomata might explain an enigmatic delay of some 40 Ma after the earliest vascular plants are recorded (Osborne *et al.* 2004). However, the fact that true leaves are demonstrated in some Early Devonian plants from Yunnan, China (Hao & Gensel 1995; Hao *et al.* 2003) has been a significant anomaly for this hypothesis.

The same modelling indicates a steep increase in atmospheric O₂ between about 400 and 300 million years ago (Berner 2006; Berner *et al.* 2007). The COPSE model (Bergman *et al.* 2004) has this as a steady increase (see Figure 7b), but the GEOCARBSULF model (Berner 2006) showed a large drop after a latest Silurian peak, to a minimum level in the early Frasnian (early Late Devonian). Although several papers attempted to link significant evolutionary events to these low Middle Devonian oxygen levels (e.g. Berner *et al.* 2007; Clack 2007; Clement & Long 2010), it should be noted that the data have subsequently been restored to former estimates by Berner (2009). Retallack & Huang (2011) have also suggested transient paleoclimatic perturbations and migration events as possible factors to explain a 40 Ma gap between the late Emsian trees of Spitzbergen and the Famennian CO₂ drawdown.

Atmospheric composition is a global phenomenon, but most of the data for determining this for the Paleozoic come from the Northern Hemisphere, with the largest landmass of the time (Gondwana) under-represented. Hao & Gensel (1998) noted significant floral similarities between South China and Australia during the Early–Middle Devonian, and various specific Chinese affinities in the fish fauna from the Corradigbee Formation were noted above. This is part of a well-documented vertebrate faunal affinity between East Gondwana and South China (a data set completely independent from paleobotany), the faunal resemblance becoming increasingly strong from the latter part of the Early Devonian (e.g. Young 1988, 2003; Young & Janvier 1999; Young & Goujet 2003). The much earlier evidence of leaves from the Early Devonian of China compared

with the Late Devonian of Laurussia, considered an unexplained anomaly of the fossil record in the above papers linking atmospheric change and leaf evolution, has clear parallels in the significant discrepancies in the biostratigraphic range for many Devonian fish taxa between Southern and Northern Hemispheres (e.g. Young 2003, 2005, 2006b, 2008, 2010, figure 7). There is now a strong body of evidence for a major biotic interchange between Gondwana and the Northern Hemisphere paleoblocks making up the Old Red Sandstone continent (Laurussia), so there is a good case for factoring in a biogeographic explanation to the consideration of feedback loops between the rise of vascular plants, evolution of the first forests, and major changes in atmospheric composition during the Devonian Period. These issues will be addressed in a detailed study of the paleosols, deep root casts and vascular plant remains noted above to occur in the Hatchery Creek Group.

CONCLUSIONS AND SUMMARY

The cycles identified in the Hatchery Creek Group represent climatic fluctuations on a much longer scale than seasonal events, and are attributed to Milankovitch cycles.

The Corradigbee Formation contains a unique fossil fish assemblage, not represented elsewhere in eastern Australia, but sharing features with Early Devonian faunas from Yunnan, China, and the Middle Devonian Aztec Siltstone fish fauna of Victoria Land, Antarctica.

The most recent calibrations for the Devonian time-scale indicate that most or all of the Hatchery Creek Group could have been deposited during the Emsian, giving adequate time for subsequent folding during the Middle Devonian Tabberabberan episode.

The first invertebrate fossils (freshwater gastropods, indeterminate arthropods) are recorded, and abundant plant remains at some localities include lycopsids, some early leaf-like structures and deep root systems preserved in paleosols, the earliest record of such features from Australia.

ACKNOWLEDGEMENTS

For permission to conduct fieldwork on their properties, and providing access, we thank Ian and Helen Cathles of Cookmundoon (Wee Jasper), and Chris Barber and Neil Blasford (Corradigbee). Access to the area for the 1969 field mapping was facilitated by Dudley and Graham Barber. For assistance in 2003–2008 fieldwork, we thank B. Opdyke, K. S. W. Campbell, I. Cathles, C. Klootwijk, R. Hunt and L. Bean. Dr B. Opdyke (ANU) first proposed the humid alluvial fan interpretation, and Drs Brigitte Meyer-Berthaud (Montpellier), Elizabeth Truswell (ANU) and Greg Retallack (Oregon) gave advice on fossil plant material. The late Professor Stewart Edgell (died 13 April 2010) gave much helpful advice and provided a copy of his thesis and 1949 geological map. Professor Ken Campbell provided guidance and knowledge on numerous occasions and, with Dr Brad Opdyke, gave detailed comments reviewing an earlier version of

the manuscript. Val Elder (ANU) assisted in specimen curation; B. Young helped with photography (ANU V3505); and we thank Xiong Cuihua for superb mechanical preparation of osteolepid specimens (ANU V3338, ANU V3133) at the Institute of Vertebrate Palaeontology & Palaeoanthropology, Beijing, and Professor M. Zhu and Ms Lu Jing for facilitating this, and providing images during preparation. We also thank the following for general advice on structural (M. Rickard, S. Cox) and stratigraphic geology (K. Crook, A. Felton, D. Strusz), and G. Retallack for a very helpful review which greatly improved the manuscript. This research was supported by ARC Discovery Grant DP0558499, and a contribution to IGCP Project 491. Provision of facilities at ANU in the Frank Fenner Building, College of Science, and D. A. Brown Building, Research School of Earth Sciences, is gratefully acknowledged.

REFERENCES

- ALGEO T. J. & SCHECKLER S. E. 1998. Terrestrial–marine teleconnections in the Devonian: links between the evolution of land plants, weathering processes, and marine anoxic events. *Philosophical Transactions of the Royal Society of London B* **353**, 113–130.
- BASDEN A. M. 2001. *Early Devonian fish faunas of eastern Australia, documentation and correlation*. PhD thesis, Macquarie University (unpublished), 349 pp., 63 figs.
- BEERLING D. J., OSBORNE C. P. & CHALONER W. G. 2001. Evolution of leaf-form in land plants linked to atmospheric CO₂ decline in the Late Palaeozoic era. *Nature* **410**, 352–354.
- BERGMAN N. M., LENTON T. M. & WATSON A. J. 2004. COPSE: A new model of biogeochemical cycling over Phanerozoic time. *American Journal of Science* **304**, 397–437.
- BERNER R. A. 2003. The rise of trees and their effects on Paleozoic atmospheric CO₂ and O₂. *Comptes Rendus Geoscience* **335**, 1173–1177.
- BERNER R. A. 2004. *The Phanerozoic carbon cycle: CO₂ and O₂*. Oxford University Press, Oxford, 150 pp.
- BERNER R. A. 2005. A different look at biogeochemistry. *American Journal of Science* **305**, 872–873.
- BERNER R. A. 2006. GEOCARBSULF: A combined model for Phanerozoic atmospheric O₂ and CO₂. *Geochimica et Cosmochimica Acta* **70**, 5653–5664.
- BERNER R. A. 2009. Phanerozoic atmospheric oxygen: new results using the Geocarbsulf model. *American Journal of Science* **309**, 603–606.
- BERNER R. A., VANDENBROOKS J. M. & WARD P. D. 2007. Oxygen and evolution. *Science* **316**, 557–558.
- BLIECK A., GOLSHANI F., GOUJET D., HAMDI A., JANVIER P., MARK-KURIK E. & MARTIN M. 1980. A new vertebrate locality in the Eifelian of the Khush-Yeilagh Formation, Eastern Alborz, Iran. *Palaeovertebrata* **9**, 133–154.
- BLODGETT R. B., ROHR D. M., KARL S. M. & BAICTAL J. F. 2001. Early Middle Devonian (Eifelian) Gastropods from the Wadleigh Limestone in the Alexander Terrane of Southeastern Alaska Demonstrate Biogeographic Affinities with Central Alaskan Terranes (Farwell and Livengood and Eurasia. *US Geological Survey Professional Paper*, pp. 105–110.
- BRANAGAN D. F. & PACKHAM G. H. 2000. *Field geology of New South Wales*. Department of Mineral Resources, New South Wales, Sydney, Australia.
- BROWNE I. 1959. Stratigraphy and structure of the Devonian rocks of the Taemas and Cavan areas, Murrumbidgee River, south of Yass, N.S.W. *Journal of the Royal Society of New South Wales* **92**, 115–128.
- BURROW C. 2002. Lower Devonian acanthodian faunas and biostratigraphy of south-eastern Australia. *Memoirs of the Association of Australasian Palaeontologists* **27**, 75–137.
- BURROW C. J., TURNER S. & YOUNG G. C. 2010. Middle Palaeozoic microvertebrate assemblages and biogeography of East Gondwana (Australasia, Antarctica). *Palaeoworld* **19**, 37–54.

- CAMPBELL K. S. W. & BARWICK R. E. 1999. A new species of the Devonian lungfish *Dipnorhynchus* from Wee Jasper, New South Wales. *Records of the Australian Museum* **51**(2), 123–140.
- CHANG M.-M. & YU X. 1997. Reexamination of the relationship of Middle Devonian osteolepids—fossil characters and their interpretations. *American Museum Novitates* **3189**, 1–20.
- CHANG M.-M. & ZHU M. 1993. A new osteolepidid from the Middle Devonian of Qujing, Yunnan. *Memoirs of the Association of Australasian Palaeontologists* **15**, 183–198.
- CHLUPÁČ I. 2000. Cyclicity and duration of Lower Devonian stages: observations from the Barrandian area, Czech Republic. *Nues Jahrbuch für Geologie und Paläontologie. Abhandlungen* **215**, 97–124.
- CLACK J. A. 2007. Devonian climate change, breathing, and the origin of the tetrapod stem group. *Integrative and Comparative Biology* **47**, 510–523.
- CLEMENT A. M. & LONG J. A. 2010. Air-breathing adaptation in a marine Devonian lungfish. *Biology Letters* **6**, 509–512.
- COOK A. G. 1997. Gastropods from the Burdekin Formation, Middle Devonian, north Queensland. *Memoirs of the Queensland Museum* **42**, 37–49.
- COOK A. G. & CAMILLERI N. 1997. Middle Devonian gastropods from the Broken River Province, north Queensland. *Memoirs of the Queensland Museum* **42**, 56–79.
- CRAMSIE J. N. POGSON D. J. & BAKER C. J. 1978. *Geology of the Yass 1:100 000 sheet 8628*. Geological Survey of New South Wales.
- EDGEcombe G. D. 1998. Devonian terrestrial arthropods from Gondwana. *Nature* **394**, 172–174.
- EDGEll H. S. 1949. *The geology of the Burrinjuck-Wee Jasper District*. BSc (Hons) thesis, University of Sydney, 75 pp.
- EDWARDS D. FAIRON-DEMARET M. & BERRY C. M. 2000. Plant megafossils in Devonian stratigraphy: a progress report. *Courier Forschungsinstitut Senckenberg* **220**, 25–37.
- ELICK J. M., DRIESE S. G. & MORA C. I. 1998. Very large plant and root traces from the Early to Middle Devonian: implications for early terrestrial ecosystems and atmospheric (CO₂). *Geology* **26**, 143–146.
- FRANCIS J. 2003. *Depositional environment, palaeontology and taphonomy of the Hatchery Creek Formation*, NSW. BSc (Hons) thesis, Australian National University, 59 pp.
- GENSEL P. G. 2008. The earliest land plants. *Annual Review of Ecology, Evolution and Systematics* **39**, 459–477.
- HAO S. G. & GENSEL P. G. 1995. A new genus and species, *Celatheca beekii*, from the Siegenian (Early Devonian) of southeastern Yunnan, China. *International Journal of Plant Science* **156**, 896–909.
- HAO S. G. & GENSEL P. G. 1998. Some new plant finds from the Posongchong Formation of Yunnan, and consideration of the phytogeographic similarity between South China and Australia during the Early Devonian. *Science China (SD)* **41**, 1–13.
- HAO S. G., BECK C. B. & WANG D. M. 2003. Structure of the earliest leaves: adaptations to high concentrations of atmospheric CO₂. *International Journal of Plant Science* **164**, 71–75.
- HAO S. G., XUE Z. J., LIU Z. F. & WANG D. M. 2007. *Zosterophyllum penhallow* around the Silurian–Devonian boundary of North-eastern Yunnan, China. *International Journal of Plant Science* **168**, 477–489.
- HARVEY A. M. 2004. The response of dry-region alluvial fans to Quaternary climate change. In: Alsharhan A., Wood, W. W., Goudie, A. S., Fowler, A. & Abdellat, E. M. eds. *Desertification in the third millennium*, pp. 83–98. Balkema, Rotterdam.
- HARVEY A. M., MATHER A. E. & STOKES M. 2005. Alluvial fans; geomorphology, sedimentology, dynamics—introduction, a review of alluvial-fan research. *Geological Society Special Publication* **251**, 1–7.
- HILLS E. S. 1958. A brief review of Australian fossil vertebrates. In: Westoll T. S. ed. *Studies on fossil vertebrates*, pp. 86–107. Athlone Press, London.
- 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.
- HOUSE M. R. & GRADSTEIN F. M. 2004. The Devonian Period. In: Gradstein F. M., Ogg J. G. & Smith A. G. eds. *A geologic time scale 2004*, pp. 202–221. Cambridge University Press, Cambridge.
- HUNT J. 2005. *An examination of stratigraphy and vertebrate fish fauna of the Middle Devonian age from the Hatchery Creek Formation, Wee Jasper, New South Wales, Australia*. Dept Earth & Marine Sciences, Australian National University, BSc (Hons) thesis (unpublished).
- HUNT J. 2008. *Revision of osteolepiform sarcopterygians (lobe-finned fishes) from the Middle Devonian Hatchery Creek fish assemblage, Wee Jasper, Australia*. Research School of Earth Sciences, Australian National University, MSc thesis (unpublished), 109 pp.
- HUNT J. R. & YOUNG G. C. 2010. Stratigraphic revision of the Hatchery Creek sequence (Early–Middle Devonian) near Wee Jasper, New South Wales. *Proceedings of Linnean Society of New South Wales* **131**, 73–92.
- HUNT J. R. & YOUNG G. C. 2011. A new placoderm fish of uncertain affinity from the Early–Middle Devonian Hatchery Creek succession at Wee Jasper, New South Wales. *Alcheringa* **35**, 53–75.
- JOHNSON J. G., KLAPPER G. & ELRICK M. 1996. Devonian transgressive-regressive cycles and biostratigraphy, Northern Antelope Range, Nevada: establishment of reference horizons for Global Cycles. *Palaios* **11**, 3–14.
- KARATAJŪTĖ-TALIMAA V. 1960. *Byssacanthus dilatatus* (Eichw.) from the Middle Devonian of the U.S.S.R. *Collectanea Acta Geologica Lithuanica* (1960), 293–305.
- KASPER A. E. & ANDREWS H. N. 1972. *Pertica*, a new genus of Devonian plants from northern Maine. *American Journal of Botany* **59**, 897–911.
- KAUFMANN B. 2006. Calibrating the Devonian Time Scale: a synthesis of U–Pb ID-TIMS ages and quantified conodont stratigraphy. *Earth Science Reviews* **76**, 175–190.
- KEER B. P., HAMILTON-BRUCE R. J., SMITH B. K. & GOWLETT-HOLMES K. L. 2003. Reassessment of Australia's oldest freshwater snail, *Viviparus* (?) *albiscopularis* Etheridge, 1902 (Mollusca: Gastropoda: Viviparidae) from the Lower Cretaceous (Aptian, Wallumbilla Formation) of White Cliffs, New South Wales. *Molluscan Research* **2003**, 23, 149–158.
- KELLY S. B. 1992. Milankovitch cyclicity recorded from Devonian non-marine sediments. *Terra Nova* **4**, 678–684.
- KELLY S. B. & SADLER S. P. 1995. Equilibrium and response to climatic and tectonic forcing: a study of alluvial sequences in the Devonian Munster Basin, Ireland. In: House M. R. & Gale A. eds. *Orbital forcing timescales and cyclostratigraphy*. *Geological Society Special Publication* **85**, 19–36.
- KUMAR R., SANGODE S. J. & GHOSH S. K. 2004. RA multistory sandstone complex in the Himalayan Foreland Basin, NW Himalaya, India. *Journal of Asian Earth Sciences* **23**, 407–426.
- LANDRUM R. S. 1975. *Silurian and Devonian of the Cobar Basin, N.S.W.* PhD thesis (unpublished), Australian National University, Canberra, 262 pp., 42 pl.
- LELIEVRE H., JANVIER P. & BLIECK A. 1993. Siluro-Devonian vertebrate biostratigraphy of western Gondwana and related terranes (South America, Africa, Armorica-Bohemia, Middle East). In: Long J. A. ed. *Palaeozoic vertebrate biostratigraphy and biogeography*, pp. 139–173. Belhaven Press, London.
- LINDLEY I. D. 2002. Acanthodian, onychodontid and osteolepidid fish from the middle-upper Taemas Limestone (Early Devonian), Lake Burrinjuck, New South Wales. *Alcheringa* **26**, 103–126.
- MARSHALL J. E. A., ASTIN T. R., BROWN J. F., MARK-KURIK E. & LAZAUSKIENE J. 2007. Recognizing the Kačák Event in the Devonian terrestrial environment and its implications for understanding land–sea interactions. In: Becker R. T. & Kirchgasser W. T. eds. *Devonian events and correlations*. Geological Society, London, Special Publications, **278**, 133–155.
- MAWSON R. & TALENT J. A. 2000. The Devonian of eastern Australia: stratigraphic alignments, stage and series boundaries, and the transgression-regression pattern re-considered. *Courier Forschungsinstitut Senckenberg* **225**, 243–270.
- MCPHERSON J. G. 1979. Calcrete (caliche) palaeosols in fluvial redbeds of the Aztec Siltstone (Upper Devonian), southern Victoria Land, Antarctica. *Sedimentary Geology* **22**, 267–285.
- MIALL A. D. 1978. Tectonic setting and syndepositional deformation of molasses and other nonmarine-paralic sedimentary basins. *Canadian Journal of Earth Sciences* **15**, 1613–1632.
- MILES R. S. & WESTOLL T. S. 1968. The placoderm fish *Coccosteus cuspidatus* Miller ex Agassiz from the Middle Old Red Sandstone of Scotland. Part I. Descriptive morphology. *Transactions of the Royal Society of Edinburgh* **67**, 373–476.

- 1885 (5) MILLER H. 1841. *The Old Red Sandstone*. First edition. Edinburgh.
- MINTZ J. S., DRIESE S. G. & WHITE J. D. 2010. Environmental and ecological variability of Middle Devonian (Givetian) forests in Appalachian basin paleosols, New York, United States. *Palaïos*, **25**, 85–96.
- 1890 NILSEN T. 1985. Modern and ancient alluvial fan deposits. Van Nostrand Reinhold Company. *Benchmark papers in Geology*. Vol. **87**.
- (6) ORI G. G. 1982. Braided to meandering channel patterns in humid-region alluvial fan deposits, River Reno, Po Plain (northern Italy). *Sedimentary Geology* **31**, 231–248.
- 1895 OSBORNE C. P., BEERLING D. J., LOMAX B. H. & CHALONER W. G. 2004. Biophysical constraints on the origin of leaves inferred from the fossil record. *Proceedings of the National Academy of Science* **101**, 10360–10362.
- OTTO M. 1997. Vertebrate fossils of the Middle Devonian (Eifelian) Muhlenberg Formation in the Bergisches Land, northwestern Germany. *Paläontologische Zeitschrift* **71**, 107–116.
- 1900 OTTO M. 1998. New finds of vertebrates in the Middle Devonian Brandenburg Group (Sauerland, Northwest Germany). *Paläontologische Zeitschrift* **72**, 117–134.
- OTTO M. 1999. Antiarchi-Funde aus der Brandenburg-Gruppe (Mitteldevon, Eifelium) des nördlichen Sauerlandes. *Mainzer geowissenschaften Mitteilungen* **28**, 41–62.
- 1905 OWEN M. & WYBORN D. 1979. Geology and Geochemistry of the Tantangara and Brindabella area. *Bureau of Mineral Resources, Australia, Bulletin* **204**.
- PACKHAM G. H. 1969. The Geology of New South Wales. *Journal of the Geological Society of Australia* **16**, 1–654.
- 1910 PACKHAM G. H. 2003. Discussion and Reply, Sequence and Kinematics of multiple deformation around Taemas Bridge, Eastern Lachlan Fold Belt, New South Wales. *Australian Journal of Earth Sciences* **50**, 827–833.
- PEDDER A. G. H. 1967. Devonian rocks of the Murrumbidgee River area, New South Wales, Australia. In: Oswald D. H. ed. *International symposium of the Devonian system* **2**, 143–146.
- 1915 PEDDER A. G. H., JACKSON J. H., & PHILIP G. M. 1970. Lower Devonian biostratigraphy of the Wee Jasper region, New South Wales. *Journal of Paleontology* **44**, 206–251.
- POLLARD J. E., STEEL R. J. & UNERSRUD E. 1982. Facies sequences and Trace Fossils in Lacustrine/Fan Delta Deposits, Hornelen Basin (M. Devonian) Western Norway. *Sedimentary Geology* **32**, 63–87.
- 1920 POWELL C. McA. 1984. Late Devonian to Early Carboniferous: continental magmatic arc along the eastern edge of the Lachlan Fold Belt. In: Veevers J. J. ed. *Phanerozoic Earth history of Australia*. pp. 329–334. Clarendon Press, Oxford.
- QUIGLEY M. C., SANDIFORD M. & CUPPER M. L. 2007. Distinguishing tectonic from climatic controls on range-front sedimentation. *Basin Research* **19**, 491–505.
- 1925 RAVEN J. A. & EDWARDS D. 2001. Roots: evolutionary origins and biogeochemical significance. *Journal of Experimental Botany* **52**, 381–401.
- RETALLACK G. J. 1991. Untangling the effects of burial alteration and ancient soil formation. *Annual Review of Earth and Planetary Sciences* **19**, 183–206.
- 1930 RETALLACK G. J. 1997. Early forest soils and their role in Devonian global change. *Science* **276**, 583–585.
- RETALLACK G. J. 2001. *Soils of the past: an introduction to paleopedology*, 2nd edition. Blackwell, Oxford, 600 pp.
- 1935 RETALLACK G. J. 2005. Pedogenic carbonate proxies for amount and seasonality of precipitation in paleosols. *Geology* **33**, 333–336.
- RETALLACK G. J. & HUANG C. M. 2011. Ecology and evolution of Devonian trees in New York, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology* **299**, 110–128.
- 1940 RETALLACK G. J., HUNT R. R. & WHITE T. E. 2009. Late Devonian tetrapod habitats indicated by palaeosols in Pennsylvania. *Geological Society of London Journal* **166**, 1143–1156.
- RETALLACK G. J., ROBINSON S. E. & KRULL E. S. 1997. Middle Devonian paleosols and vegetation of the Lashly Mountains, Antarctica. *Antarctic Journal* **30**, 62–65.
- 1945 RICKARDS R. B. 2000. The age of the earliest club mosses: the Silurian *Baragwanathia* flora in Victoria, Australia. *Geological Magazine* **137**, 207–209.
- SADLER S. P. & KELLY S. B. 1993. Fluvial processes and cyclicity in terminal fan deposits: an example from the Late Devonian of southwest Ireland. *Sedimentary Geology* **85**, 375–386.
- SCHAARSCHMIDT F. 1974. *Mosellophyton hefteri* n.g. n.sp. (?Psilophyta), ein sukkulenter Halophyt aus dem Unterdevon von Alken an der Mosel. *Palaeontologische Zeitschrift* **48**, 188–204.
- 1950 SCHEIBNER E. & BASDEN H. eds. 1998. Geology of New South Wales Synthesis Volume 1: Structural Framework. Volume 2: Geological Evolution. Department of Mineral Resources. *Geological Survey of New South Wales Memoir Geology* **13**.
- SHELDON N. D. 2005. Do red beds indicate paleoclimatic conditions? A Permian case study. *Palaeogeography, Palaeoclimatology, Palaeoecology* **228**, 305–319.
- 1955 TALENT J. A. 1989. Transgression-regression pattern for the Silurian and Devonian of Australia. In: R. W. Le Maitre ed. *Pathways in geology. Essays in honour of Edwin Sherbon Hills*, pp. 201–219. Blackwell Scientific Publications, Melbourne, ix + 463 pp.
- 1960 TASSELL C. B. 1982. Gastropods from the Early Devonian 'Receptaculites' Limestone, Taemas, New South Wales. *Records of the Queen Victoria Museum (Launceston)* **77**, 1–59.
- TURNER S. 1997. Sequence of Devonian thelodont scale assemblages in East Gondwana. *Geological Society of America Special Paper* **321**, 295–315.
- 1965 VANDENBERG A. H. M., WILLMAN C. E., MAHER S., SIMONS B. A., CAYLEY R. A., TAYLOR D. H., MORAND V. J., MOORE D. H. & RADOJKOVIC, A. 2000. *The Tasman Fold Belt System in Victoria*. Geological Survey of Victoria Special Publication, 462 pp.
- VAN HOUTEN F. B. 1973. Origin of Red Beds A review—1916–1972. *Annual Review of Earth and Planetary Sciences* **1**, 39–61.
- 1970 WELLS N. A. & DORR J. A. Jr. 1987. Shifting of the Kosi River, northern India. *Geology* **15**, 204–207.
- WHITE M. E. 1986. *The greening of Gondwana*. Reed Books, Sydney.
- YOUNG G. C. 1969. *Geology of the Burrinjuck-Wee Jasper area*, N.S.W. BSc (Hons) thesis, Australian National University, 115 pp., 21 pls.
- (3) YOUNG G. C. 1988. Antiarchs (placoderm fishes) from the Devonian Aztec Siltstone, southern Victoria Land, Antarctica. *Palaeontographica* **202A**, 1–125.
- YOUNG G. C. 1989. The Aztec fish fauna of southern Victoria Land—evolutionary and biogeographic significance. In: Crame J. A., ed. *Origins and evolution of the Antarctic biota*. Geological Society of London Special Publication **47**, 43–62.
- 1980 YOUNG G. C. 1996. Devonian (chart 4). In: Young G. C. & Laurie J. R. eds. *An Australian Phanerozoic timescale*, pp. 96–109. Oxford University Press, Melbourne.
- YOUNG G. C. 1999. Preliminary report on the biostratigraphy of new placoderm discoveries in the Hervey Group (Upper Devonian) of central New South Wales. *Records of the Western Australian Museum, Supplement* **57**, 139–150.
- 1985 YOUNG G. C. 2003. North Gondwanan mid-Palaeozoic connections with Euramerica and Asia: Devonian vertebrate evidence. *Courier Forschungsinstitut Senckenberg* **242**, 169–185.
- YOUNG G. C. 2004. A Devonian brachyothoracid arthrodire skull (placoderm fish) from the Broken River area, Queensland. *Proceedings of the Linnean Society of New South Wales* **125**, 43–56.
- 1990 YOUNG G. C. 2005. An articulated phyllolepid fish (Placodermi) from the Devonian of central Australia: implications for non-marine connections with the Old Red Sandstone continent. *Geological Magazine* **142**, 173–186.
- 1995 YOUNG G. C. 2006a. Devonian fish remains, biostratigraphy and unconformities, Narramine 1:250 000 sheet area, central New South Wales (Lachlan Fold Belt). *Australian Journal of Earth Sciences* **53**, 605–615.
- YOUNG G. C. 2006b. Biostratigraphic and biogeographic context for tetrapod origins during the Devonian: Australian evidence. In: Reed L., Bourne S., Megirian D., Prideaux G., Young G. & Wright, A. eds. *Proceedings of CAVEPS 2005. Alcheringa (Special Issue 1) Supplement to Volume* **30**, 409–428.
- 2000 YOUNG G. C. 2007. Devonian formations, vertebrate faunas, and age control on the far south coast of New South Wales and adjacent Victoria. *Australian Journal of Earth Sciences* **54**, 991–1008.
- 2005 YOUNG G. C. 2008. Relationships of tristichopterids (osteolepiform lobe-finned fishes) from the Middle–Late Devonian of East Gondwana. *Alcheringa* **32**, 321–336.
- YOUNG G. C. 2010. Placoderms (armored fish): dominant vertebrates of the Devonian Period. *Annual Review of Earth and Planetary Sciences* **38**, 523–550.
- 2010

YOUNG G. C. 2011. Wee Jasper-Lake Burrinjuck fossil fish sites: scientific background to National Heritage Nomination. *Proceedings of Linnean Society of New South Wales* **132**, 83–107.

YOUNG G. C. & GORTER J. D. 1981. A new fish fauna of Middle Devonian age from the Taemas/Wee Jasper region of New South Wales. *Bureau of Mineral Resources Geology & Geophysics, Bulletin* **209**, 83–147.

YOUNG G. C. & GOUJET D. 2003. Devonian fish remains from the Dulcie Sandstone and Cravens Peak Beds, Georgina Basin, central Australia. *Records of the Western Australian Museum, Supplement* **65**, 1–85.

YOUNG G. C. & JANVIER P. 1999. Early–middle Palaeozoic vertebrate faunas in relation to Gondwana dispersion and Asian accretion. In: Metcalfe I., Ren J. S., Charvet J., Hada S. eds. *Gondwana dispersion and Asian accretion*. IGCP 321 Final Results Volume. A. A. Balkema, Rotterdam, pp. 115–140.

YOUNG G. C. & TURNER S. 2000. Devonian microvertebrates and marine-nonmarine correlation in East Gondwana: Overview. *Courier Forschungsinstitut Senckenberg* **223**, 453–470.

YOUNG G. C., BURROW C., LONG J. A., TURNER S. & CHOO B. 2010. Devonian macrovertebrate assemblages and biogeography of East Gondwana (Australasia, Antarctica). *Palaeoworld* **19**, 55–74.

YOUNG G. C., SHERWIN L. & RAYMOND O. L. 2000. Hervey Group. In: Lyons P., Raymond O. L. & Duggan M. B. eds. *Forbes 1:250 000 geological sheet S155-7*, 2nd edition, explanatory notes, pp. 125–149. *AGSO Record* **2000/20**, xviii + 230 pp.

ZHU M. 2000. Catalogue of Devonian vertebrates in China, with notes on bio-events. *Courier Forschungsinstitut Senckenberg* **223**, 373–390.

Received 11 April 2011; accepted 16 September 2011

2015

2020

2025

2030

2035

2040

2045

2050

2055

2060

2065

2070

2075

2080

2085

2090

2095

2100

2105

2110

2115

2120

2125

2130

2135