A new Early Devonian spinose phacopid trilobite from Limekilns, New South Wales: morphology, affinities, taphonomy and palaeoenvironment

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Abstract
Paciphacops (Paciphacops) crawfordae n.sp. is a distinctive spinose phacopid trilobite of late Pragian (Early Devonian) age from the deepwater, dysaerobic Rosedale Shale, Limekilns district, New South Wales. It is characterised by short occipital, genal and intergenal spines on the cephalon, and short thoracic spines on the axial rings and pleurae. Various combinations of such spines are developed in P. (Paciphacops) serratus Foerste (Lochkovian, New South Wales; Ludlovian, Kazakhstan?) and P. (Paciphacops) claviger Haas (Siegenian, Nevada), but the three species cannot be shown to be related.

Keywords
GeoQuest

Disciplines
Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

This journal article is available at Research Online: http://ro.uow.edu.au/smhpapers/1847
ABSTRACT. Paciphacops (Paciphacops) crawfordae n.sp. is a distinctive spinose phacopid trilobite of late Pragian (Early Devonian) age from the deepwater, dysaerobic Rosedale Shale, Limekilns district, New South Wales. It is characterised by short occipital, genal and intergenal spines on the cephalon, and short thoracic spines on the axial rings and pleurae. Various combinations of such spines are developed in P. (Paciphacops) serratus Foerste (Lochkovian, New South Wales; Ludlovian, Kazakhstan?) and P. (Paciphacops) claviger Haas (Siegenian, Nevada), but the three species cannot be shown to be related.

In 1969, Elizabeth Crawford collected shelly fossils from temporary exposures of shales belonging to the Rosedale Shale in the Limekilns district, near Bathurst, New South Wales (Fig. 1). This collection included the eight known specimens of the new trilobite species which is the focus of this paper.

Setting and Stratigraphy

The stratigraphic succession in the Limekilns district (Table 1), where the Devonian strata between the Merrions Tuff and the Winburn Tuff (Table 1) have been assigned to the Limekilns Group by Packham (1968), was first mapped and studied by the late L.V. Hawkins (1953). The stratigraphic terminology was established by Packham (1968) and the age of the succession was discussed by Wright & Chatterton (1988). The area lies just inside the eastern margin of the Hill End Trough of Packham (1968), as indicated by the deepwater sedimentary rocks of the Limekilns sequence.

Devonian fossils occur in three units in the sequence, as summarised by Wright & Chatterton (1988, Table 1). The lowest fossils (?late Lochkovian; Wright &
Fig. 1. Map showing the trilobite locality in relation to limestones of the Diamond Creek and Fernbrook belts and Merrions Tuff as mapped by Stone (1973); base after Bathurst 1:100,000 topographic map 8831 (1st edition, 1975).
fragments; benthic faunas, mostly brachiopods (notanopiids being possibly epipelagic) with some corals, rare bivalves and trilobites, also occur. Strusz (1972) reported *Monograptus yukonensis* (identified by G.H. Packham) from this formation, and inferred a Pragian age.

As stratigraphic control within the poorly exposed Limekilns Group is poor, the relative position and relative age of the trilobite-bearing horizon in the Fernbrook belt and the Jesse Limestone (the source of all the conodont data at hand) in the Diamond Creek belt cannot be established on the basis of mapping. Further, there is the possible need to amend the stratigraphic terminology for the Limekilns district, so that the predominantly shaly sequence (currently termed the Limekilns Group) could be relegated to formation status (Limekilns Formation), containing unnamed limestone olistoliths.

Several palaeontological lines of evidence indicate a late Pragian age for the Rosedale Shale trilobites from the Fernbrook belt: 1) If the trilobites from the Rosedale Shale are at about the *Monograptus yukonensis* level, this would indicate a late Pragian age for the trilobites, according to Lenz (1987, 1988). The occurrence of *M. yukonensis* in the early Zlichovian (see Wright & Chatterton, 1988 after Jaeger, 1979) is thus not yet agreed; 2) Most important of all, tenaculitids occurring with the trilobites have been determined by one of us (W.H.) as *Nowakia acuaria*, the well-known Pragian index fossil (e.g. Liitke, 1979); 3) Garratt & Wright (1988) reported the conodont *Polygnathus cf. dehiscens* from basal beds of the Jesse Limestone in the Diamond Creek belt, and Wright & Chatterton (1988) referred to this specimen as *P. dehiscens*. Drs R. Mawson and J. Pickett (personal communication, 1987) consider the specimen more likely to be *P. pirenae* Boersma, and it could therefore indicate a late Pragian age for the lower beds of the Jesse Limestone. *Polygnathus pirenae* has been recorded from Limekilns by Mawson et al. (1988). Present conodont data from the Jesse Limestone do not conflict with faunal age data from the Rosedale Shale.

The conodont fauna from the upper beds of the Jesse Limestone in the Diamond Creek belt includes (Wright & Chatterton, 1988) *Polygnathus* sp. cf. *P. inversus* and

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### Rosedale Shale: Faunas and Age

The Rosedale Shale yields a mostly pelagic fauna (graptolites, tentaculitids, hyolithids, conulariids) and plant fragments; benthic faunas, mostly brachiopods (notanopiids being possibly epipelagic) with some corals, rare bivalves and trilobites, also occur. Strusz (1972) reported *Monograptus yukonensis* (identified by G.H. Packham) from this formation, and inferred a Pragian age.

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### Table 1. Limekilns sequence (after Packham, 1968) showing approximate positions of fossiliferous horizons and their correlation, as suggested herein and by Wright & Chatterton (1986) and Garratt & Wright (1988).

<table>
<thead>
<tr>
<th>Bohemian Stage</th>
<th>Rock Unit</th>
<th>Thickness (m)</th>
<th>Possible Age Range</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Winburn Tuff</td>
<td>600</td>
<td>late Zlichovian – early Dalejan</td>
</tr>
<tr>
<td>Dalejan</td>
<td>Limekilns Shale</td>
<td>450</td>
<td>late Pragian – early Zlichovian</td>
</tr>
<tr>
<td></td>
<td>Jesse Limestone</td>
<td>60</td>
<td>late Pragian</td>
</tr>
<tr>
<td>Pragian</td>
<td>Rosedale Shale</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Merrians Tuff</td>
<td>450</td>
<td>late Lochkovian</td>
</tr>
<tr>
<td>Lochkovian</td>
<td>Crudine Group</td>
<td>750</td>
<td></td>
</tr>
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</table>
Thompson low-diversity indicated is similar to the dysaerobic one inferred by the Rosedale Shale are indicated by the abundant pyrite being altered to a limonitic (?) mineral. The bioturbation (e.g. Raiswell 1985) of pyrite close to the recrystallised trilobite tests, most of pyrite is believed to be derived from bacterial sediments and high initial levels of organic material in the environment (Speyer, 1985; Speyer & Brett, 1986) and cannot be carcasses of individuals killed by anaerobic decomposition of organic material (Raiswell & Bemer, 1985). The trilobites must be preserved near to their living transported intact by any common mechanism, so the processes, but are not broken or abraded by turbidity extent, crushed and deformed by soft-sediment faunas from the Wilson Creek Shale.

Preservation of Fauna, and Palaeoenvironment

In addition to the eight trilobite specimens, the trilobite locality has yielded only a few benthonic species including several brachiopod taxa (in particular a notanopliid [possibly epibenthonic] and a leptocepiidiid), a few corals and rare bivalves, as well as the 'pelagic' tentaculitids, conulariids and hyolithids.

The closest comparisons appear to be with certain parts of the Siluro-Devonian Melbourne Trough sequence. For instance, the Pragian Wilson Creek Shale contains a pelagic plant-graptolite assemblage; according to Garratt (1983) this lithofacies is restricted to the basin floor in his 'shale lithofacies' which is occasionally pyritic. In the Humevale and Boola Formations Garratt (1983) recognised the Notanopia community of Savage (1974), which may be closer to the Rosedale fauna than is the fauna from the Wilson Creek Shale.

Taphonomy. One specimen of Pac. (Paciphacops) crawfordae (AMF 73417) is found as a Salterian moult (Fig.4A) with its thoracopygon intact but slightly disturbed, the hypostoma inverted and displaced (rotated by about 130°) and located under the cephalon which is inverted. The holotype (AMF 73411) consists of a thoracopygon with cephalon nearby (not inverted), and there is another thoracopygon (AMF 73415). All specimens are, to some extent, crushed and deformed by soft-sediment processes, but are not broken or abraded by turbidity or traction currents. Salterian molts cannot to be transported intact by any common mechanism, so the trilobites must be preserved near to their living environment (Speyer, 1985; Speyer & Brett, 1986) and cannot be carcasses of individuals killed by anaerobic or dysaerobic currents.

Pyritisation. The trilobite-bearing rocks contain pyrite close to the recrystallised trilobite tests, most of the pyrite being altered to a limonitic (?) mineral. The pyrite is believed to be derived from bacterial decomposition of organic material (Raiswell & Berner, 1985; Dick & Brett, 1986); some oxygenation of the sediments and high initial levels of organic material in the Rosedale Shale are indicated by the abundant bioturbation (e.g. Raiswell et al., 1988). The environment indicated is similar to the dysaerobic one inferred by Thompson & Newton (1987) for the well-preserved, low-diversity in situ Late Devonian Litorhyhnchus fauna of New York which occurs in generally poorly fossiliferous pyritic black shales. Thompson & Newton (1987: 279) argue for "...abundant calcareous fauna..." at "...lower oxygen levels..." than those set by Rhodes & Morse (1971) that, is, down to 0.3ml/l O₂.

Depth. The sparse assemblage dominated by pelagic elements which occurs at places in laminated or bioturbated shales in the formation, together with rare graded sandy turbidites, strongly suggests a deepwater muddy 'outer shelf' or 'continental slope' environment. The shales are occasionally finely bedded and lack the chaotic structure indicative of deposition as slumps. Thus, aspects of both the restricted fauna and the sedimentary rocks demonstrate that the environment was deep and dysaerobic (perhaps episodically, see Wignall & Myers, 1988). If the dysaerobic (see above) interpretation is correct, ponding or some other mechanism may be indicated to account for the reduced oxygenation.

Similar trilobites from similar environments have not yet been described from Australia. The only other Pragian phacopid trilobite described from New South Wales is Phacops microps Chatterton, Johnson & Campbell, 1979, but this is a clearly different form from a different biofacies, being from shallow marine carbonates of the Garra Formation. A restricted trilobite fauna of Zlichovian age from the top of the Jesse Limestone described by Wright & Chatterton (1988) not lacks phacopids, but has a distinctly 'European' aspect.

Systematic Palaeontology

Phylum Trilobita

Suborder Phacopina Struve, 1847

Family Phacopidae Hawle & Corda, 1847

Paciphacops (Paciphacops) Maximova, 1972

Type species. Phacops logani Hall, 1861 by original designation.

Paciphacops (Paciphacops) crawfordae n.sp.

Figs2,3A–K,4A–H

Material examined. HOLOTYPE. AMF 73411a-b; PARATYPES. AMF 73410a-b, AMF 73412a-b, AMF 73413, AMF 73414a-b, AMF 73415, AMF 73416a-b, AMF 73417a-b. All are from the late Pragian Rosedale Shale, at Limekilns, New South Wales. Grid reference 581185, Bathurst 1:100,000 topographic sheet 8831. All material is deposited in the Australian Museum, Sydney.

Derivation of name. The species is named for
Elizabeth Crawford, collector of the described material.

**Diagnosis.** *Paciphacops (Paciphacops)* with short, stout occipital, genal and intergenal spines on cephalon, and spines on thoracic axial rings and pleurae. Axial furrow in front of S1 diverging at 75°–90°. Small, anteriorly-placed eye with 11 or 12 vertical files and from 48–57 lenses. Pygidium with about 8 axial rings and up to 5 straight pleural furrows.

**Description.** Cephalon transverse, with prominent overhanging sub-pentagonal glabella. Axial furrows deep and diverge at 75°–90° in front of S1, so that ratio of maximum to minimum glabellar width (tr.) is up to 1:2.25. L1 not as long (exsag.) as median part of occipital ring; L2 at least as long (sag.) as occipital ring. Occipital furrow shallow medially, S1 almost absent medially; both are incised laterally and swing forward laterally; posterior branch of S3 arcuate, anterior branch straight and almost parallel to axial furrow. Facial suture indistinguishable. Sculpture of glabella and posterior parts of fixigenae poorly preserved, consisting of tubercles. Posterior border furrow long (exsag.), shallow and basally rounded, swinging anteromedially well inside genal angle, deepening lateral to eye and again at junction with axial furrow; very shallow but persistent preglabella furrow. Cephalic doublure broad (sag.) anteriorly. Vincular furrow well defined beneath border, becoming deeper and notched on both sides laterally, with about 8 notches. Short, stout occipital, intergenal and genal spines present.

Palpebral furrow faint to absent; deep furrow below elevated, reniform eye developed posteriorly; weak furrow developed just above the lenses. Eyes small and low, with 11 or 12 files; posterior end located just anterior of S2, anterior end located just in front of abaxial end of S3 and very close to both axial and border furrows. Sclera depressed and narrow below lenses, and thin where seen in internal moulds. Lens composition (Fig.3) can be confidently interpreted in only a few specimens, as follows:-

- AMF73411 (ant.) 45564544443 (post.) Total lenses: 48
- AMF73416 35656664543 Total lenses: 57
- AMF73417 34555544443 Total lenses: 51

AMF 73410 (Fig.3I) and AMF 73416 have irregular lens arrangement at about midlength of eye. The difference in lens number between AMF 73411 (Fig.3A) and AMF 73416 (Fig.4G) does not appear to be size related, as the specimens are of similar size. AMF 73410 has 54 (± 2) lenses and 11 or 12 files, but is deformed and difficult to interpret. Hypostoma rather broad, with wide, gently convex forward anterior margin, acute anterior wings, convex, relatively short (sag.) oval middle body with posterior median depression of possible tectonic nature; border furrow present; 3 small posterior spines.

Thorax with prominent spines on axial rings, and on posterior pleural band just lateral to articulation point. Pleurale furrows narrow (exsag.), trend obliquely across the pleurae, and extend from near wide (tr.) but poorly defined axial nodes (not completely isolated by notches) to upper part of spatulate facet. Pleurae apparently taper steadily in width (tr.) from cephalon to pygidium. Pygidium transverse, with about 8 axial rings and a terminal piece, and up to 5 pleural furrows. Axis high and narrow, tapering slightly to ring 5, then tapering more rapidly towards the terminal piece. Axial rings longer (sag.) than narrow (sag.) ring furrows, only 5 of which are developed. Axial furrow weak over anterior few pleurae; strong concentric-forwards apodemes on the first few segments extend from axial furrow on to side of axis. Pleural furrows shallower and narrower than interpleural furrows, producing a smaller posterior portion of the pleurae which expand weakly and curve only slightly, so that the posterior pair of pleurae make an angle of about 30°–40° with the axis. Doublure narrow (sag.), almost horizontal. Border wide (sag.) and smooth, width constant.

![Fig.2. Pattern of lenses in eyes of 3 specimens of Paciphacops (Paciphacops) crawfordae (see Campbell, 1977: fig.11).](image-url)
Fig. 3. A-K: *Paciphacops (Paciphacops) crawfordae* n.sp., all from Rosedale Shale (late Pragian), Limekilns district, New South Wales. A-D, holotype AMF 73411. A, latex cast of cephalon showing occipital and intergenal spines, x2.5. B, latex cast of eye (anterior to right), x10. C, latex cast of thorax (showing spines) and pygidium, x2.5. D, latex cast of pygidium, x3. E, paratype thoracopygon AMF 73415, internal mould, x2. F, paratype partly testiferous thorax AMF 73413, x1.5. G, paratype pygidium AMF 73414, latex cast, x3. H–K, paratype cephalon AMF 73410. H, latex cast, dorsal view, x2. I, cephalon in anterolateral view, x3. J, internal mould of eye (anterior to right), x8. K, doublure showing continuous vincular furrow, x3.
Generic assignment. Although this material is poorly preserved by comparison with many Silurian and Devonian phacopids and details of the sculpture are obscure, a firm generic assignment can be made. One of the characteristics of Paciphacops (Paciphacops) is the presence of perforated glabellar tubercles in large-eyed forms (Campbell, 1977), but perforations are not visible in the glabellar tubercles in this small-eyed form. Campbell (1977) placed emphasis on the continuous vincular furrow, the thickened sclera in small-eyed forms (in particular) and the straight or slightly convex posteroventral vincular furrow. Chlupac (1977) further considered that, in Paciphacops (Viaphacops) which is not closely related to the species from Limekilns. There are no substantial differences between the eyes of Limekilns specimens which might suggest dimorphism as discussed for other phacopids by (Clarkson, 1966; Campbell, 1977).

Paciphacops (Paciphacops) claviger differs from Pac. (Pac.) crawfordae in having a greater number of pygidial pleural furrows, pseudo-half rings on the pygidial axis, spines on alternating thoracic axial rings, larger eyes with 17 vertical files, granules on the tubercles, and a prominent facial suture.

Paciphacops (Paciphacops) serratus differs from Pac. (Pac.) crawfordae in many features, including the posterior location of the large eye (14-17 files, 61 lenses), the strong palpebral furrow, the facial suture described by Sherwin (1972), the moderately deep anterior vincular furrow, the spines on some pygidial axial rings, and the absence of genal and intergenal spines. There is some suggestion that the anterior 3 or 4 pygidial axial rings in Pac. (Pac.) crawfordae bear transverse elevations, but no nodes or spines have been observed.

Balashova (1968: 206–207, pl.54, figs 1a,b, 2) erected Reedsops serratus spiniferus for a Ludlovian form from central Kazakhstan. The illustrated material has a small anteriorly placed eye having about 12 vertical files each having six lenses, a stubby occipital spine and apparently a short genal spine as seen in Pac. (Pac.) crawfordae, but no definite intergenal spine. This taxon is probably best viewed as another spinose Paciphacops but it may be close to Pac. (Pac.) crawfordae as Pac. (Pac.) serratus lacks a genal spine. Balashova’s specific assignment of this material is suspect. Many described Russian and Chinese phacopids are apparently known only from internal moulds, and external surfaces are crucial for the recognition of spines. A second Russian form, described by Maximova (1968: 84–85, pl.12, figs 7, 8a) as Reedsops aff. sternbergi, appears to have an intergenal spine.

A further Pac. (Paciphacops) specimen (AMF73418a-b) has recently been collected at Queens Pinch, near Mudgee, NSW, from the Warrata Mudstone (Wright, 1966; Offenberg et al., 1968) which is a deepwater unit dominated by a pelagic fauna (of slightly different aspect to that of the Rosedale Shale) and overlain by the mid-Zlichovian Sutchers Creek Formation yielding
Polynathus perbonus. The generic assignment is based on the weakly continuous anterior vincular furrow and a few apparently perforated glabellar tubercles; S1 is poorly preserved. This incomplete and crushed specimen (Fig. 5A–C) differs from Pac. (Pac.) crawfordae in having a genal spine placed more medially, a possible intergenal node, and a distinct facial suture. The eye has 11 vertical files and 54 lenses (ant. 3, 5, 5, 6, 6, 6, 5, 5, 4, 2), a similar number to Pac. (Pac.) crawfordae. This specimen is different from Pac. (Pac.) crawfordae, but seemingly similar to it, and offers some support for the contention that the spinose condition of these phacopids was an...

Fig. 4. A-G: Paciphacops (Paciphacops) crawfordae n.sp., all from the Rosedale Shale (late Pragian), Limekilns district, New South Wales. A-E, Paratype AMF 73417A, A, dorsal view of Salterian molt, with cephalon and hypostoma inverted, x2. B, latex cast of cephalon, showing genal and intergenal spines, x3. C, latex cast of hypostoma, x6. D, latex cast of eye (anterior to right), x10. E, latex cast of thorax showing spines, x2. F-G, paratype cephalon AMF 73416. F, internal mould showing genal spine and vincular furrow, x3. G, latex cast showing occipital and intergenal spines, x3. H. Paratype cephalon AMF 73412, latex cast showing glabellar furrows, x3.
adaptation to a deepwater environment. Available conodont data indicate different ages (Zlichovian, contrasted with late Pragian) for the two occurrences. However, both are in deepwater muds overlain by calcareous units containing abundant allochthonous limestone blocks; thus, reworked blocks could be yielding conodonts indicating only maximum ages.

**General comments on some Australian phacopids.** One of the above species (Phacops serratus) was revised by Sherwin (1972) along with other species described from New South Wales by Etheridge & Mitchell (1896) and Fletcher (1950). Victorian species of Siluro-Devonian age include the poorly known forms Phacops sweeti (Etheridge & Mitchell, 1896: 487, pl.38, fig.9; pl.39, figs 1–2; pl.40, fig.10) and Phacops mansfieldense (Etheridge & Mitchell, 1896: 501, pl.39, fig.12). Other Phacopidae described from eastern Australia, with ages suggested herein or by the original authors, include Phacops n.sp. (Talent, 1963: 106, pl.75, figs 1–6; pl.76, figs 1–8), Pragian; Phacops n.sp. B (Talent, 1963: pl.76, fig.10), Pragian; Denckmannites rutherfordi Sherwin (1969), Pragian; Phacops spedeni Chatterton (1971), early Zlichovian; Paciphacops (Paciphacops) microps Chatterton, Johnson & Campbell (1979), Pragian; Phacops serratus (Foerste, 1888); (Holloway & Neil, 1980; Talent, 1965), latest Pridolian to early Lochkovian; Reedsops n.sp., Jell & Holloway (1983), Pridolian; Phacops (Phacops) sp., Chatterton & Wright (1986), Zlichovian; and Ananaspis ekphyma Wright in Jones et al. (1986), Lochkovian. For the Late Silurian species, in particular, there is considerable disagreement concerning generic and subgeneric assignment (Sherwin, 1972; Campbell, 1976:fig.6); Strusz, fig.20in Jenkins, 1986).

It is possible that Pac. (Pac.) serratus (Pridolian-Lochkovian), Pac. (Pac.) claviger (Sienegian), Pac. (Pac.) crawfordiae (Pragian) and the form from the Warratra Mudstone discussed and figured here are related, and form a compact group which is spinose to a degree not seen in other stocks of phacopids. With so few occurrences a new genus cannot be justified, especially as some of the differences between the three taxa are substantial. Both Eldredge (1973) and Campbell (1977) caution that such spines are of uncertain taxonomic value, and we have no reason to dispute this. For instance, a prominent occipital spine is developed in a probably unrelated Middle Devonian species (Geesops battidohmi Struve, 1982).

With regard to a pattern in East Australian Early Devonian phacopids, Chatterton, Johnson & Campbell (1979) stated that Phacops spedeni is a 'late Paciphacops' transitional to true Phacops in having a long L1 and perforated tubercles, and a similar doublure ornament to Pac. (Pac.) microps. If so, spinosity may have been an early random trend seen in the Lochkovian Pac. (Pac.) serratus and the Pragian Pac. (Pac.) crawfordiae which was reversed or at least absent in the Pragian Pac. (Pac.) microps (which has juvenile genital spines and an adult genital node) and the Zlichovian Pac. (Pac.) spedeni (no spines). Preservation does not permit evaluation of the position of crawfordiae in any morphcline based on criteria relating to tubercles or ornament, as discussed by Chatterton, Johnson & Campbell (1979: 819). Dimorphism is not known in Pac. (Pac.) microps or Pac. (Pac.) spedeni, but may be present in the serratus-crosslei complex (Etheridge & Mitchell, 1896), as the latter two taxa differ only in the absence of thoracic and pygidial axial spines in Pac. (Pac.) serratus.

**ACKNOWLEDGMENTS.** We thank Elizabeth Crawford for allowing us to describe her material, and Gabor Foldvary for facilitating the loan of material. The research has been carried out during a study visit by Wright to Germany under the auspices of the Deutscher Akademischer Austauschdienst scheme; during this time he has been at the Institut für Paläontologie, Universität Bonn while on leave from the University of Wollongong. Dr K.A.W. Crook made available Voorhoeve's thesis. Professor K.S.W. Campbell and Dr D.J. Holloway commented on an early draft of the paper. For all this assistance we express our sincere thanks. Wright's work on Devonian biostratigraphy of the Lachlan Fold Belt has also been supported by the Australian Research Grants Scheme and the University of Wollongong.

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**Fig.5.** A–C: Paciphacops (Paciphacops) sp., Warratra Mudstone (Zlichovian), Queens Pinch district via Mudgee, New South Wales, AMF 73418. A, latex cast of exterior showing genal spine, x3. B, latex cast of eye (anterior to right), x10. C, internal mould of eye (anterior to right), x10.
References


Accepted 30 November 1989